VTT

Fibre and polymer separation

Mechanical recycling of polymer coatings

Chemical recycling of polymer coatings via gasification

Life cycle assessment

Fiber and Polymer-Coated Barrier Material Recycling

Final Report of the VTT ReMatCh Project

Minna Kurkela | Ilkka Hiltunen | Esa Kurkela | Sanna Tuomi | Christian Frilund | Marjo Määttänen | Ilkka Rytöluoto | Joonas Mikkonen | Kalle Kinnunen | Hanna Pihkola

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Cover image: Stora Enso

Preface

This report “Fiber and Polymer-Coated Barrier Material Recycling - Final Report of the VTT ReMatCh project” provides an overview of the research results of VTT’s ReMatCh project, mainly funded by Stora Enso Oyj. The project was a collaborative research initiative conducted between VTT and Stora Enso Oyj from May 2023 to December 2025.

VTT researched ways to make polymer-coated board more recyclable and tested new recycling methods. The report brings together the key findings from the project's four work packages. WP1 covers fibre and polymer separation; WP2 focuses on mechanical recycling of polymer coatings; WP3 examines chemical recycling of polymer coatings through gasification; and WP4 presents life cycle assessment.

Espoo, May 2026

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Foresight and data economy - Sustainable business:
Kalle Kinnunen, Hanna Pihkola (WP4)

Contents

List of symbols

ASU	Air Separation Unit
BFB	Bubbling Fluidized Bed
CHP	Combined Heat and Power
daf	Dry ash free
d.b.	Dry basis
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
FT	Fischer-Tropsch
FTIR	Fourier Transform Infrared Spectroscopy
GC	Gas Chromatograph
GHG	Greenhouse Gas
GWP	Global Warming Potential
HHV	Higher Heating Value
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
LHV	Lower Heating Value
LPB	Liquid Packaging Board
MFR	Melt Flow Rate
MTO	Methanol to Olefins
NIR	Near-infrared
OCP	Olefin Cracking Process
PE	Polyethylene
PDU	Process Development Unit

PolyAl	Polymer and aluminium residue after paper repulping process
POX	Partial Oxidation
TGA	Thermogravimetric Analysis
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

1 Introduction

The transition to a circular economy for plastics is advancing, reflected in both industrial practices and legislative developments. Potential methods and pathways for integrating recycled raw materials and feedstock into the manufacture of high-quality recycled products are being examined. At the same time, legislation is introducing increasingly stringent targets for plastic waste recycling rates, recyclability, and the proportion of recycled material used in plastic packaging. Multiple recycling methods are necessary, with regulations prioritizing those that minimize CO_2 emissions and energy use, as well as promoting re-use and material-to-material recycling.

The collection rate for beverage cartons in Europe is typically about 40% - 50 %, varying on the country. However, Germany has achieved a collection rate as high as 87%. The recycling rate remains between 20% and 50% depending on the country. Certain types of packaging are easier to recycle than others. Plastic packaging materials that contain aluminium, often used for e.g. food products, are challenging to recycle due to its multi-layered plastic and metal composition (Zero waste Europe 2020).

At present, polymer barrier-coated board waste is collected with other types of paperboard waste. Typical beverage carton composition is 75% board, 21% polymer and 4% aluminium. The recycling rate comes from the board that can be used in lower grade fibre products due to reduced fiber length, where the polymer and aluminium are more challenging to recycle and is typically sent to waste to energy treatment (Lahme et al. 2020).

Stora Enso has joined a collaboration ecosystem of leading value chain players and research institutes to solve major challenges in packaging circularity. Recycled Material Challenge (ReMatCh)[1] program by Stora Enso is part of the larger collaborative platform with Business Finland, focused on a core mission to improve the circularity of polymer (i.e., plastic) barrier-coated board materials.

Stora Enso's ReMatCh project was further strengthened by its collaboration with VTT, whose research project focused its activities on addressing challenges related

[1] ReMatCh: Advancing circularity of fiber and polymer-coated barrier material through collaboration.

to polymer recycling, utilizing both mechanical and chemical recycling processes. The VTT ReMatCh project began in early 2023 and continued until the end of 2025. The separation techniques of polymer, fiber, and aluminium layers from the supplied feedstock were studied, as well as R&D efforts to develop and test advanced pretreatment methods and recycling processes. Recycled polymer materials were further evaluated through experimental gasification research and development activities, allowing for practical assessment of new approaches. VTT's major focus was on advancing the gasification process, conducting gasification test campaigns of aluminium-containing plastic rejects to produce synthesis gas.

2 Objectives

This report examines the challenges associated with recycling polymer-coated board materials and address major packaging circularity challenges. The goals were here to develop advanced methods for separating polymers from fibers in polymer barrier-coated materials and to optimize both material streams for enhanced recovery and recycling. The project also examined the integration of separated polymers into mechanical and chemical recycling processes, with the aim of facilitating potential reuse by Stora Enso in different applications. In addition, a life cycle assessment (LCA) was conducted for the new recycling options studied. The research project was organised into the following four work packages (Figure 1):

- WP1: Fibre and polymer separation
- WP2: Mechanical recycling of polymer coatings
- WP3: Chemical recycling of polymer coatings via gasification
- WP4: Life cycle assessment

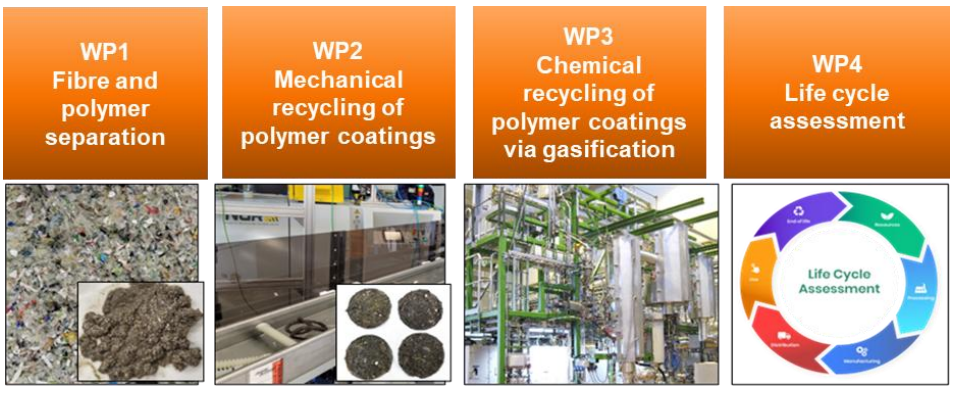


Figure 1. Project research topics.

Several potential solutions for polymer coating recycling were investigated in this report, such as fibre, aluminium and polymer separation, mechanical recycling and thermal gasification. The research findings for each topic are presented in the following chapters.

3 WP1: Fiber and polymer separation

Polymer-coated board waste is currently recycled primarily from separately collected packaging board waste by separating the cellulose fibre component and the plastic-rich component during the re-pulping process. After separation, the plastic-rich fraction still contains cellulose fibres and aluminium. As a result, it is typically utilized for energy production rather than being recycled. To enable effective mechanical recycling of plastic, it is necessary to remove any residual cellulose fibres.

Fiber and polymer separation research work was divided into three phases: state-of-the-art review for the separation of fibre materials from plastics, laboratory trials for fibre material separation and demonstration trials for fibre material separation. The purification and separation of larger batches are addressed in WP2 of this report.

3.1 Literature review

The work in WP1 began with a state-of-the-art review on fibre separation from plastic rich fraction of polymer-coated board. The literature review examined topics related to separation of aluminium and PE-layers as well as enzymatic hydrolyses of wastepaper and cardboard fibers. The objective was to remove residual fibers from the polymer material through either enzymatic or acid hydrolysis. Additionally, requirements for purification and the removal of harmful impurities prior to the mechanical recycling of plastics were assessed. The necessary chemical characterization methods and available laboratory and demonstration equipment were also evaluated. An overview of the literature review is provided in Appendix A.

The review showed that the separation of the aluminium foil layer from the polyethylene (PE) layer can be effectively achieved using acid treatments. Acids facilitate the delamination of these layers, although some stickiness may remain. Based on the literature review it was agreed that laboratory trials will focus on the delamination of PE and aluminium layers using organic acids such as citric acid, lactic acid and oxalic acid. Separation of fiber material from cupboard was agreed to carry out with the combination of hydra pulping and hydrolysis of fiber residual from PE layer with the use of acids and enzymes.

Based on the review, the most suitable approaches were selected and tested at the laboratory scale, and materials characterized. The most effective separation technology was then demonstrated on a batch of plastic material.

3.2 Laboratory trials for fibre material separation

Research was focused on the separation of fibre, aluminium and polymer from the supplied feedstocks. The feedstocks studied were plastic waste containing aluminium and fibre materials, and polyethylene (PE) coated cupboard (Figure 2).

A plastic waste sample was collected from the same feedstock bale used in the gasification experiments of WP3. This material, known as PolyAl, is the coating found on cardboard and represents the leftover fraction after carton packaging waste is recycled. Specifically, PolyAl is made up of the aluminium and polyethylene layers that remain once the paper fibres have been removed and processed for recycling. Table 1 presents the average analysis for the plastic waste raw material used.

Figure 2. Plastic waste with aluminium and fiber residues (left) and cupboard with fiber material and PE (right).

Table 1. Analysis of plastic waste containing aluminium and fibre material.

Feedstock properties	
Moisture, wt%	8.8
Volatile matter, wt% (d.b.)	82.9
Dry matter analysis, wt%	
C	70.8
H	10.5
N	0.2
Cl	0.14
S	0.021
O (diff.)	2.7
Ash	15.6
LHV, MJ/kg (d.b.)	38
HHV, MJ/kg (d.b.)	41
Aluminium (metallic), wt% (d.b.)	12

The work concentrated on delamination testing and the combination of hydra pulping and hydrolysis methods, as described below.

Delamination experiments

The objective was to conduct experiments aimed at delaminating polyethylene (PE) and aluminium layers with different acids (citric, lactic, oxalic) and water as a reference.

Small scale trials used a 10 g plastic waste sample at 5% consistency. After treatment, residual acid or water and the solid waste material were separated. The solid waste material was washed with cold water, then disintegrated for five minutes at approximately 0.3% consistency using a British disintegrator. The suspension was diluted to 5L and left for sedimentation for one hour. Light plastic fraction was collected from the top of the suspension, and the rest of the suspension (including heavy fraction and liquid) was filtered through a 1µm fiberglass filter media. The residual acid was filtered using the same filter media. Both the light plastic fraction and the filter media were dried in the oven and weighed. The amounts of aluminium particles in each fraction were measured manually. Appendix B provides detailed images of plastic and aluminium fractions after acetic acid treatment.

The plastic waste material was very heterogeneous, and the sample size used was insufficient to give reliable results between experimental points. The proportion of the light plastic fraction varied from 44-69 wt% with Al content 0.9-9.5 wt%. The heavy fraction was 27-42 wt% with Al content 9.5-44 wt% and PE content of 8.2-23 wt%. Figure 3 illustrates the process to separate plastic and aluminium particles from the sample.

Figure 3. Example of manual determination of PE and Al content of the heavy fraction.

Small-Scale Delamination Test Results

- Raw material was nonhomogeneous and influenced the quality of sampling.
- The light (mainly PE) fraction ranged from 44–69 %, with Al content between 0.9–9.5 %.
- The heavy fraction ranged from 27-42 %, with Al content 9.5-43.7 % and PE content 8.2-23 %.
- For laboratory-scale trials, reference water and acid treatment conditions were selected based on the purity (low Al content) and the particle size of the PE fraction.

The experiments continued on a slightly larger scale using a 300 g (as o.d.) sample size with one acid treatment and a reference water treatment. The test was conducted using the procedure in Figure 4 with oxalic acid (9.5w-%) for two hours at 40°C and with 60°C hot water for three hours.

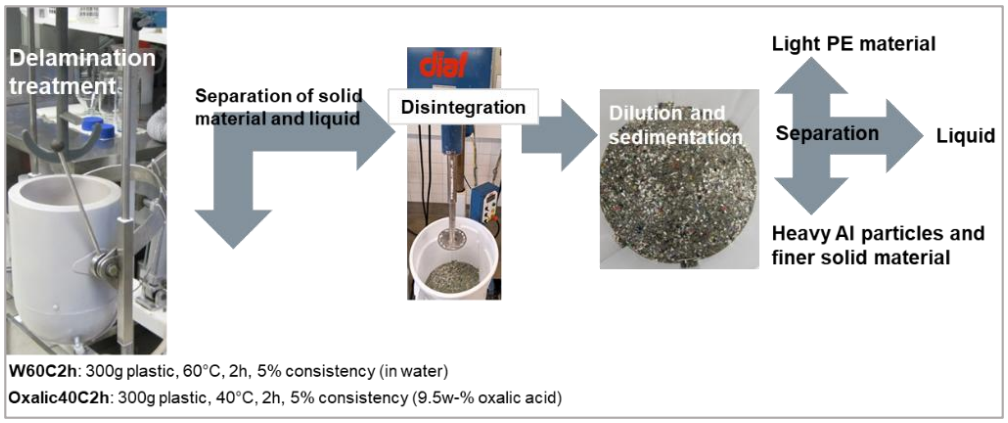


Figure 4. Larger scale procedure of delamination trials of waste plastic with oxalic acid and water.

During processing, several fractions were separated: a light plastic fraction, a heavy fraction containing aluminium, wood, and plastic pieces, a heavy solid fine material, and solid material from filtrates (Figure 5). Experimental results indicated that the separation efficiency of the light plastic fraction using oxalic acid was slightly higher (72 %), than with hot water (65%).

Figure 5. Light plastic fraction (left), heavy fraction (middle) and heavy solid fine material (right).

The recovered light plastic fractions were first characterized and then sent to WP2 within this project for further testing. Plastic grade was analyzed by differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA) determined the amounts of fiber, plastic and inorganic materials. CHNOS and heat value analyses determined the plastic and residual fiber content (Table 2). The heavy solid fine material was also analyzed to identify its composition.

Table 2. Characterization of fractions.

Sample	Hot water (W60C 2h)	Oxalic acid (Oxalic40C 1h)	Heavy solid fine material
C, wt%	81.0	78.4	11.7
H, wt%	13.6	13.2	1.45
N, wt%	<0.05	<0.05	0.08
S, wt%	<0.02	<0.02	<0.02
O (diff.), %	1.2	4.2	8.3
Total, %	95.8	95.7	21.5
Ash, wt%	8.4	4.5	58.7
LHV, MJ/kg	39	40	n.m.
HHV, MJ/kg	42	43	n.m.
Plastic[1], %	90	93	
Al[2], %	4.3	0.3	
Al[3], %	1.25	0.14	30.7
Ca[3], %	0.56	0.33	0.53
Cl[4], mg/kg	80	134	-
Fe[3], mg/kg	801	167	5160
Si[3], mg/kg	628	<600	736
Ti[3], mg/kg	106	2040	107

[1]: ISO 1833-11:2017 [2]: Determined from plastic content analysis (VTT). [3]: EN ISO 17294-2:2023, US EPA Method 200.8:2008 [4]: EN ISO 17294-2:2023, US EPA Method 200.8:1994

Findings from Laboratory-Scale Delamination Experiments

- Delamination with water or acid, followed by sedimentation, separates the aluminium and plastic layers.
- Aluminium content in the plastic fraction was lower with acid delamination treatment as shown by ICP, TGA and visual analysis.
- TGA results showed that some organic material is present in the plastic fraction with water delamination treatment.
- After sedimentation, the heavy fraction can be separated into larger aluminium particles and fine materials containing aluminium, PE and cellulose-based material.
- Increasing particle size may enhance separation efficiency for all materials.

Hydra pulping and hydrolysis of residual fibre from cupboard

PE layers and cellulosic fibres were separated from cupboard using hydra pulping, followed by enzymatic hydrolysis to purify residual fibres from the PE stripes. The original plan was also to try acid hydrolysis for purification, but due to low melting temperature of PE it was not conducted. The hydro pulping procedure is described in Figure 6. Soaking and disintegration were carried out either in pure water or in mild alkaline conditions with cupboard consistency of 2.5 or 5% in the suspension. After disintegration, the feedstock was diluted and screened using two-stage screening. Most of the PE stripes were collected from a 1 mm slot screen. The purity of the PE stripes was analyzed according to method ISO 1833-11:2017 (exception in drying temperature 80°C). Enzymatic hydrolysis treatments were carried out with Cellic®CTec3 HS using dosages of 5 and 10 mg protein/g pulp fibre for the post-purification of the stripes. Treatment conditions were 55°C, consistency 5%, pH 5 and treatment time 60-240 min. Enzymatic treatments were first tested on a small scale for about 13 g of PE stripes to find right enzyme dosage and treatment time. Then, for a larger amount, 115 g, with the selected condition (Cellic®CTec3 HS 5 mg/g pulp and treatment time 120min).

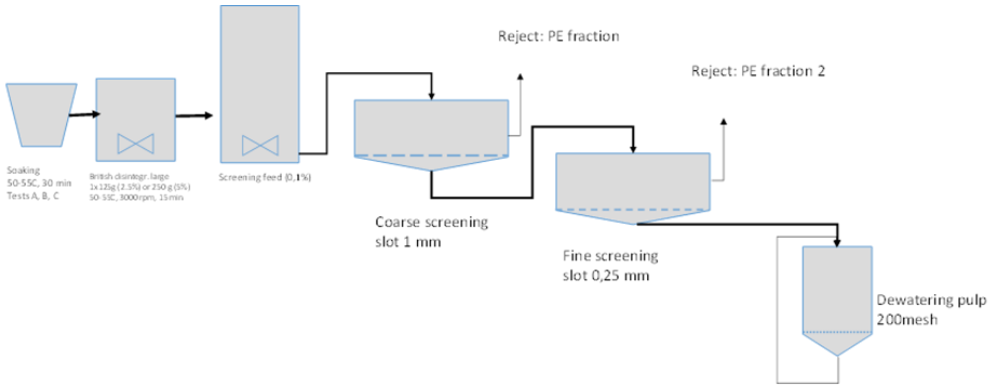


Figure 6. Hydra pulping procedure for the separation of cellulosic fibres and PE layer.

Based on the experimental results, it can be concluded that hydropulping using an effective British disintegrator successfully separated cellulosic fibres and PE stipes, achieving a high PE purity of 96-98 % (Table 3). Less effective disintegration with Diaff yielded 93 % purity. Mild alkaline conditions in the disintegration seemed to slightly improve the purity. In small scale trials, enzymatic hydrolysis removed almost all the fibres, but in the larger scale trial, the increase was about 2%-units in PE purity. The PE stripes from the larger scale trial were sent for further testing (Chapter 4: WP2).

Table 3. The purity of PE stripes after hydra pulping and enzymatic hydrolysis.

	Water	**5% NaOH,** (disinteg. Britt.)	**5 % NaOH,** (disinteg. Britt.)	**5 % NaOH,** (Two batches, disinteg. Diaf)
Disintegration consistency, %	2.5	2.5	5.0	5.0
5% After hydra pulping				
PE content, %	96.4	97.7	98.1	92.6
Post purification with Cellic®CTec3 HS				
PE content, % Cellic 5mg/g		99.3-101 (small scale trials)		94.8 (large scale trial)
PE content, % Cellic 10mg/g		99.7-101.1 (small scale trials)		

3.3 Demonstration trials for fibre material separation

Delamination trials using plastic waste (2 x 15 kg) containing aluminium were performed at VTT's Process Chemistry Pilot. Figure 7 presents the flow charts for these trials (Pilot W60°C 3h). Appendix C outlines the procedures for conducting pilot delamination demonstration trials.

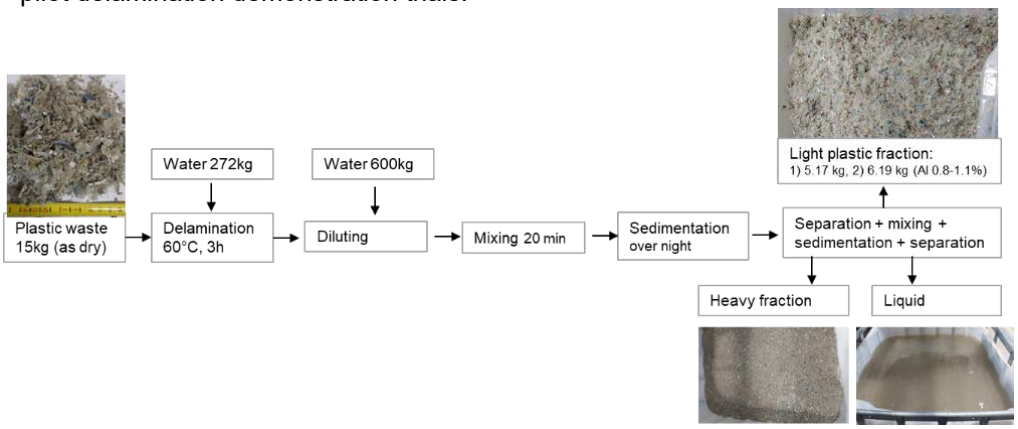


Figure 7. Flow chart of the pilot scale delamination trials.

The light plastic fraction collected from these tests was forwarded for thermomechanical processing tests, as detailed later in this report. The yield of the light plastic fraction (38%) recovered from delamination trials was clearly lower than the amount recovered on the laboratory scale (65%). This was because the delamination of the Al layer from the plastic layer was less effective than on a laboratory scale, caused by insufficient material disintegration after water treatment.

The analysis of the light plastic fraction showed that its purity was better than on the laboratory scale. Comparison of the properties of the light fraction and the original plastic waste is shown in Table 4.

Table 4. Characteristics of the original plastic waste and the light fraction.

	Plastic waste	Pilot W60°C, 3h batch 1	Pilot W60°C, 3h batch 2	Lab Hot water (W60°C 2h)	Lab Oxalic acid (40°C 2h)
Plastic, %[1]	-	92.1	95.3	89.7	93.0
HHV, MJ/kg	40.5	43.9	43.8	41.9	42.8
LHV, MJ/kg	38.2	40.7	40.7	39.0	39.8
Moisture, wt%	8.8	0.2	0.1	-	-
Volatile, wt% (d.b)	82.9	95.6	96.0	95.8	95.7
Dry matter analysis, wt%					
C	70.8	80.8	81.4	81.0	78.36
H	10.5	14.4	14.5	13.6	13.17
N	0.2	0.4	0.2	<0.05	<0.05
O (as diff.)	2.7	<0.02	0.5	1.20	4.17
S	0.021	0.009	0.005	<0.02	<0.02
Ash[2]	15.6	4.3	3.5	8.44	4.52
Cl	0.14	0.4	0.008	0.008	0.013
Al	12	1.1[3]	0.8[3]	1.3-4.3	0.3-0.14

[1] Quantitative chemical analysis (for textiles) ISO 1833-11:2017, exception drying temperature 80°C. Reference PE film purity 99.9% (VTT). [2] Al included. * Determined/collected from plastic content analysis (VTT).

Findings from Pilot-Scale Delamination Testing

- Delamination of the Aluminium layer from the plastic layer was not as effective as in a laboratory scale due to less effective disintegration of materials after water treatment (a container mixer vs Diaf)
- The purity of the separated light fraction was better in the pilot scale (higher plastic content, lower Al content, higher heating values)

4 WP2: Mechanical recycling of polymer coatings

One option for polymer coating recycling is mechanical recycling with melt filtration and valorization of the polymer to be suitable for reuse in Stora Enso coating line. VTT examined mechanical recycling of polymer from the coated board material by melt filtration and explored options to upgrade with additives and/or virgin LDPE to result usable material for coating extrusion. These properties can be tailored to meet the specific requirements for efficient processing into new products.

In addition, the VTT's pilot-scale coating extrusion line (PLASCO), as well as the laboratory-scale extrusion and biaxial orientation line, can be used to show the feasibility of the upgraded plastic.

VTT examined mechanical recycling of polymer from the coated board material by melt filtration and explored options to upgrade with additives and/or virgin LDPE to result usable material for coating extrusion. The research included literature review on melt filtration and mechanical recycling, and experimental research for plastic fraction from the cardboard and pilot scale mechanical recycling process development. Additionally, experiments were carried out on the plastic fraction with fewer fibres.

4.1 Literature review

Literature review focused on mechanical recycling options for liquid packaging boards. The work covered a comprehensive SoA-review on mechanical recycling and requirements and limits for the material feed. Below is a summary of the topics reviewed:

Mechanical Recycling (Prajapati et al. 2021, Lahme et al. 2020, Schyns et al. 2021, Maris et al. 2018)

- Mechanical recycling is preferred to chemical recycling due to lower costs, easier to manage, and compatible with current equipment.
- Mechanical recycling of plastic from beverage cartons has been implemented at certain facilities in the past, but these operations were

discontinued after a few years due to financial challenges compared to alternative disposal methods.

- Extrusion is typically used in mechanical recycling to produce regranulated material from waste plastics.
- The process usually involves extrusion, which includes filtering, degassing, and drying to enhance polymer quality, and often requires the addition of materials like virgin polymers, fillers, or compatibilizers to improve the final product.

Melt Filtration (Obermayer 2020, Pachner et al. 2017, Koller et al. 2021)

- Melt filtration is one of the crucial processes in the mechanical recycling of multi-material plastic components. Impurities e.g. paper, cardboard, aluminium, rubber, etc., and leftover plastics in the recycling stream lower the quality of recycled feedstock. Melt filtration helps remove these contaminants, producing recycled materials with properties like virgin plastics.
- Melt filtration units and mesh screens are chosen based on the input feedstock and the required properties of the final pellets.
- The two main filtration designs are: (a) automatic back flushing filters with wire mesh screens, and (b) self-cleaning continuous filters using steel screen discs.
- Operation of a Self-Cleaning Continuous Melt Filtration System is shown in Figure 8.
- In general, an extruder alone can deliver the melt through the filter, if it produces enough pressure for the needed throughput.
- The extruder plays a key role in controlling contaminant size and ensuring material is well mixed before the melt filter; evaluating different designs and components is recommended.

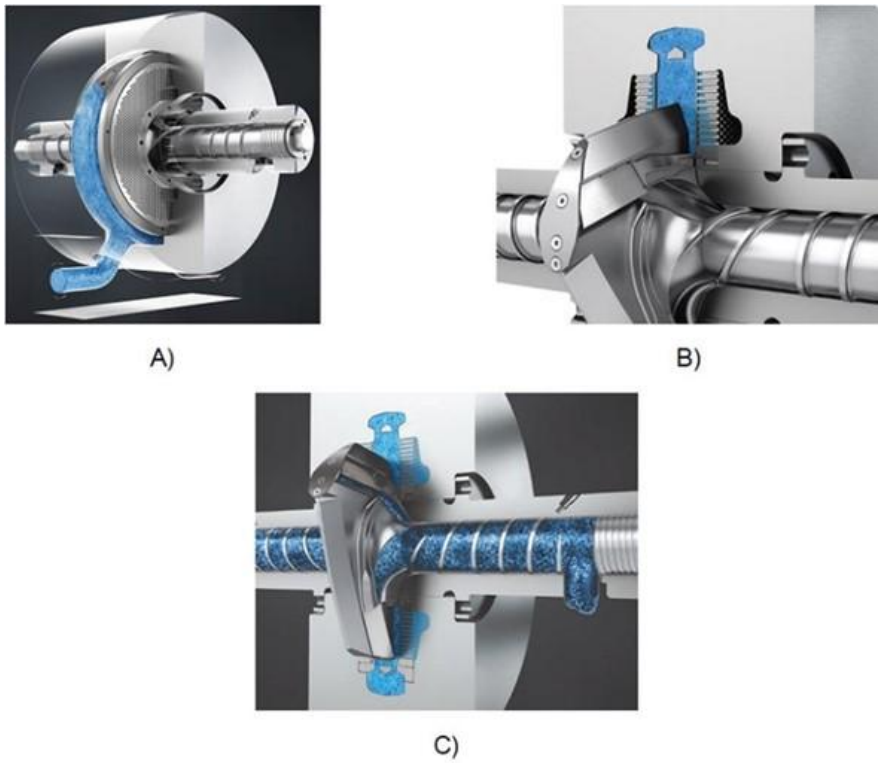


Figure 8. A) Contaminated plastic melt from the extruder enters a circular distributor ring into a housing with two parallel laser-drilled screen discs B) The melt is squeezed through the screen discs which penetrates through and leaves the filter in a clean state via the collection channel. C) The contaminant particles accumulate on the screen during the melt flow. A disc equipped with three scrapers on each side revolves between the screen discs. The affixed scrapers swiftly elevate the contaminants from the sleek, hardened screen discs, directing them straight to the discharge system (Obermayer 2020).

Selection criteria for a Low-Maintenance Filter (Obermayer, R., 2020)

- Piston screen changers and laser filters, built for post-consumer recycling with upstream preparation, sorting, and washing, are designed for reliability. The robust construction ensures efficient, long-term filtration in demanding recycling processes.
- Prioritizing simplicity and robust design, melt filtration systems should facilitate smooth melt flow without dead spots or clogged material.

Commercial Melt Filters

- Commercial melt filter manufacturers and their product options with the performance indicators were examined.

Addivation for upgraded plastic (Schyns et al. 2021)

- Polyethylene typically requires stabilizers to reduce thermo-oxidative degradation during melt processing. These additives also enhance UV stability.
- Irganox 1010 is commonly used but can be replaced also by bioderived antioxidants if migration of potentially carcinogenic agents needs to be avoided.
- Virgin polymers are often added to LDPE waste plastics to compensate the changes in the waste plastic property loss.

4.2 Pilot scale mechanical recycling process development

The task focused on the characterization of the processed feedstock samples from WP1 with VTT's analytical equipment like FTIR/NIR, TGA, DSC, DMA and the mechanical recycling process development using VTT's pilot scale mechanical recycling line (VAREX, VTT Polymer Pilot) with melt filtration, degassing unit and inline melt rheology control and additivation. The pilot mechanical recycling line is illustrated in Figure 9. It was used to demonstrate the capabilities of mechanical recycling on the feedstock, aiming to improve the properties to be used in coating film extrusion. The properties of the upgraded plastic will be evaluated using VTT's analytical equipment.

The plan also included the coating film extrusion with VTT Polymer Pilot PLASCO line suitable for coating extrusion or lab scale sheet extrusion and biaxial orientation line. However, this was not feasible.

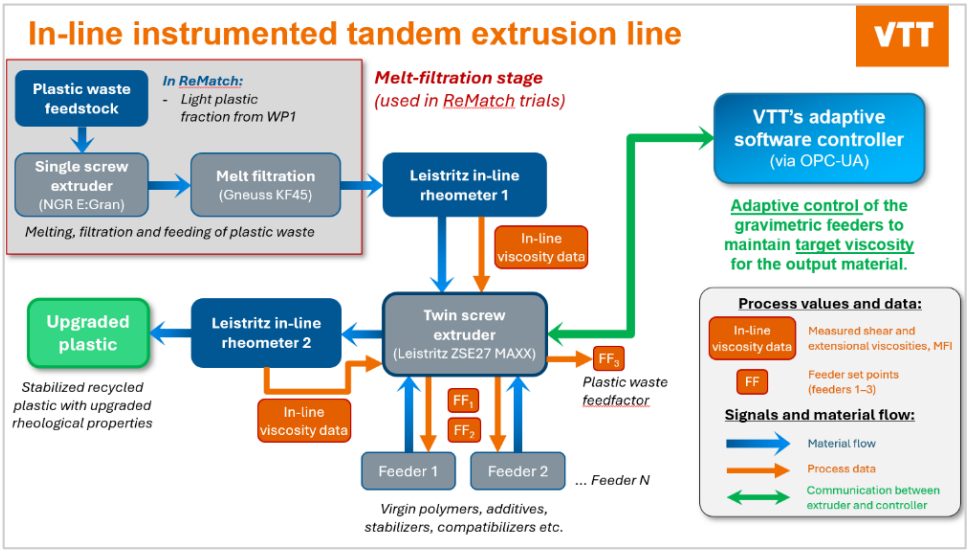
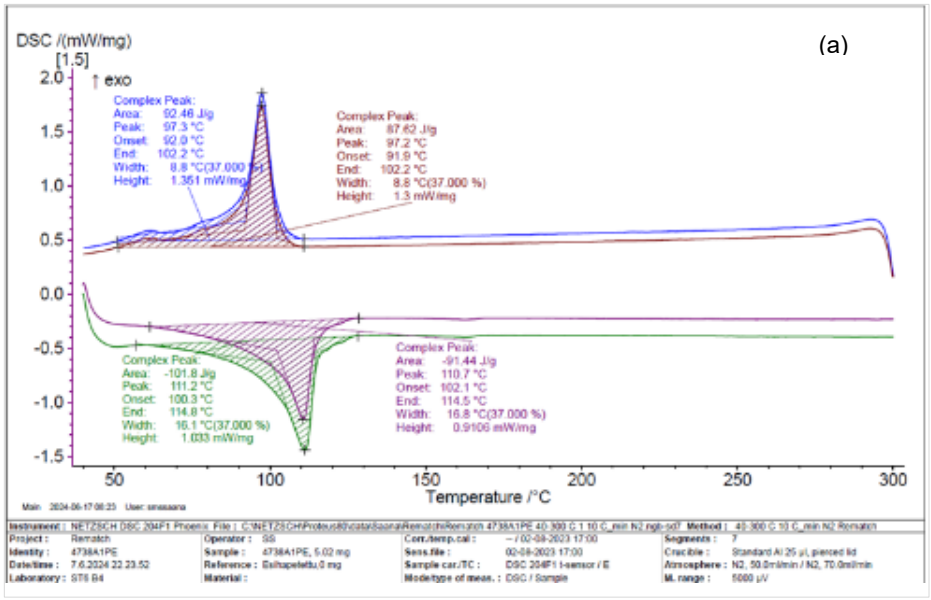
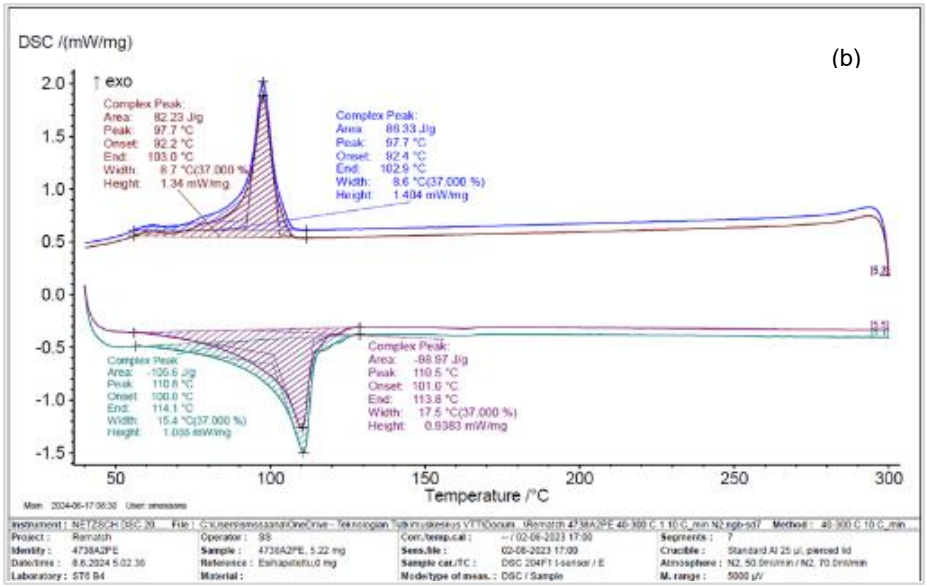


Figure 9. VAREX pilot scale mechanical recycling line: designed for the mechanical recycling and upgrading of plastics.

Laboratory characterization

Different samples from WP1 (W60C2h sample: ~90% PE, Al 1,3-4%, Oxalic40C2h sample: ~93% PE, Al ~ 0,2% and PE stripes from hydropulping) were analyzed by differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and melt flow rate (MFR). The DSC results are shown in Figure 10. There was not much difference between the samples, and they consisted mostly of LD-PE (melting peak at ~110°C) with a barely noticeable amount of PP as well (small peak at 160-170°C).





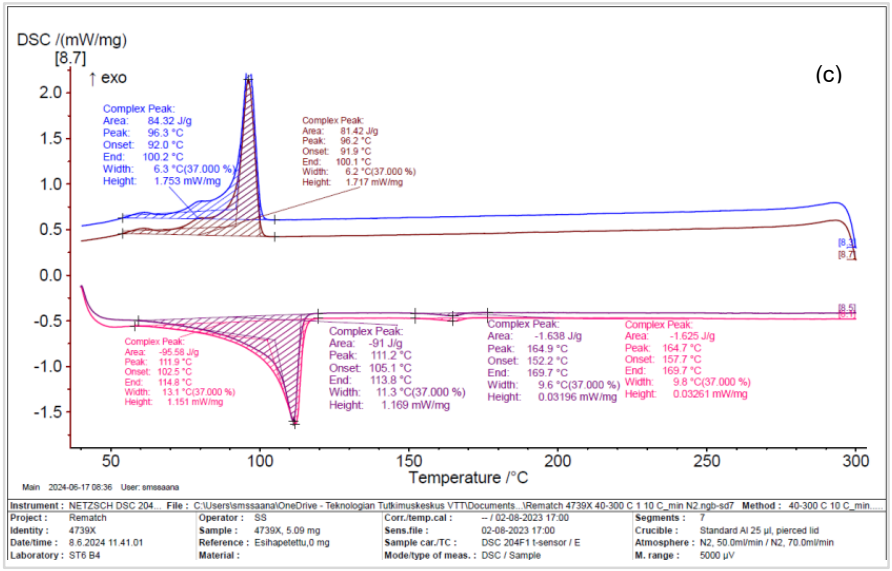
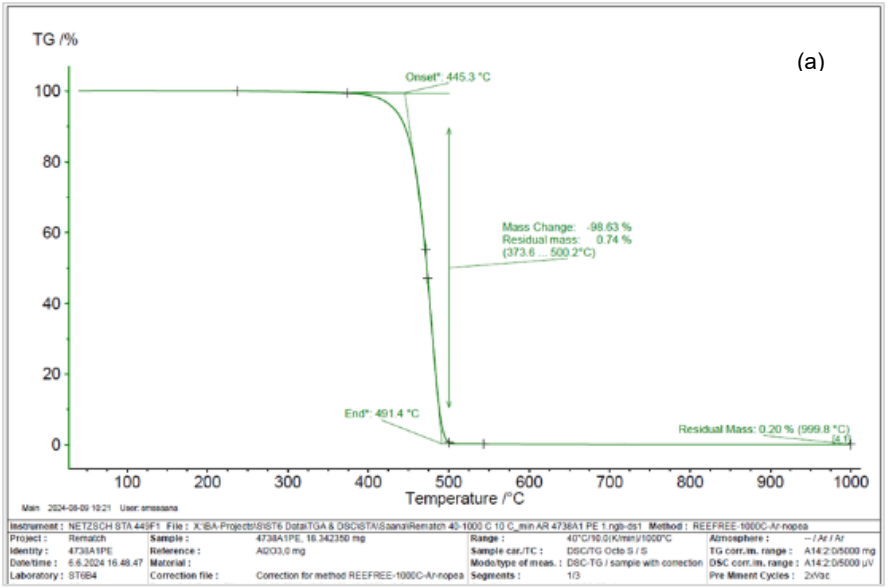


Figure 10. DSC graphs of the light plastic fractions. Samples: (a) W60C2h; Plastic ~ 90%, Al 1,3-4% (b) Oxalic40C2h; PE content in samples: ~ 93%, Al ~ 0,2 and (c) PE stripes from hydropulping, PE95%).

The TGA analysis results for all three samples are presented in Figure 11. There is a slight difference in the curve when comparing sample a (W60C2h) to b (Oxalic40C2h) and c (PE stripes from hydropulping). No clear explanation for this was found and could be equipment related. The residual mass was the highest with sample b (Oxalic40C2h), which can be associated with inorganic impurities and aluminium, for instance.



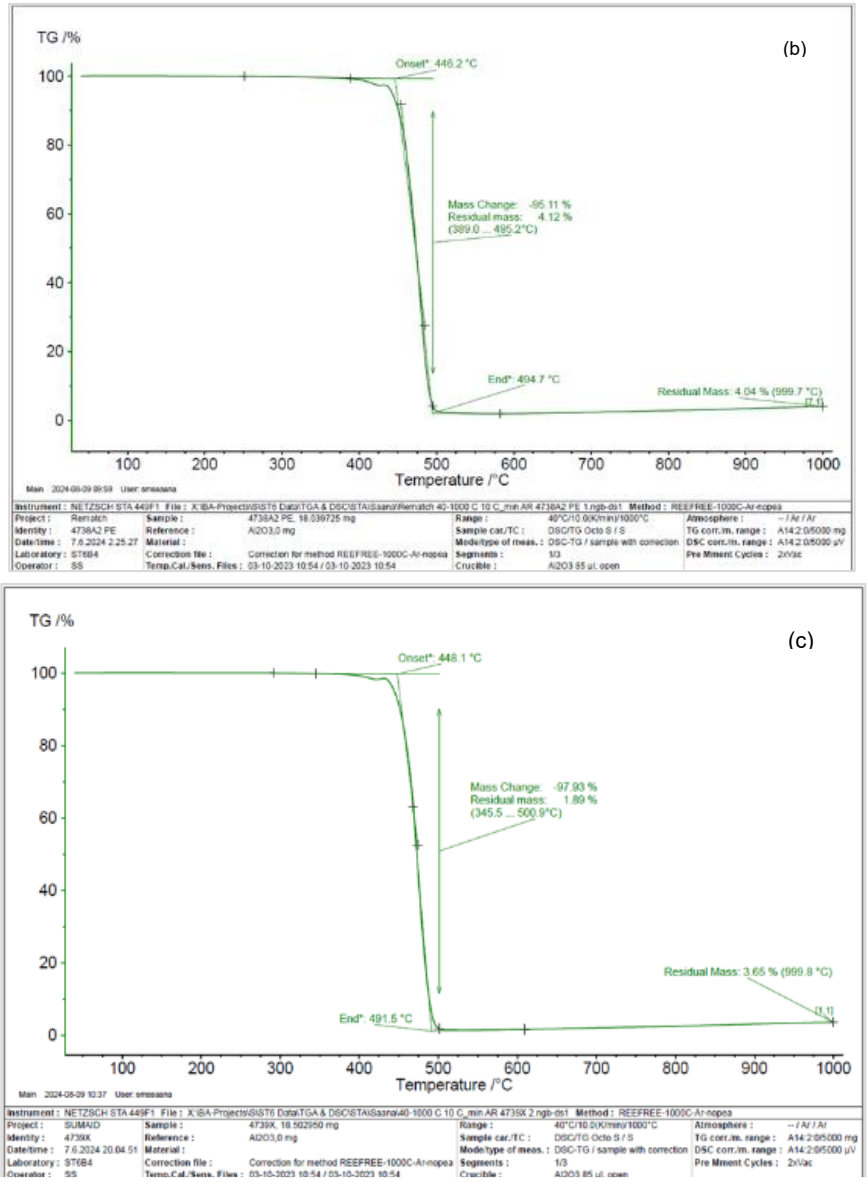


Figure 11. TGA analysis results. Samples: (a) W60C2h, (b) Oxalic40C2h and (c) PE stripes from hydropulping.

The MFR analysis results are presented in the Table 5. For LDPE, the standard method of 2.16 kg weight was changed to 5kg due to high viscosity of the samples. As a reference, the typical MFR value for coating extrusion grade LD-PE is around 4-8 g/10 min (190°C/2.16kg) and for sheet extrusion grade LD-PE ~0.3 g/10 min (190°C/2.16kg).

It is evident that the plastic goes through transformation towards much higher viscosity after the coating extrusion process and without high load of virgin plastic, the same use will not be possible.

Table 5. The MFR analysis results for the samples.

Sample	MFR mean	MFR std
PE stripes from hydropulping (190C 5.00kg)	1.16	0.03
W60C2h (190C 5.00kg)	1.41	0.03
Oxalic40C2h (190C 5.00kg)	1.24	0.03

4.2.1 Pilot scale mechanical recycling process development

Because laboratory characterization showed challenging melt flow rate properties of the materials, instead of upgrading the plastic after the cleaning process, it was more beneficial to try if compacting it would be possible.

The bigger batch of material was also planned to be run through VTT VAREX advanced mechanical recycling line with melt filtration and degasification, aiming to compact, homogenize and pelletize the material for further processes. However, only melt-filtration test could be realized, as the material was found to be too contaminated to be used for the pilot-scale extrusion and upgrading process.

The test setup consisted of a single-screw feeding extruder (NGR E:Gran) and a disc-type screen changer (Gneuss KF45), allowing the material to be extruded and cooled in a water bath after melt filtration, see Figure 12. The mesh size of the used filter was 315 µm.

Figure 12. Melt filtration of light plastic fraction from WP1.

During the melt-filtration tests, it was necessary to increase the processing temperature gradually from 210 °C to 230 °C as the material showed extremely low melt flow properties. Moreover, it was soon observed that the melt filter disc became clogged very rapidly during the extrusion which is a clear indication of excessive impurity content for extrusion and upgrading trials. As is evident from Figure 12, the output material was dirty, discolored and showed signs of severe melt fracture which is associated with flow instability. This can also be partly related to degradation during the extrusion processing, as increasing the processing temperature can also lead to more rapid degradation of the fiber residues in the plastic.

Approximately 1.5 kg of the material was processed by melt-filtration. A photograph of the melt-filtered and granulated material is presented in Figure 13, along with images of the filter discs and residues. Lots of metals (i.e. aluminium foil) and other impurities (fibers, dirt, non-melted polymers) were removed in the melt filtration step.

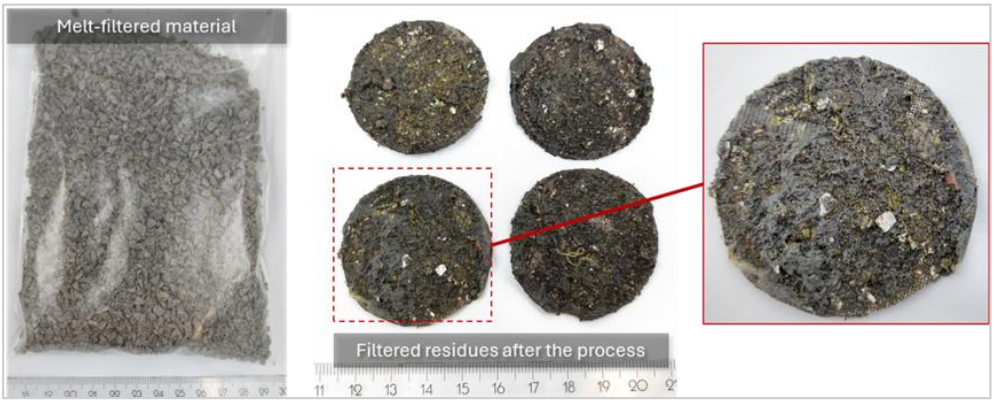


Figure 13. Melt filtered material and filter disc residues.

Further analysis of the filtered residues was performed by optical microscopy (see Figure 14, Figure 15, Figure 16), confirming the presence of significant amounts of aluminium foil, fibers and non-PE polymer in the light fraction feedstock.

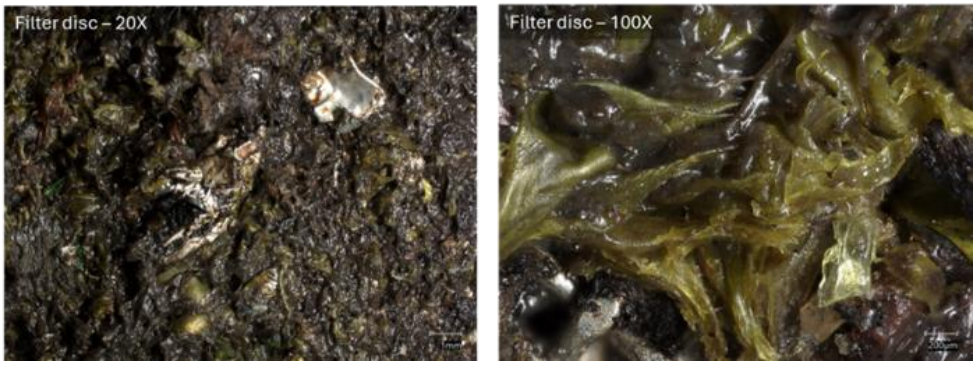


Figure 14. Optical microscopy of the filter discs after melt-filtration.

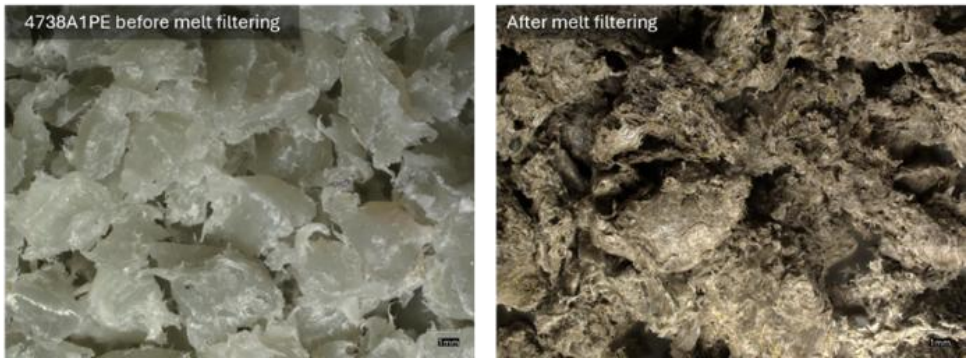


Figure 15. Optical microscopy of the material before (left) and after melt filtration (right). Magnification of 20X.

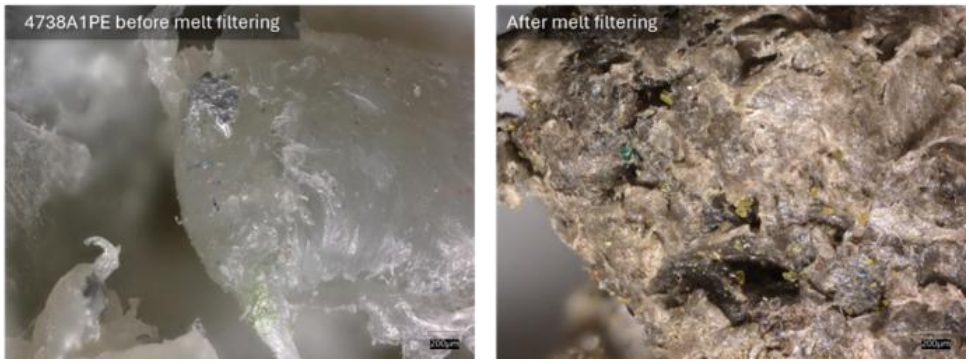


Figure 16. Optical microscopy of the material before (left) and after melt filtration (right). Magnification of 100X.

Findings from melt-filtration trials

As a conclusion of the melt-filtration trials, it was not found to be feasible to perform further extrusion and upgrading experiments for the material due to the excessive impurity content and low-flow properties. For instance, viscosity measurement by in-line rheometer would not be possible due to the risk of clogging or even damaging the measurement capillary. Moreover, upgrading of this feedstock would likely necessitate compounding with (very) high virgin polymer content. Thus, improving the efficiency of aluminium-PE separation would be necessary before proceeding with such tests.

5 WP3: Chemical recycling of polymer coatings via gasification

Chemical recycling through thermal gasification presents a viable method for the recycling of polymer coatings (Figure 17). In gasification, fiber-containing plastic reject is converted into synthesis gas, which is then processed into olefins. The primary process alternatives for producing polyolefins from polymer barrier coated board material are methanol/ethanol to olefins production and Fischer-Tropsch naphtha production.

VTT has developed gasification and gas cleaning technologies for converting various wastes and biomass residues into synthesis gas. Between 2006 and 2012, VTT collaborated with Stora Enso on the development and demonstration of biomass gasification technology for Fischer-Tropsch diesel production. The knowledge and experience gained from that project has been used in this study.

In this VTT ReMatCh project, VTT conducted research on the chemical recycling of polymer-barrier coated board material via gasification. The work included experimental research at both laboratory and PDU scale supported by process concept development and evaluation.

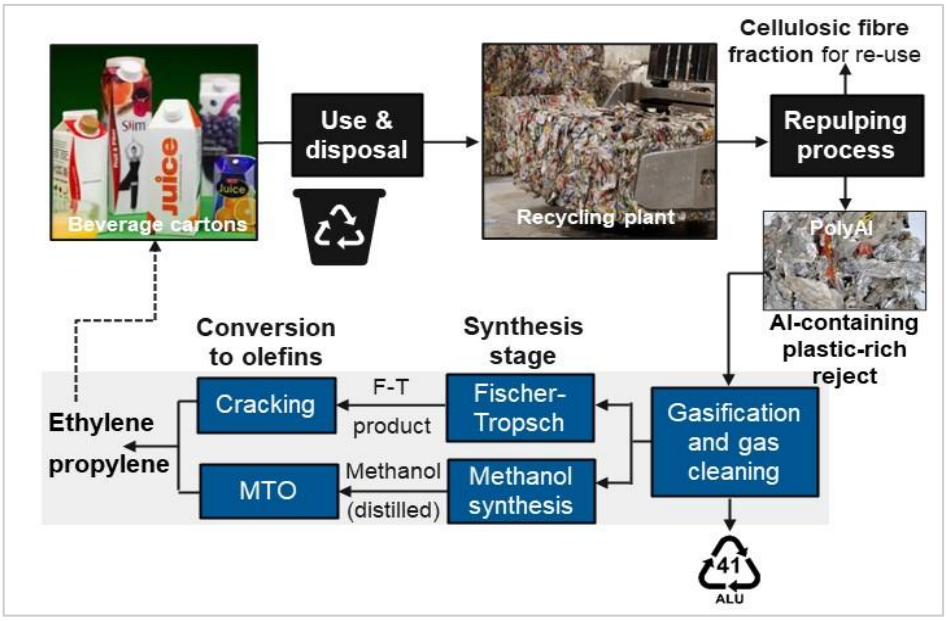


Figure 17. Chemical recycling of polymer barrier-coated board reject via gasification.

5.1 Process concept development and preliminary evaluation

The work of WP3 was started by carrying out preliminary process modelling and by considering the possible gasification and gas cleaning conditions for the received reject material, which has higher plastic and aluminium contents than the reject material gasified in the previous Corenso[2] project (VTT and Foster Wheeler worked together to developed the technology and carried out bench-scale & pilot tests between 1997-1998).

Gasification process alternatives are illustrated in Principal gasification process alternatives for the aluminium containing plastic-rich feedstock. Figure 18. Basically, the gasification can be conducted below the melting temperature of aluminium or by operating the bed at a higher temperature but using water quenching at the top of the gasifier. The quenching process was developed and patented by VTT in the late 1990's and it is especially attractive if the feedstock contains cellulosic residues which cannot be gasified at below 750 °C. However, this reject material of Stora Enso has remarkably high aluminium and extremely low fibre contents and so the low temperature alternative seems to be the most promising. Consequently, the plant selected plant configuration was based on operating the gasifier at below 670

[2] Modern Power Systems (1999). Producing electricity from plastic packaging.

°C, separating the metallic aluminium and reforming or cracking the tars and hydrocarbons in the secondary processing stage.

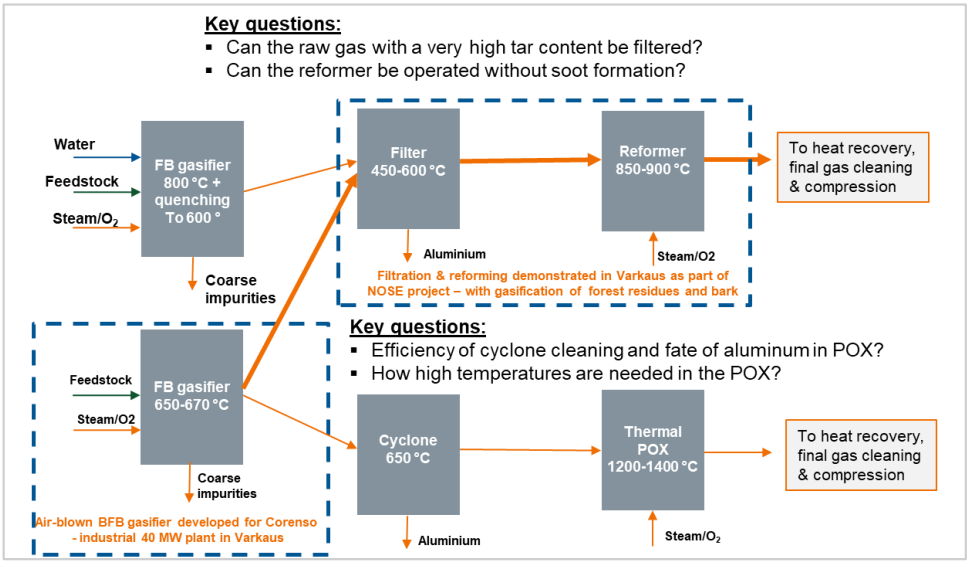


Figure 18. Principal gasification process alternatives for the aluminium containing plastic-rich feedstock.

Preliminary process evaluation work was started already before carrying out the experimental work. An existing MS Excel gasifier model was applied using experimental data on tar and hydrocarbon yields obtained in air-blown gasification tests of 1990's. Later, the model was updated using the data obtained from the BFB gasification tests of this project. The updated data on tar and hydrocarbon gas yields significantly improved the model for the primary gasification stage. It was also observed that the conventional method of using the equilibrium of homogenous water-gas shift reaction is not applicable for low-temperature gasification of plastic fuels. Instead, much better model coherence was achieved by using experimentally determined CO/CO_2 ratio, along with the overall energy balance and elemental mass balances.

Two concepts for methanol production and four cases of producing Fischer-Tropsch syncrude were preliminarily assessed (where "Reje" stands for Reject):

Methanol production

- Reje-M1: BFB 1.2 bara_670 °C; filter 550 °C; Reformer 890 °C; ASU, separation of CO_2, synthesis of CO
- Reje-M2: BFB 1.2 bara_670 °C; filter 550 °C; Reformer 890 °C; synthesis of CO and CO_2, additional H_2 by electrolysis

FT-syncrude production

- Reje-FT1: BFB 1.2 bara_670 °C; filter 550 °C; Reformer 890 °C; ASU, separation of CO_2, FT with own tail gas recycle loop.
- Reje-FT2: BFB 1.2 bara_670 °C; cyclone for Al removal, POX 1250 °C; WGS, ASU, separation of CO_2, FT with own tail gas recycle loop.
- Reje-FT3: BFB 1.2 bara_670 °C; filter 550 °C; Reformer 890 °C; ASU, separation of CO_2, FT with long tail gas recycle loop (to reformer)
- Reje-FT4: BFB 1.2 bara_670 °C; filter 550 °C; Reformer 890 °C; CO_2 recycling to gasification, additional H_2 by electrolysis, FT with own tail gas recycle loop.

In all cases gasification was carried out in a BFB gasifier operated at 670 °C. Two principally different raw gas cleaning routes were identified. Most of the studied concepts had raw gas filtration at 550 °C followed by catalytic reforming, while case Reje-FT2 was based on cyclone removal of metallic aluminium, followed by thermal cracking reactor operating at 1250 °C. Key parameters used in the gasification process model are presented in Appendix D and the results for the carbon and energy balance calculations are presented in Appendix E.

The first methanol case M1 is based on conventional syngas-to-methanol design, where a pure stream of carbon monoxide and hydrogen is fed into the synthesis while a major part of CO_2 is separated prior to synthesis. Conventional air separation plant (ASU) is utilized to produce oxygen. This process can be realized without additional hydrogen, but the drawback is that 40-50 % of feedstock carbon is lost to the flue gas streams. Concept M2 is designed for simultaneous use of both CO and CO_2. This process utilizes most of the feedstock carbon but also requires additional hydrogen, which can be produced by electrolysis. In case M2 the electrolysis unit also produces all oxygen required in the gasification process and thus there is no need to invest in conventional air separation unit (ASU). As illustrated in Appendix E this process consumes roughly 50 MW of electricity for 100 MW of gasified feedstock capacity. Methanol production is also increased by 40 %.

FT-cases 1 and 2 compare the two raw gas cleaning alternatives, catalytic reforming and thermal POX using conventional FT design realized with own internal syngas recycling. Case FT3 applies a once-through FT with a long tail gas recycle loop (to the reformer), which might be most promising for the targets of this project as the recycled light hydrocarbon products of FT are converted back to syngas in the reformer. Finally, case FT4 applies CO_2 recycling to increase the CO yield significantly. In this case, additional hydrogen is needed to reach the targeted molar ratio of feed gas. All FT concepts are calculated using a low temperature FT process for which VTT has required performance data.

The principal findings of the initial process evaluation were as follows:

- Product yields as well as energy and carbon efficiencies are significantly higher in methanol production than in the production of FT-syncrude.
- Highest carbon utilization efficiency is achieved in methanol production when synthesis gas is boosted with electrolysis hydrogen.
- Processes applying catalytic reformers have higher efficiency than concepts applying thermal oxidation.

The first preliminary estimates of the capital and production costs of the studied concepts were also made, and the results indicated that the levelized production cost for methanol would be in the range 600-700 €/t and that of FT-syncrude in the range 1400-1700 €/t.

5.2 Experimental research and development of the gasification process

Based on the preliminary process evaluation the target process concept was low-temperature BFB followed by aluminium separation by filtration and catalytic reforming of the hydrocarbon rich filtered raw gas. The key research questions include:

- Is it possible to conduct the gasification process with aluminium-containing plastic reject at temperatures below the melting point of aluminium, or would it be more appropriate to utilize the quench-cooling technique?
- Can raw gas with very high levels of tar and hydrocarbons be effectively filtered, and is it feasible to operate the reformer without producing soot?
- Can the aluminium from the feedstock be recovered, and where is it concentrated?

5.2.1 Feedstock

VTT received a bale of aluminium-containing plastic reject feedstock (PolyAl) from Stora Enso, sourced from an industrial beverage carton recycling plant in Germany. Before performing PDU-scale gasification tests with the Bubbling Fluidized Bed (BFB) gasification unit at the Bioruukki Pilot Centre in Espoo, the feedstock was pretreated and characterized.

Prior to the gasification experiments, the plastic rich waste was milled and pelletized. The manufactured pellets were highly loose and fluffy. Pellets were analyzed for proximate and ultimate analysis, and ash composition (Table 6). Figure 19 shows both the unprocessed feedstock before preparation and plastic reject pellets that were produced.

Table 6. Proximate and ultimate analysis of plastic reject and composition of ash.

Plastic Reject feedstock[1]	
Moisture, wt%	0.5
Proximate analysis, wt% (d.b)	
Volatile matter	84.3
Fixed carbon	~ 0
Ash	15.8
Ultimate analysis, wt% (d.b.)	
C	68.6
H	11
N	0.19
O (as diff.)	3.9
S	0.018
Ash	15.8
Cl	0.46
HHV, MJ/kg	35
LHV, MJ/kg	37
Al (metallic)[2], wt% (d.b.)	12
Composition of Ash, wt%[3] (d.b.)	
Al metallic	65
C	2.1
Al_2O_3	19
SiO_2	4.3
CaO	6.1
TiO_2	2.6
Fe	0.56

[1] Analyses by Eurofins Environment Testing Finland Oy, FTF Fuel Testing Finland Oy & VTT. [2]CEN/TS 15412. [3] XRF analysis; predominant components > 0.5 wt%.

Figure 19. The original feedstock (left) and pelletized plastic reject (right).

The feedstock had high volatile matter (84.3 wt%), significant ash (15.8 wt%), low sulfur, and low fixed carbon, suggesting low char yield in pyrolysis. The reject had approximately 12 wt% metallic aluminium but hardly any cellulosic fibers. The feedstock also had a high heating value. The inhomogeneity of the feedstock and the presence of contaminants made the material particularly challenging for analysis.

5.2.2 Plastic reject gasification experiments

The fluidized-bed gasification tests were conducted using the atmospheric-pressure BFB100 Bubbling Fluidized-Bed gasification rig equipped with a hot filter and catalytic reformer (Figure 20.). Below is a summary of the tests. A more comprehensive description of the BFB test facility, along with detailed results is available in Kurkela et al. (Kurkela et al. 2026).

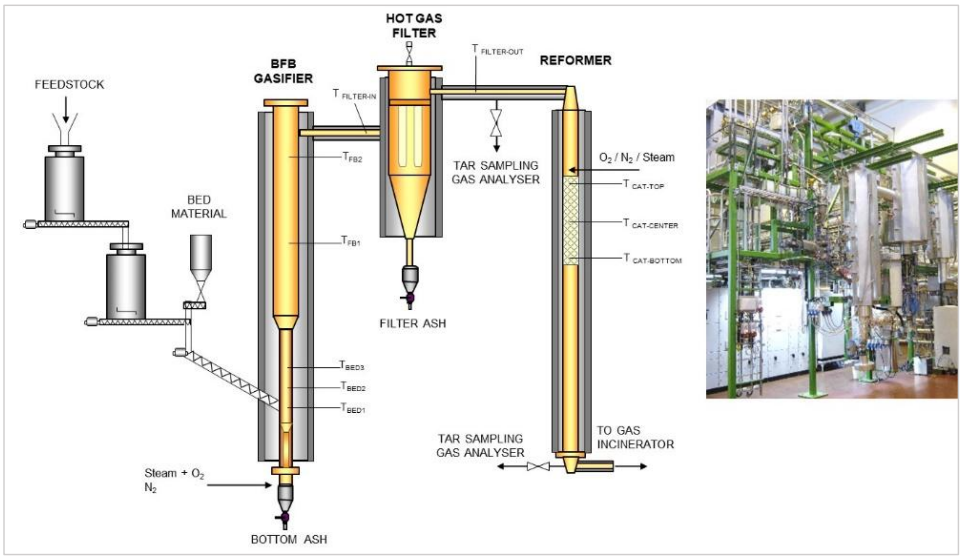


Figure 20. Bubbling fluidized bed (BFB) gasifier at VTT Bioruukki Pilot Centre, Finland

Operating conditions and performances

Five Steam/O_2-blown gasification tests with aluminium rich plastic reject were conducted to study the technical feasibility of the gasification, hot filtration and catalytic reforming process and to create data for process performance. Initial preliminary tests showed that stable operation could be achieved. A series of extended test runs, A, B, and C, were conducted over a duration of 6.5 hours, including a comprehensive measurement program. The composition of the product gas was analyzed after both the filter unit and the reformer (see sampling points from Figure 20.). Additionally, tars and nitrogen compounds (NH_3) were sampled

following hot filtration and the reformer. Mass balances were calculated based on average measured values.

The temperature for gasification was 650-670°C to avoid aluminium melting in the gasifier. Silica sand (100 %) was used as the bed material in all test runs. The bed temperatures remained consistent and stable throughout all test runs. An example of the gasifier bed temperature from test B is shown in Figure 21.

The raw gas, which contained high levels of tars and aluminium-rich dust, was filtered using metal filters (at 500/550 °C), and the tar and hydrocarbon-containing gas that passed through the filter was sent to the catalytic reformer. Special attention was given to the safe handling of aluminium-containing filter dust, as the feedstock had a high level of aluminium. The detailed operation conditions of the gasifier and filter are provided in Appendix F.

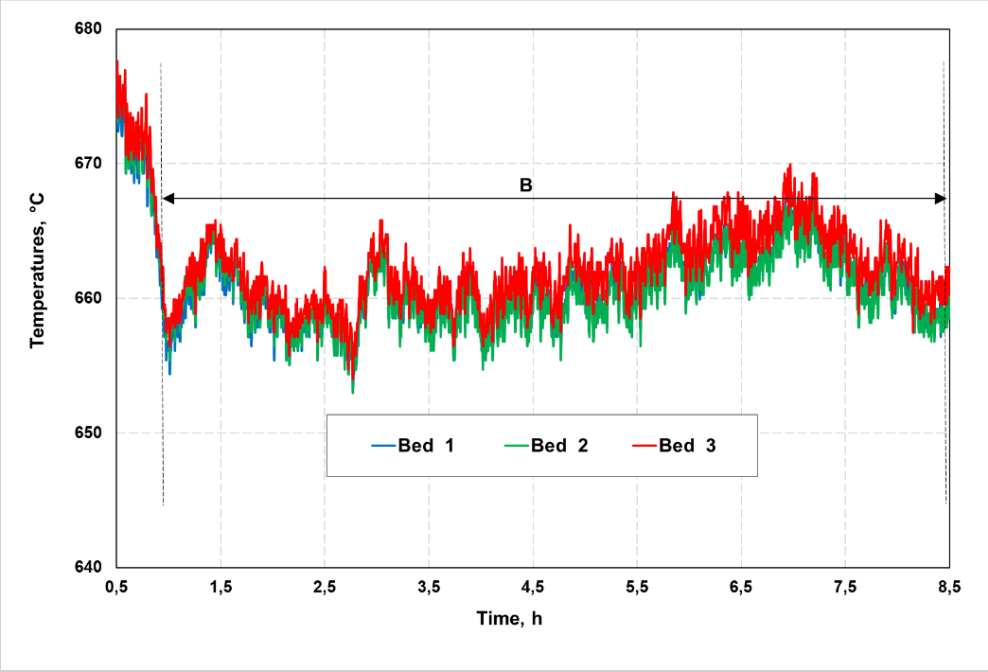


Figure 21. An example of the process temperature (test run B).

The stability of the gasification process can also be assessed based on pressure drop measurements. A typical pressure drop curve for the gasifier, filter unit and reformer is presented in Figure 22. The pressure drops remained stable, with a slight increase in gasifier bed pressure drop due to bottom ash buildup that was cleared only after testing.

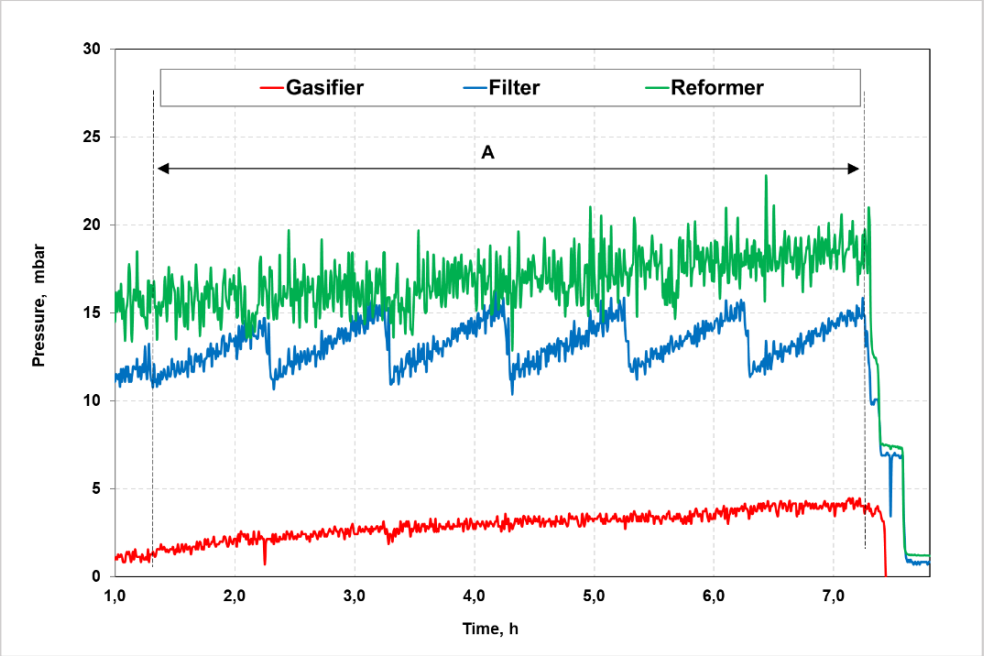


Figure 22. Pressure drops of the gasifier, filter and reformer (test A).

Carbon conversion, gas compositions

The conversion of feedstock carbon to gas and tars was remarkably high, with carbon losses from filter dust measured at about 0.5 % and final bed material under 0.1%. This shows that more than 99% of feedstock carbon was converted into gas. Figure 23 illustrates the conversion of feedstock carbon to various products in the gasifier, detailing the allocation gaseous products. More than 80 % of feedstock carbon is converted into hydrocarbon gases and tars, while the yield of carbon monoxide is only 6 %.

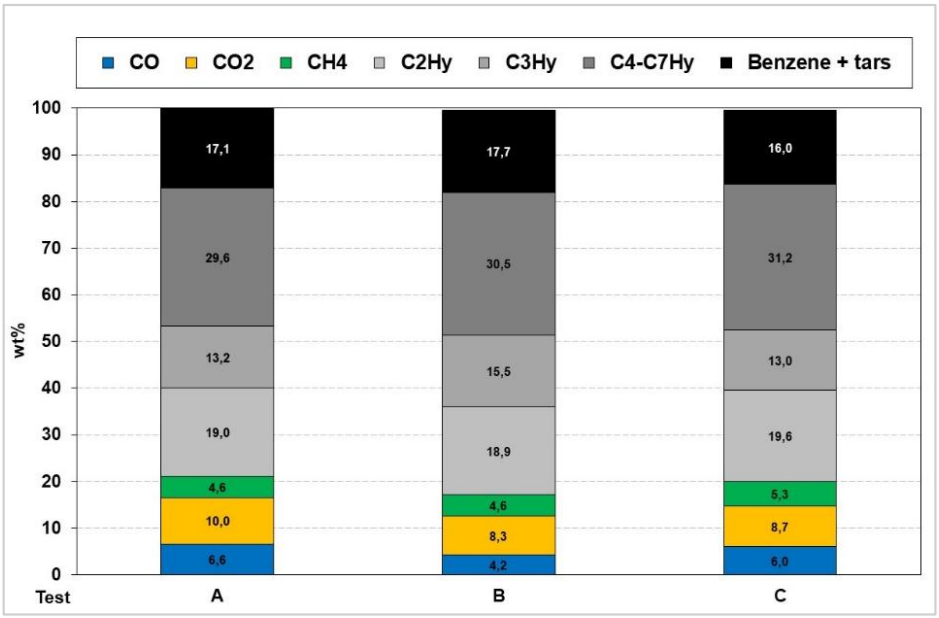


Figure 23. Conversion of feedstock carbon into various products in the gasifier.

Figure 24 presents the gas compositions for the raw gas and reformed gas (test runs A, B and C). The findings show that the reformer significantly affects the gas composition by converting hydrocarbon gases and tars into permanent gases, which is leading the gas composition to approach the equilibrium of the homogeneous water gas shift reaction.

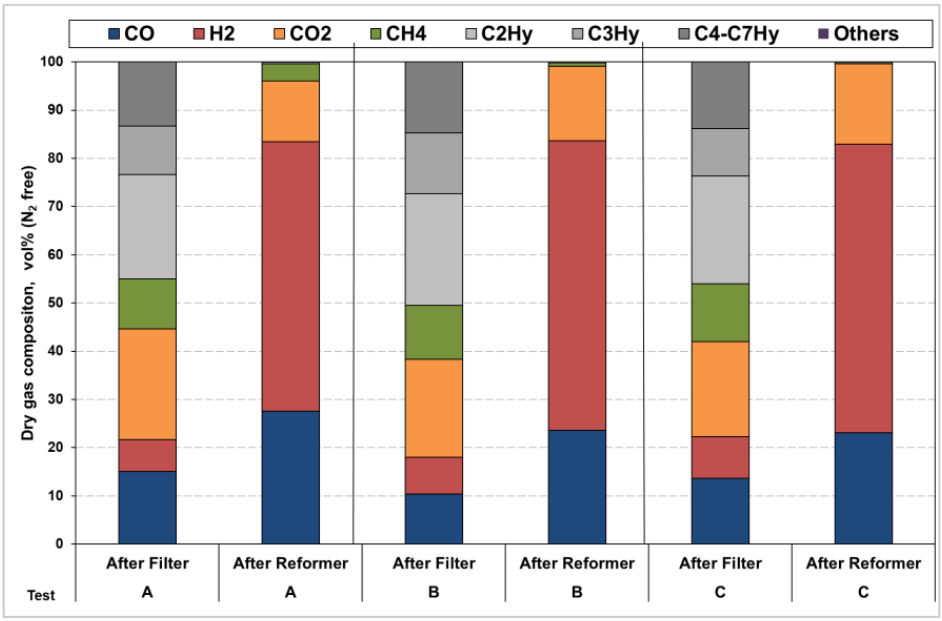


Figure 24. Comparison of gas compositions after gasifier and reformer (nitrogen free dry gas).

Fuel nitrogen conversion to ammonia

Ammonia concentrations were measured in tests B and C. Overall gasification and reforming process converted 56-58% of feedstock nitrogen to ammonia (Figure 25). The raw gas before reforming contained high amounts of organic nitrogen compounds, which decomposed during reformer.

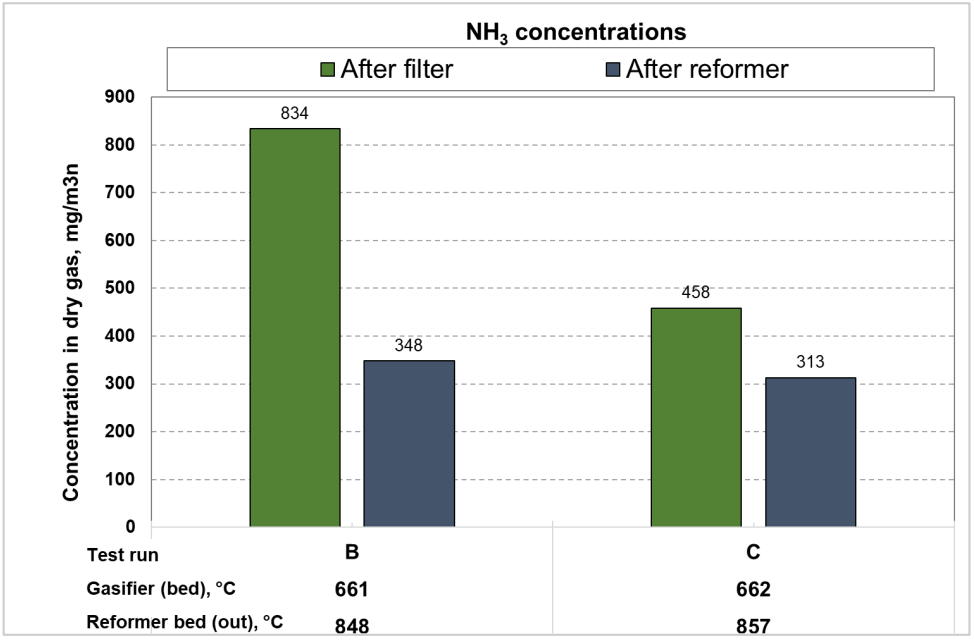


Figure 25. Ammonia concentrations after the filter and reformer.

Performance of the catalytic reformer

The raw gas, which had high levels of hydrocarbon gases and tars, was reformed in a single-stage fixed-bed catalytic reformer using a mixture of oxygen and nitrogen. In addition to oxygen, supplementary steam was introduced into the reformer during tests B and C to enhance the reforming reactions. In previous test runs, nitrogen was used to dilute the oxygen (steam was not used). The reformer operation was stable in all tests. Test C showed the best reformer performance under the highest steam feed rate and slightly increased temperature.

Figure 26 illustrates measured tar concentrations after the filter and reformer. The tar results clearly show the optimal performance of the reformer with nickel-based catalysts. The detailed operation conditions of the reformer are provided in Appendix G.

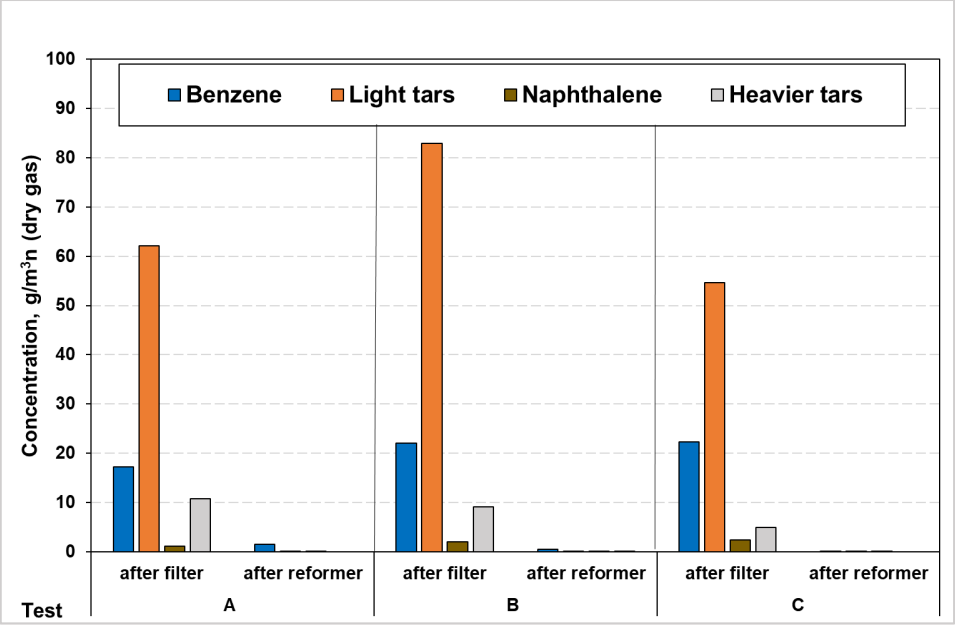


Figure 26. Benzene, light tars, naphthalene, and heavy tar levels after filtration and reforming. Light tars are compounds from pyridine to cresol including unidentified light tar compounds, and heavier tars are compounds heavier than naphthalene.

Composition of filter dust and bottom ash

The filter dust from test runs was collected and analyzed. According to the XRF/XRD analysis, the filter dust consisted of 96% ash and about 2.7% carbon. Sulphur content was 0.03% and chlorine 1.3%. The results, presented in Figure 27, showed that aluminium is the primary component in filter dust. The filter dust also had minor amounts of CaO, SiO_2, TiO_2, and Fe_2O_3.

Bottom ash contained negligible levels of combustible material, and its aluminium content was about 8 %. Bottom ash was primarily composed of bed material (start-up silica sand) and other inorganic species (Figure 28). There were no sinters or agglomerates in the bottom ash. Appendix H includes sample photos of filter dust, bottom ash, and particles collected from the gasifier plate distributor after tests. Coarse material near the grid also contains aluminium particles.

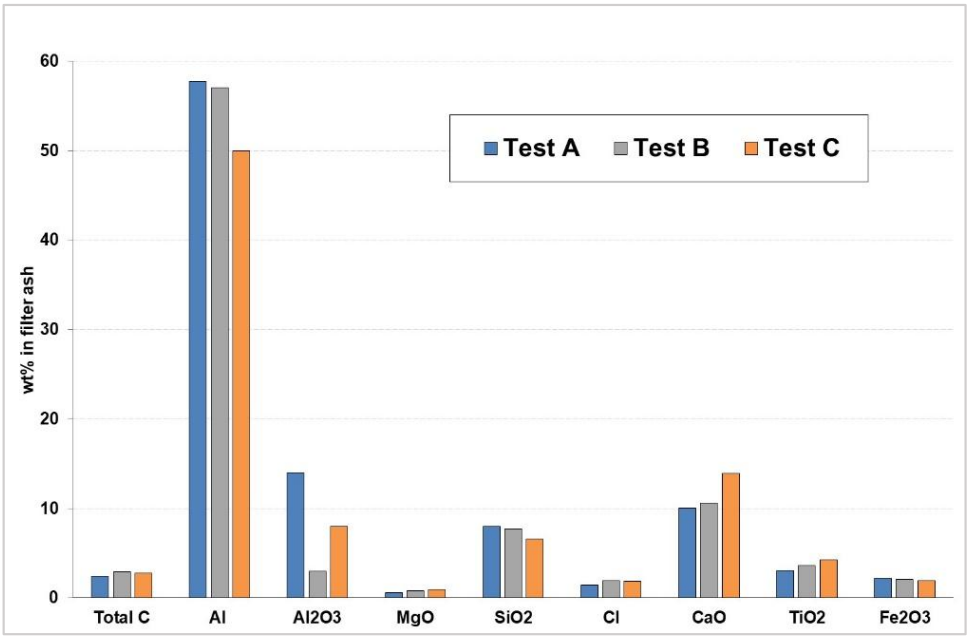


Figure 27. The chemical composition of filter dust by XRF (test runs A, B and C).

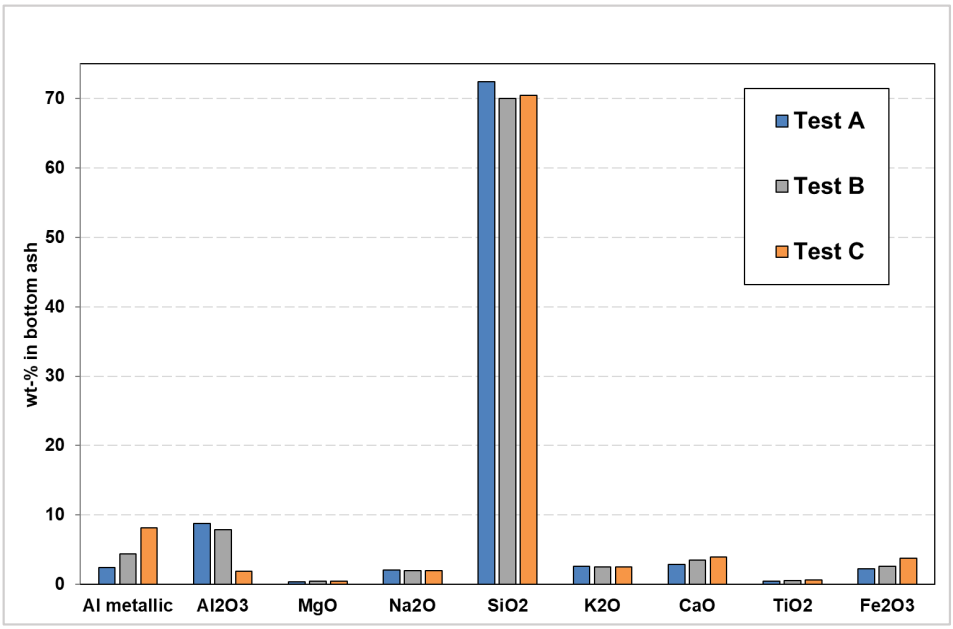


Figure 28. The chemical composition of bottom ash by XRF (test runs A, B and C).

The findings show that aluminium is effectively recovered from both the filter and bottom ash, and that most of the aluminium found in the filter dust exists in metallic form. During gasification tests, 56-70% of feedstock aluminium was recovered in the filter dust, with approximately 89-97% of it in metallic form. The aluminium mass balances are also relatively consistent. The calculated distribution of feedstock aluminium in the output streams is reported in greater detail in (Kurkela et al. 2026).

Conclusions from Gasification of Aluminium-Containing Plastic Waste

- The low-temperature BFB gasification process, followed by filtration and catalytic reforming, has been successfully tested, demonstrating the effectiveness of the front-end conversion process for a chemical recycling plant. The conversion of plastic waste to syngas was successfully validated.
- Gasification tests proved stable operation of the gasifier, even though the raw gas contained particularly high concentrations of hydrocarbons and tars. Additionally, the fuel feeding system also functioned effectively with plastic reject feedstock.
- High carbon conversion (>99%) was achieved with no bed sintering or deposit issues - no signs of aluminium melting were noted.
- Raw gas with high tar content was filtered at ~500 °C without filter blockage.
- Catalytic reforming operated steadily, resulting in complete conversion of tars and C_2–C_5 hydrocarbons (>99%).
- An effective recovery rate of the feedstock aluminium was obtained in the filter dust. This shows that aluminium recycling is feasible.
- Based on these encouraging results and obtaining more precise data on the fate of aluminium, further research should be conducted at a larger facility equipped with continuous bottom ash removal systems.

5.3 Modelling and Techno-economic assessment

Following the completion of the experimental program, the collected data was applied to model the gasification process using Aspen Plus® process simulation software. This gasification model was integrated into a comprehensive process concept for the chemical recycling of plastic-rich reject material. The process model served to calculate mass and energy balances, which underpin the techno-economic assessment.

Two fundamentally different pathways for olefin production were evaluated: one involving Fischer-Tropsch naphtha production (with subsequent processing in a steam cracker), and another featuring methanol production followed by conversion to olefins via a methanol-to-olefins process. Detailed analyses of these approaches are provided in the project's second journal article. The following section presents a brief outline of the results.

The front-end gasification process was developed based on test results and preliminary process evaluations. Gasification was conducted at 650 °C, with the

resulting raw gas filtered and directed to the catalytic reformer, which operated at an outlet temperature of 900 °C. Following gas cooling, compression, and final purification, the synthesis gas was used in either Low-Temperature Fischer-Tropsch (FT) or methanol synthesis. The intermediate products—FT-product and methanol—were subsequently converted to olefins using a steam cracker and the MTO+OCP process, respectively.

A total of five different gasification-synthesis process configurations are compared in this analysis: two based on FT-synthesis, and three on methanol synthesis. The principal design features of the five examined concepts were as follows:

- Case 1: FT with internal tail gas recycling loop, no electrolysis integration, 95% CO_2 removal, partial CO_2 recycle to gasification
- Case 2: FT with tail gas recycling to reformer, no electrolysis integration, 95% CO_2 removal, partial CO_2 recycle to gasification
- Case 3: Conventional MeOH synthesis (for CO), no electrolysis integration, 95% CO_2 removal, partial CO_2 recycle to gasification
- Case 4: Advanced MeOH synthesis (for CO+CO_2), electrolysis integration, partial CO_2 removal and recycle to gasification
- Case 5: Advanced MeOH synthesis (for CO+CO_2), electrolysis integration, no CO_2 removal or recycle, all CO_2 to synthesis

Figure 29 shows simplified process diagrams for the FT-process alternative (Case 1) and two concepts for methanol production (Cases 3 and 4). The main findings are shown in Figures 30-32. Figure 32 displays the mass yield of olefins produced from one dry ton of reject material.

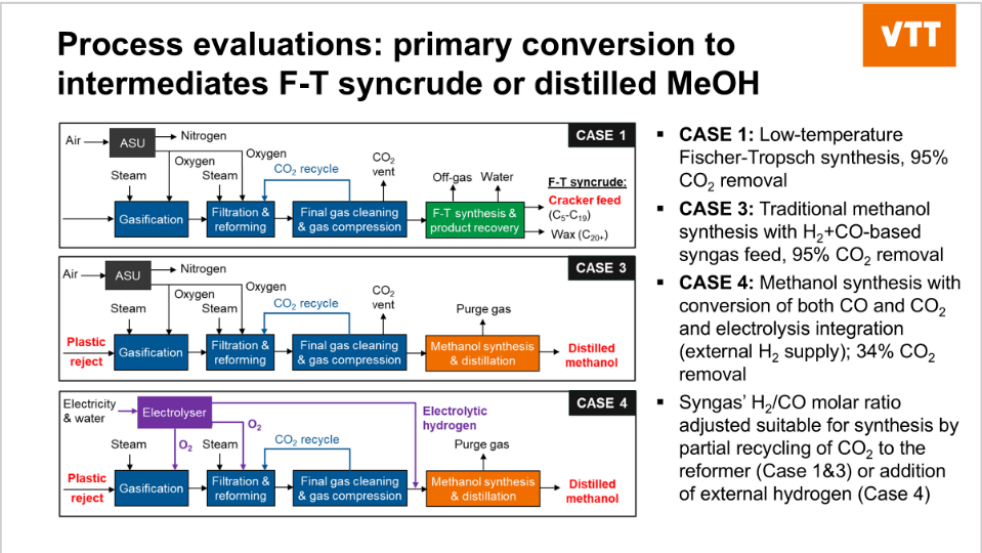


Figure 29. Simplified process flowsheets of Cases 1, 3 and 4.

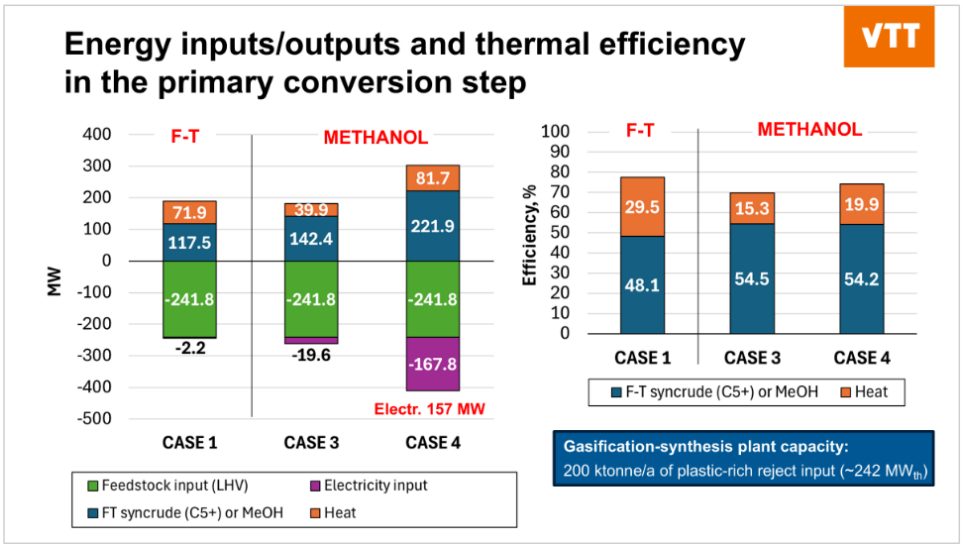


Figure 30. Estimated energy balances and energy conversion efficiencies.

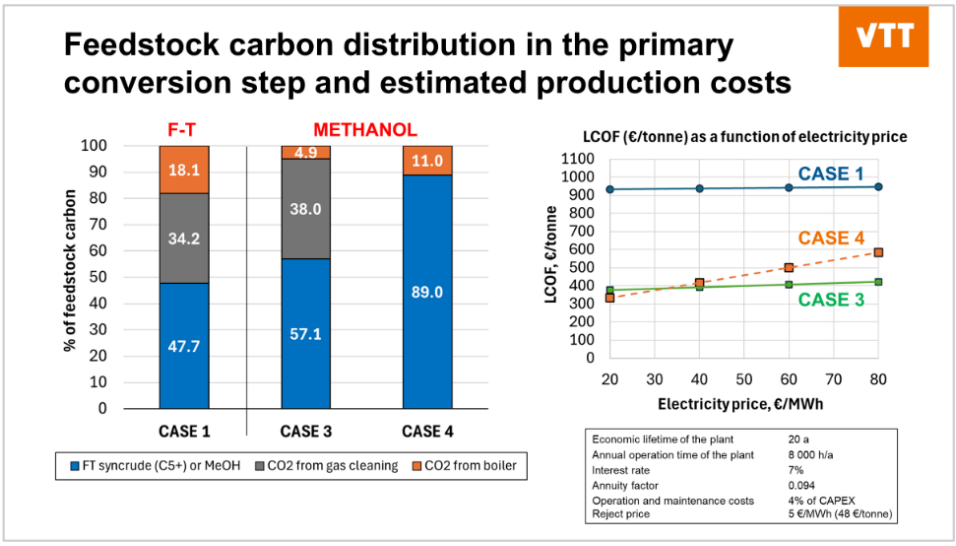


Figure 31. Distribution of feedstock carbon and estimated production cost of FT-crude and methanol as a function of electricity price.

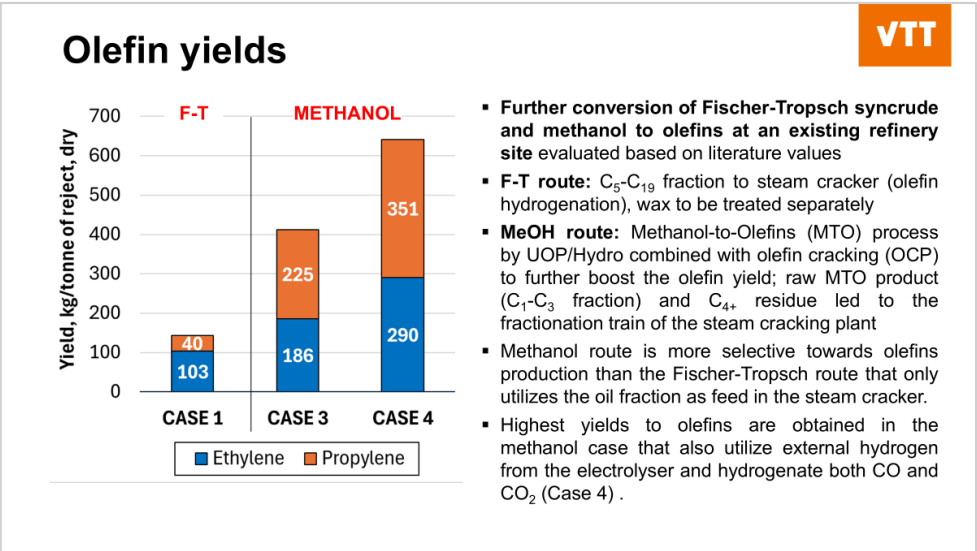


Figure 32. The olefin yields in Cases 1, 3 and 4.

Summary and conclusions of the TEA studies

Two alternative routes, namely Fischer-Trospch and methanol, were investigated for producing olefins from the plastic-rich reject. They both involved two stages:

(1) primary conversion of the reject to intermediate product (F-T syncrude or methanol) close to the origin of the feed (distributed production), and
(2) transportation of the intermediate product to a centralised refinery site (steam cracking plant) for further conversion to olefins.

- The methanol route was found to be more selective towards olefins production than the F-T-based route and achieved the highest olefin yields. Olefin production could be further boosted by ca. 56% in comparison to the 'traditional methanol case' by coupling the gasification-synthesis plant with an electrolyser (H_2 boosting) and designing the methanol synthesis to convert both CO and CO_2 to methanol.
- The required electrolyser capacity was in this case ~157 MW. Such integration becomes economically attractive when the electricity price is below ~35 €/MWh (under the economic assumptions used in this study).

Comprehensive results from the techno-economic assessments will be presented in an article scheduled for submission in 2026 (Tuomi et al., Chemical recycling of aluminium containing plastic waste derived from multilayer packaging materials via gasification – A techno-economic assessment).

5.4 Exploitation of results

The findings from experimental studies and techno-economic assessments are comprehensively presented and analyzed in two manuscripts submitted to scientific journals. Furthermore, these results were shared at an international conference and during the final event of the SPIRIT Program (https://www.spiritprogramme.com/).

Publications, Conferences and other Events
Scientific articles Kurkela E., Kurkela M., Hiltunen I. (2026), Fluidized-bed gasification of aluminum-containing plastic waste originating from multilayer packaging materials, Journal of Material Cycles and Waste Management. https://doi.org/10.1007/s10163-026-02594-4 Tuomi S., et al. Chemical recycling of aluminium containing plastic waste derived from multilayer packaging materials via gasification – A techno-economic assessment [to be submitted in 2026].
Conference Tuomi S., Kurkela E., Kurkela M., Hiltunen I., Chemical recycling of polymer barrier-coated board reject via gasification, 13th International Freiberg Conference on Circular Carbon Technologies, 15-19 September 2025, Prague, Czech Republic.
Poster (see Appendix I) Fluidized-Bed Gasification of Aluminium-containing Plastic Waste. Kurkela M., Hiltunen I., Kurkela E., & Tuomi S. Final event of the SPIRIT Programme, 28.10.2025, Porvoo.

5.5 Production of FT wax

The project included a task in which VTT operated the existing Mobile synthesis unit (MOBSU), which is equipped with a low-temperature Fischer-Tropsch synthesis reactor, to produce a batch of paraffinic FT oil and wax.

The experiments took place at VTT Bioruukki, where VTT used pilot facilities with commercially sourced industrial-grade CO and H2. Mobile synthesis unit was operated during Spring 2024 using VTT's low-temperature Fischer-Tropsch synthesis reactor and a cobalt-based catalyst with rWGS-generated syngas from CO_2 and H_2. Operating conditions included a maximum temperature of 216–222 °C, GHSV 4.8 ndm³/gcat*h, a feed H2/CO ratio of 2.4 with ca. 28 vol% inert, a pressure of 19 bar, and TOS (time on stream) 70 to 270 hours; the process was conducted in a non-continuous manner.

- VTT produced 31 kg of FT crude. The samples, including oil canisters and wax bag batches, were delivered to the customer in summer 2024. Each of the batches was analyzed using FID-GC. Product analysis results are presented in Table 7.

- VTT analyzed the gas composition of the non-condensable FT product gases, and characterized the wax and oil fractions (Figure 33). The oil and light wax fraction analysis will separate paraffins and olefins up to about C20 and n-alcohols up to about C10. The heavy wax fraction up to C100 was used to determine the FT chain growth probability value (alpha). A FT water phase analysis was also included to determine the typical water-soluble components such as alcohols and acids.

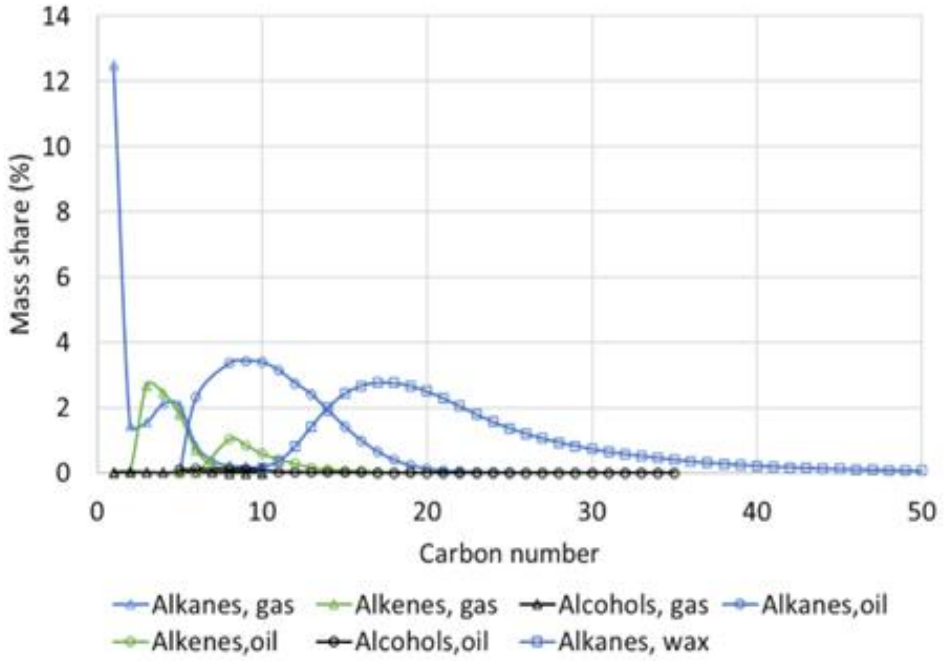


Figure 33. Example full product distribution from batch 2. A portion of the hydrocarbons is lost due to vaporization in the liquid sampling.

Table 7. Product analysis results.

	Batch 1	Batch 2	Batch 3	Total[1]
Alfa (wax (C30-C45)	0.90	0.89	0.89	0.90
mass oil, kg	4.0	3.6	4.5	4.0
Mass wax, kg	6.6	5.7	6.7	6.6
Oil to total (C5+) product, mass	0.4	0.3	0.2	0.4
C5+ productivity, kg/h	0.23	0.26	0.32	0.23
Fraction of olefins in oil[2]	0.4	0.3	0.2	0.4

[1] not analyzed separately, average of 3 batches, [2] waxes contain small amounts of olefins as well, not quantitatively determined

6 WP4: Life Cycle Assessment

The conducted Life Cycle Assessment (LCA) study evaluated the potential environmental impacts associated with the manufacturing of Liquid Packaging Board (LPB), with a particular focus on the end-of-life options for the PolyAl fraction, that is separated from fibres during recycling. The compared end-of-life scenarios were incineration and gasification. The assessment covered all life cycle stages from LPB production to the final treatment of PolyAl, excluding the use phase of the packaging. In case of gasification, recovered methanol was further converted to olefins, which were then polymerized into polymers. Simplified versions of the compared systems are illustrated in Figure 34. LCA modelling was done with Sulca software, ecoinvent 3.11 database, and EF 3.1 impact assessment method, with the functional unit defined as one ton of PolyAl reject. While the data allowed for the examination of several impact categories, the interpreted results focus only on Global Warming Potential (GWP).

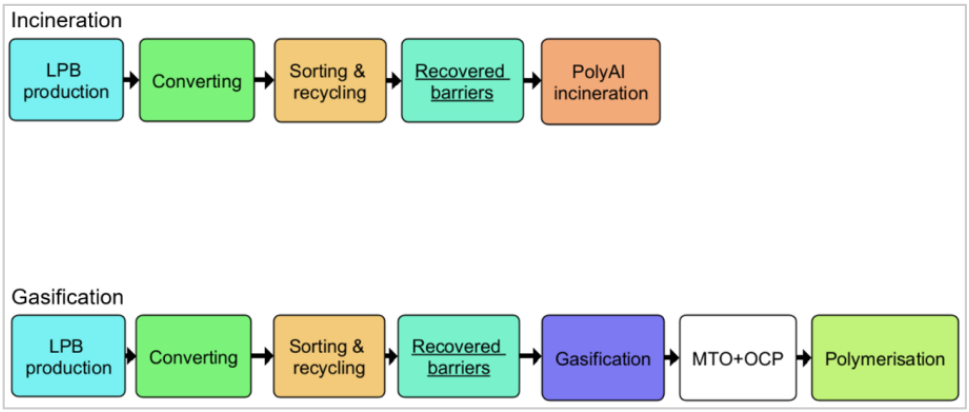


Figure 34. Simplified flowsheets for compared PolyAl treatments.

6.1 LCA Modelling

The study used data from several different sources, which are presented by process in Table 8. The processes were assumed to be located in Germany, except for LPB production, which takes place in Sweden. Upstream impacts were allocated between fibres and recovered PolyAl reject on a mass basis. No allocations were applied to other processes. By-products generated in the gasification and MTO+OCP processes were assumed to substitute the production of similar flows elsewhere, and the system was credited for substitution of these. The gasification process produced steam as a by-product, which was used to cover the system's own energy demand. Surplus steam was directed to a CHP plant, where it was used to produce electricity and district heat, for which the system received credits.

Table 8. Data sources for assessed life cycle stages. (*Fossil GHG emissions were calculated according to energy and carbon contents of PolyAl fraction.)

Life cycle stage	Origin of data
LPB converting	Stora Enso
Converting	ORIENTING project
Aluminium foil production	Environmental profile report for the European aluminium industry
Sorting of used carton	Ecoinvent LCI data
Recycling of used carton	Stora Enso
Incineration*	Stora Enso
Gasification	Aspen modelling
MTO + OCP	Literature
Polymerization	Ecoinvent LCI data
Background data	Ecoinvent

6.2 Results

The modelling provided GWP results for the incineration and gasification of PolyAl reject. The impacts of the gasification route and their sensitivities were assessed in more detail using four different parameters: The amount of aluminum recovered from gasification, the electricity mix used in the gasification process, the utilization rate of high-pressure steam released from the MTO+OCP process, and the energy mix assumed to be replaced by the district heat produced at the CHP plant. The results varied depending on the selected parameters, and the base, best-case, and worst-case scenarios are presented in Figure 35. Based on the LCA study, gasification of PolyAl reject results in lower GHG emissions compared to incineration. In the worst-case scenario, emissions from gasification were about 62% of those from incineration, while in the best-case scenario, only about 42%.

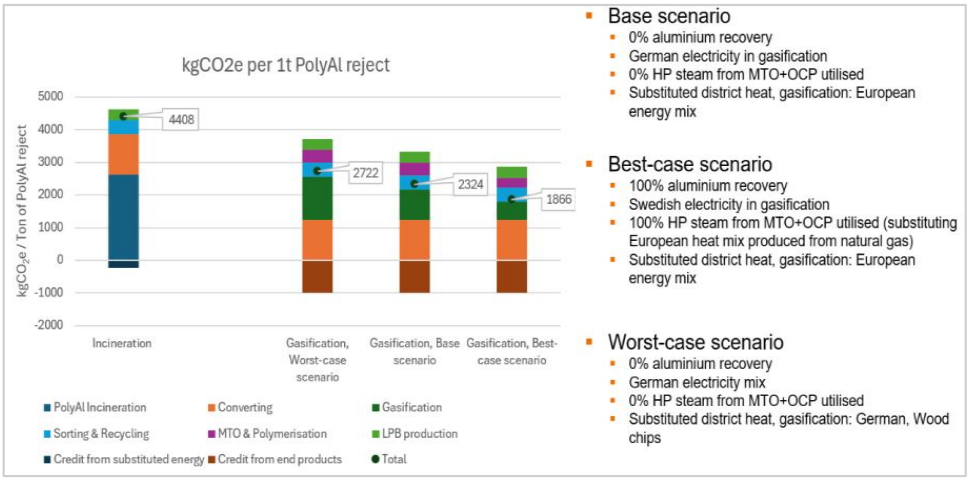


Figure 35. Variance of results with assessed parameters.

6.3 Conclusions

The ReMatCh LCA study modelled the environmental impacts of manufacturing of LPB and recycling PolyAl reject recovered from it via gasification versus incineration with energy recovery. Results indicate that gasification reduces GWP by approximately 38–58% compared to incineration, depending on scenario parameters. The most influential factors affecting total life-cycle emissions were the type of substituted district heat and the electricity mix used; greener electricity reduced emissions by up to 15%, while less favorable district heat substitution increased emissions by 17% relative to the base scenario.

Recovered polyethylene and polypropylene from the process can be reused, with recycled polyethylene potentially meeting about 16% of product demand when directed to the same LPB application, enhancing circularity. Polypropylene can be used in other applications, as can the by-products from the MTO+OCP process, which account for about 5,6% of the MTO+OCP yield. In the gasification process itself, the most significant source of GHG emissions were direct CO_2 emissions from CO_2 venting, which accounted for 41% of the total life-cycle emissions. If these CO2 emissions would be captured and utilized, substantial emission reductions could be achieved. Using greener electricity also reduced emissions, whereas the impact of aluminum recovery on the results was minimal.

While the presented results focus on GWP, modelling enables assessment of other environmental impact categories, which could be explored in future work. Another opportunity for further research relates to allocations. Environmental burdens from the gasification and MTO+OCP processes could be allocated to the by-products instead of giving credits from them. Another allocation-related possibility concerns the upstream allocation for LPB production. Instead of the estimated mass-based allocation, for example economic allocation and its impact on the results could be tested. More detailed follow-up research could also be

conducted on the data used for modelling the MTO+OCP process and the polymerization process. Data regarding these were sourced from literature and databases, and their uncertainty regarding validity and suitability is the greatest among all data used. A more thorough investigation and modelling of these could significantly affect the results.

7 Summary

This report examined several potential approaches for recycling polymer coating barrier materials, including separating fibers from polymers, using mechanical recycling methods, and applying chemical recycling through gasification. Additionally, life cycle assessment evaluated the environmental effects of producing beverage cartons when PolyAl was recycled via gasification and compared them to incineration. In conclusion, this study demonstrated noteworthy and encouraging possibilities for recycling fiber and polymer-coated barrier material. The research findings for each topic are as follows:

WP1: Key Findings from Fiber and Polymer Separation Experiments

Delamination Test Results

- The heterogeneous raw material affected sample quality. The light (mostly PE) fraction constituted 44–69%, with 0.9–9.5% aluminium, while the heavy fraction was 27–42% with higher aluminium (9.5–43.7%) and 8.2–23% PE.
- Water and acid treatment conditions were chosen for lab trials based on the purity (low Al) and the particle size of the PE fraction.

Laboratory-Scale Delamination

- Both water and acid delamination, followed by sedimentation, successfully separated aluminium and plastic layers.
- Acid treatment resulted in lower aluminium content in the plastic fraction.
- Water treatment left some organic material in the plastic (shown by TGA).
- After sedimentation, the heavy fraction is separated into large aluminium particles and fine materials containing aluminium, PE, and cellulose. Increasing particle size may improve separation for all materials.

Pilot-Scale Delamination

- At the pilot scale, the delamination of aluminium from plastic was less effective compared to laboratory conditions, due to less efficient material disintegration after water treatment.
- The purity of the separated light fraction was higher at pilot scale, with greater plastic content, lower aluminium content, and higher heating values.

WP2: Key findings from Mechanical recycling of polymer coatings

Pilot scale mechanical recycling process development

- Mechanical recycling process development was carried out using VTT's pilot-scale mechanical recycling line (VAREX).
- Melt-filtration trials revealed that further extrusion and upgrading experiments were not feasible due to excessive impurities and the risk of clogging or damaging equipment.
- Successful upgrading would require compounding with a very high proportion of virgin polymer. It was concluded that improving the efficiency of aluminium-PE separation is essential before proceeding further extrusion or upgrading tests.
- The planned coating film extrusion using VTT's PLASCO line was not feasible due to these material limitations.

WP3: Key findings from Chemical recycling of Plastic reject via gasification

The initial process evaluations:

- Methanol production achieves higher product yields and greater energy and carbon efficiencies than FT-syncrude production. Carbon utilization is maximized when synthesis gas for methanol is boosted with electrolysis hydrogen.
- Processes applying catalytic reformer have higher efficiency than concepts applying thermal oxidation.

Gasification tests:

- The low-temperature BFB gasification process, followed by filtration and catalytic reforming, was successfully validated for converting aluminium-containing plastic reject (PolyAl) to a hydrogen-rich synthesis gas. Gasification experiments demonstrated the efficiency of the front-end conversion process for a chemical recycling plant.
- The BFB gasifier operated efficiently without problems in all tests; stable operation during tests runs.
- Operating at gasification temperatures between 650 and 670 °C enabled almost complete carbon conversion, effectively turning the plastic into a raw gas rich in hydrocarbons and tars. No signs of aluminium melting or other operational issues were observed.
- The raw gas with high tar content was filtered efficiently at around 500 °C without filter blockage. The filter dust is rich in aluminium, offering potential for its recovery. Most of the aluminium found in the filter dust exists in metallic form.
- Raw gas with high tars and hydrocarbons can be reformed using VTT's catalytic reforming technology, resulting in a clean gas with high concentrations of hydrogen and carbon monoxide.
- Under best conditions, the conversion efficiency of hydrocarbon gases and tars approaches 100%, while benzene conversion reaches 99.6%.

- The results from these tests support process modelling and techno-economic studies evaluating the feasibility of chemical recycling of plastic-rich rejects by gasification and subsequent methanol or FT-route for producing recycled polymer feedstock.
- It is important to note that the proof-of-concept was validated a small-scale process development unit (PDU) and has not yet been fully demonstrated at pilot or industrial scale. However, these findings highlight the potential for future optimization and development of this process.
- Additionally, collaboration with the gasification technology company should be considered to facilitate more detailed engineering studies.

Process concept evaluations & Modelling and Techno-economic assessment

- Fischer-Trospch and methanol routes were investigated for producing olefins from the plastic-rich reject. Both processes involved two stages: first, primary conversion of the reject to intermediate product (either F-T syncrude or methanol) close to the origin of the feed, and then transportation of the intermediate product to a centralised refinery site (steam cracking plant) for further conversion to olefins.
- The methanol route was found to be more selective towards olefins production than the F-T-based route and achieved the highest olefin yields.
- Coupling a gasification-synthesis plant with an electrolyser and converting both CO and CO_2 to methanol can increase olefin production by about 56% compared to traditional methods.
- The required electrolyser capacity was ~157 MW, and integration becomes economically attractive when the electricity price is below ~35 €/MWh.

WP4: Key findings from Life cycle assessment studies

- The LCA study shows that incorporating gasification can lead to emission reductions compared to incineration with energy recovery. The magnitude of these reductions depends strongly on the assessed parameters, the most significant of which were the type of substituted district heat and the electricity mix used during gasification.
- In addition to decreased GWP emissions, gasification also enables the recovery of different recycled raw materials. These materials can be reused in various applications, enhancing circularity.
- It is possible to further reduce the emissions from gasification. For example, a significant share of the system's GHG emissions originates from direct CO_2 emissions. This stream can be captured and utilized, offering substantial emission reduction potential.

Acknowledgements

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We also thank the VTT research staff in Espoo and Tampere for their valuable expertise and collaboration toward the project's goals.

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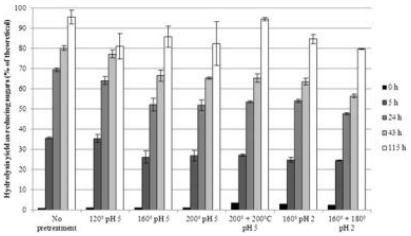
Appendix A: Literature review (WP1)

Literature review – enzymatic hydrolysis

Enzymatic hydrolysis of waste fibres as a pre-treatment before fermentation

- *Kemppainen et al (2012)* [1]: 10 FPU/g cellulase and 1000 nkat/g β-glucosidase in 100 g/kg substrate (pH 5, 45°C, 5-115 h, 30% consistency).
  - Sanitation (sterilization) of raw material with steam (keeping 70-80°C for 10 min) before drying
  - Thermal and acidic pre-treatment didn't improve the hydrolysis yield
    - The material appeared to contain a major part of the carbohydrates in easily hydrolysable form (e.g. fibre derived from chemical pulping methods), and a minor part in resistant form (e.g. mechanical pulp, wood residues).
    - The feedstocks contain components such as lignin that re-distribute within the material as a result of high-temperature pre-treatment and consequently may cover and mask partially the cellulose, make the access of cellulase enzymes to cellulose difficult, and slow down hydrolysis.



Literature review

Enzymatic hydrolysis of waste fibres as a pre-treatment before fermentation

- *Verhe et al. (2022)* [2]: Pre-treated OFMSW (the organic fraction of municipal solid waste, mainly paper and cardboard fibres).
  - Acid pre-treatment with 1% HNO_3 solution to liberate the cellulosic fibers, to remove inorganic material/additives used in paper and improve accessibility of the enzyme. Soluble components (mainly $Ca(NO_3)_2$) were removed, fine sieving
  - pH adjusting to 5, drying
  - Enzymatic saccharification with Cellic CTEC3 (Novozymes) of 3.75 FPU/g paper pretreated OFMSW fiber, total solid load 21%

  - In pilot process " Pasteurisation" 5% consistency, 70°C 45 min

Literature review

Structure	Methods used earlier for separation	Methods in the paper *Diop et al. (2017)* [3]
a PE outer layer		
a printed cardboard layer (10 % lignin, 10 % hemicellulose, α-cellulose content 76 %)	separation by hydrapulping from PE-layer	Hydrapulping. Utilization of fibers: partially fractionation into fermentable sugars and MCC using H_2SO_4. MCC was used in as a reinforcement in the polyethylene
a PE tie-layer		
a thin aluminium foil layer (Adhesives, generally a methacrylic acid-modified polyolefin resin, are used between PE and aluminium layers to reinforce their adhesion in the packaging.)	acid separation (acetic acid[4], nitric acid[5])	Organic acid separation + completed by a flotation/sedimentation
an inner layer of PE		

Hydrapulping

- The multilayer packaging was shredded into small pieces (about 3 cm x 3 cm) using a Salsco woodchipper.
- A laboratory scale pulp disintegrator (Labtech, model 500-1). The shredded packaging was placed in the disintegrator reservoir and mixed with water at a solid-to-liquid mass ratio of 1:10. The disintegrator blades were rotated at 1200 rpm for a period of 6 min.
- The fibre suspension was then passed through a filtration grid (diameter 1 cm) that removed the polyethene/aluminium residues but let the cellulose fibre through.

Separation of Al and PE

- The polyethylene-aluminum residues were immersed in a 50 % (v/v) solution of formic acid for 10 h. The material was then removed from the solution, washed with water after which the pH was neutralized with a saturated solution of Ca(OH)2. At this stage, the PE and aluminum layers were delaminated but were still very sticky. Complete detachment was obtained through agitation in water for 1 h at a solid to liquid ratio of 1 kg: 20L. The delaminated polyethylene floated on the water surface while the denser delaminated aluminum layer sedimented at the bottom of the container. Separated components were then washed with water and dried at room temperature.

Extraction of Microcrystalline Cellulose (MCC)

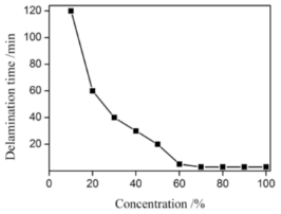
- The fibers were first decrystallized at 30 C using a72 wt% H2SO4 solution. A ratio of 1 kg of cellulose per 2L of acid solution was used. The carbohydrates were precipitated in acetone, vacuum filtered and washed with the same solvent. The recovered precipitate was then dispersed in distilled water, in order to obtain a solid suspension in 4 wt% H2SO4 solution. The solution was heated to 121 C for 1 h in an autoclave to carry out the hydrolysis.
- Finally, the solution was centrifuged at 5000 rpm for 20 min to separate the residual microcrystalline cellulose from the sugar-rich fraction. The extracted microcrystalline cellulose (MCC) was washed with water and centrifuged several times until a neutral pH was reached. Freeze-drying was used to remove water. The dry material was grinded in a mortar and sieved at 60 mesh in order to have particles with a uniform size distribution.

VTT

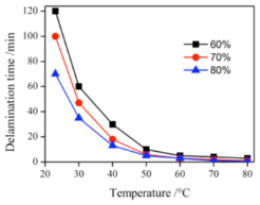
Literature review

Delamination and Separation of Aluminum-Polyethylene-Paper Packing Material
(Wang et al 2014, *Journal of Research Updates in Polymer Science*, 2014, *3,* 136-141)[6]

- The packaging material was delaminated under conditions of 60 °C, 70 v% GAA (Glacial Acetic Acid) solution, liquid/solid ratio 20:1 and delamination time 60 min, and separation of polyethylene, paper and aluminum foil was conducted through sink-float method and air separation.



Delamination time as a function of GAA concentration (60 °C, liquid/solid ratio 20:1).



Delamination time as a function of temperature, (v% of GAA are 60, 70 and 80; liquid/solid ratio 20:1).

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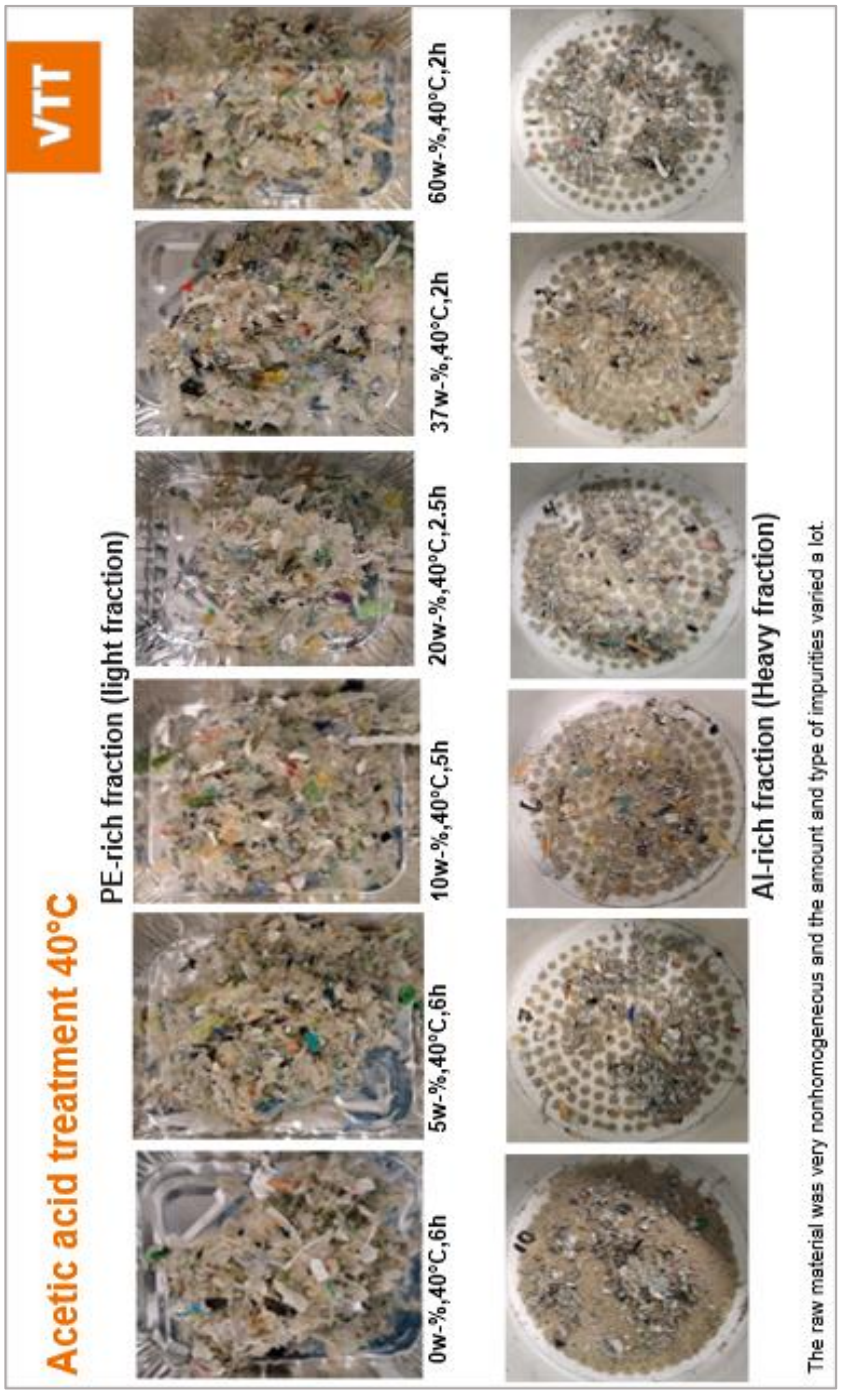
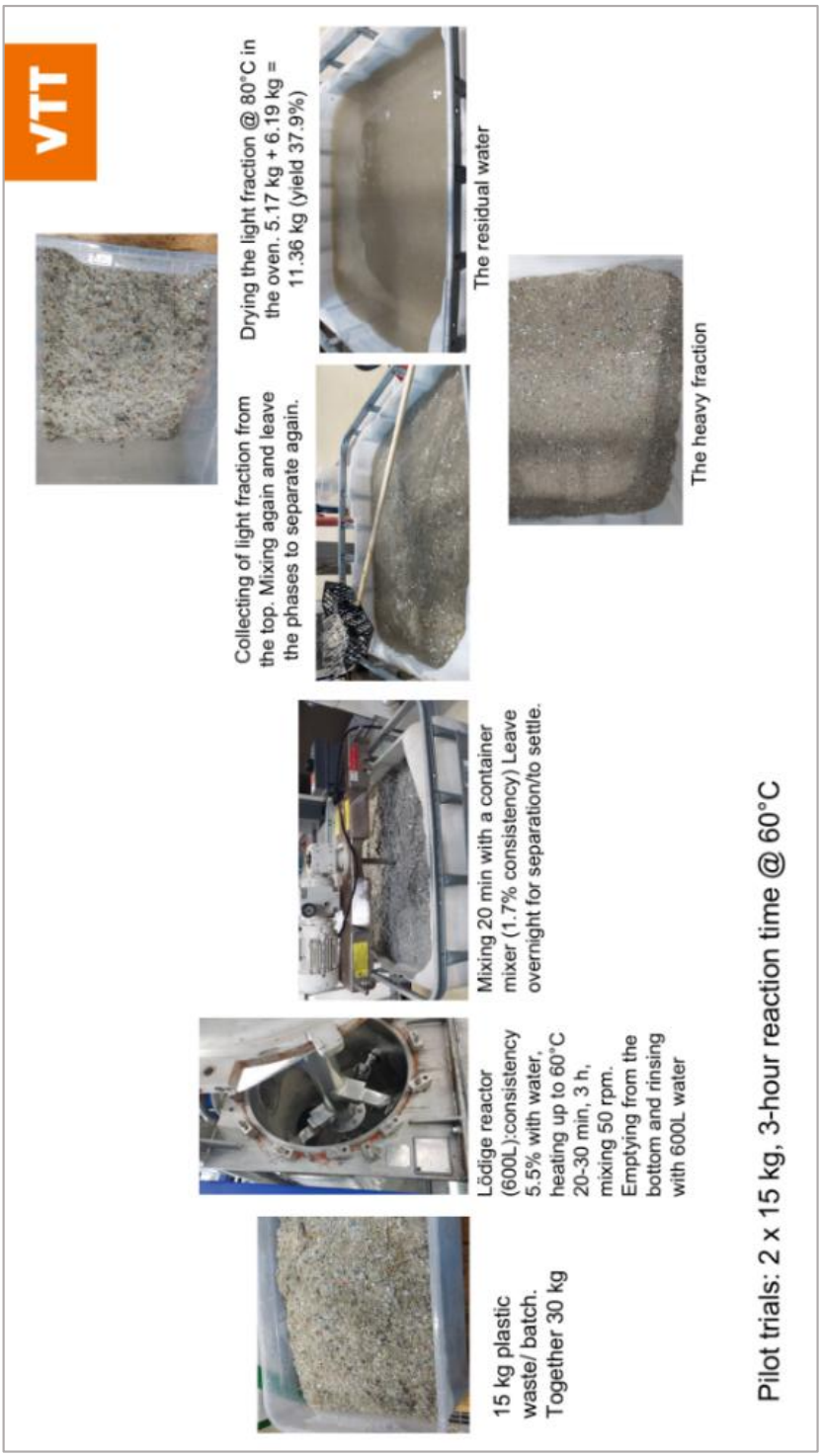
Appendix B: PE- and Al-rich Fractions from Acetic Acid Treatment (WP1)



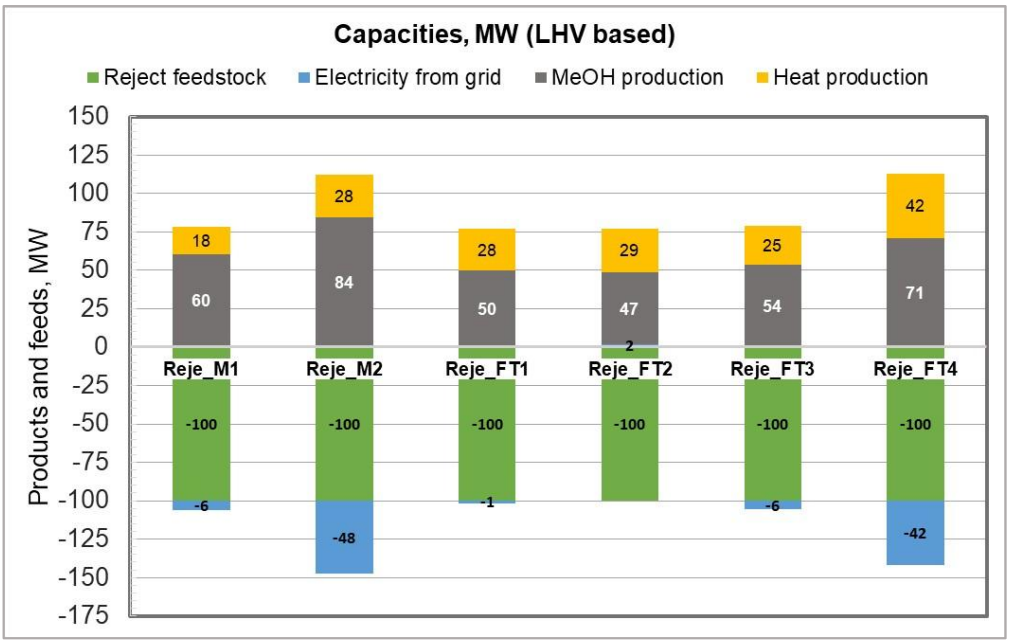
Appendix C: Delamination Pilot trials set up (WP1)

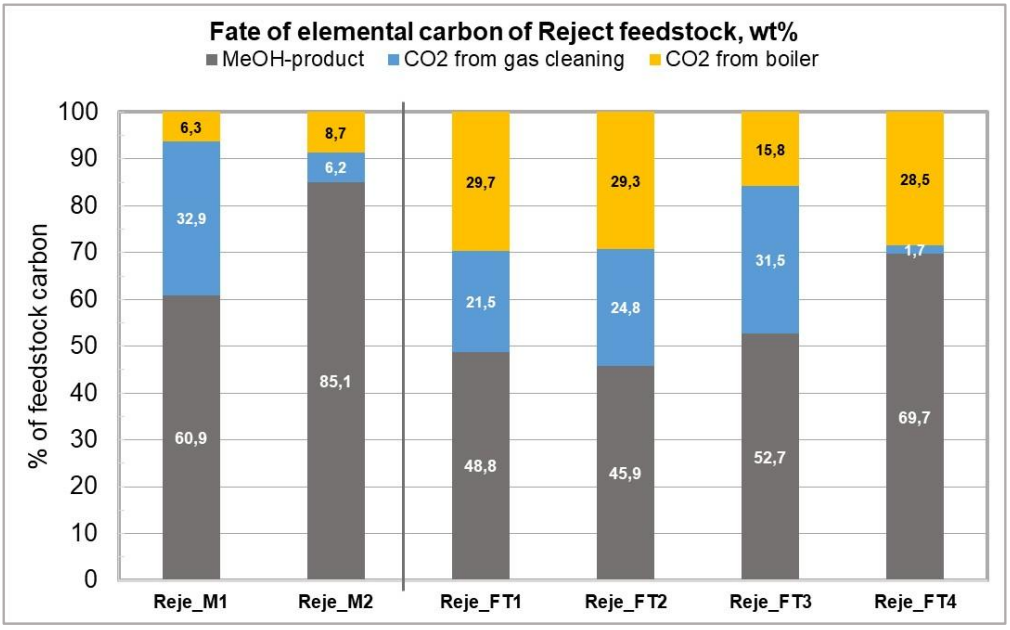


Appendix D: Key parameters in the excel-based gasification process model (WP3)

Conversion efficiencies, elemental	C	H	N	O	Cl	S		
from feedstock to filtered raw gas, wt%	**99**	**100**	**99**	**100**	**50**	**99**		
Fate of released fuel-N, %	NH3	HCN	N2					
	70	**0,5**	29,5					
Fate of released fuel-S, %	H2S	COS						
	95	**5**						
Released chlorine to HCl, %	100							
Tar and hydrocarbon gas yields	CH4	C2H2	C2H4	C2H6	C3H6	C6H6	C10H8	C16H10
mol/kg volatile matter of feedstock	**3,68**	**0,04**	**6,01**	**0,81**	**7,3**	**0,99**	**0,3**	**0,3**
Fate of solid residues	Ash	C	N	S	Cl	H		
wt% to filter dust	**80**	**99**	**99**	**99**	**99**	100		
wt% to bottom ash	20	1	1	1	1	0		
Gasifier feed gas composition, wt%	O2	N2	steam	CO2	Total	Steam/O2ratio	4,00	
	20	**0**	**80**	**0**	*100*	CO2/O2 ratio	0,000	
Bed material feeding and fate into ash streams								
Feed, % of fuel feeding	**1**							
calcined, % of carbonate	**100**							
residue to filter fines, %	**50**							
residue to bottm ash, %	50							
Pressures and pressure drops	gasif.fb/bara	bed/mbar	cyclone/mbar	filter/mbar	refo/mbar	rest/mbar	p/aft.scrub	compr/bara
	1,3	**100**	**10**	**70**	**100**	**10**	1,11	**85**
Temperatures, C	gasifier	filter	refo-out	after GC2	aft.scrub			
	650	**600**	**900**	**200**	**40**			
CO/CO2 ratio from experiments	**mol/mol**						**0,69**	

Appendix E: Preliminary process evaluation results from the MS Excel process model (WP3).





Appendix F: Operating conditions of the gasifier and filter (WP3).

Test run	Test A	Test B	Test C
Fuel feed rate, g/s	0.61	0.55	0.57
Moisture content, wt%	0.5	0.5	0.5
Oxygen feed rate, g/s	0.15	0.14	0.15
Steam feed rate, g/s	0.60	0.60	0,60
Fluidization nitrogen, g/s	0.27	0.20	0.27
Purge nitrogen, g/s	0.30	0.30	0,30
Bed / freeboard temperature, °C	657/478	661/487	662/592
Pressure in freeboard, bar(a)	1.04	1.04	1.04
Fluidising velocity, m/s	0.43	0.41	0.43
Steam-to-fuel feed ratio, kg/kg-daf	1.17	1.30	1.25
O_2 feed, % of stoich. combustion	9.3	9.5	9.9
Filter temperature, °C (inlet/outlet)	500/484	549/531	553/537
Filter Face velocity, cm/s	1.2	1.0	1.2
Dust content is gas[a], g/s	36	53	48
Filter Pd, mbar	13	17	18
Bottom ash[b], g/s	0.14	0.10	0.10
Bottom ash, ash content, wt%	100	100	100
Filter dust, g/s	0.062	0.077	0.078
Filter dust, C content, wt%	2.4	2.9	2.8
Dry gas composition after filter, vol-%			
CO	6.0	4.8	5.4
CO_2	9.2	9.4	7.9
H_2	2.7	3.5	3.5
N_2	60.0	53.8	60.0
CH_4	4.2	5.2	4.8
C_2H_2	0.0	0.0	0.0
C_2H_4	7.7	9.2	7.8
C_2H_6	0.9	1.4	1.1
C_3Hy (C_3H_6)	4.0	5.8	3.9
C_4-C_5Hy (C_4H_8)	2.4	3.1	2.4
C_6+Hy (C_6H_{12})	2.9	3.7	3.1
H_2O content in wet gas, vol-% (calc.)	49.4	56.1	49.8
H_2O content in wet gas, vol-% (measured)	54.7	55.2	48.7
Benzene, g/m3n (dry gas)	17.3	22.0	22.3
Tars[c], g/m3n (dry gas)	74.1	94.1	62.0
Ammonia, g/m3n (dry gas)	n.m.	834	458
Fuel N-to- NH_3, %	-	43	29
Fuel N-to-tar N	52	46	31
Oxygen balance closure, out/in[d]	1.06	0.98	0.99
Carbon conversion, %	99.6	99.3	99.4

[a] Calculated based on weighed amount of removed filter dust and gas flow rate, [b] Final bed divided with the test time, [c] Includes unidentified light tar compounds [d] Calculated elemental oxygen balance defined as sum of O in output streams divided by sum of O in input streams.

Appendix G: Operating conditions of the reformer (WP3).

Test run	Test A	Test B	Test C
Reformer feed gases			
Oxygen, g/s	0.15	0.22	0.23
Nitrogen, g/s	0.210	0	0
Steam, g/s	0	0.27	0.35
S/C ratio in input streams, mol/mol[a]	1.2	1.9	2.0
Reformer average temperature, °C	835	784	804
Residence time in catalyst bed, s	0.17	0.18	0.16
Dry gas composition after reformer, vol-%			
CO	18.3	19.5	17.9
CO_2	8.4	12.8	12.9
H_2	36.9	49.8	46.3
N_2	33.9	17.2	22.7
CH_4	2.3	0.6	0.3
C_2H_2	0.0	0.0	0.0
C_2H_4 & $C_{2\text{-}3}H_6$ hydrocarbons	0.2	0.1	0.0
Benzene, mg/m^{3}n (dry gas)	1550	510	43
Tars, mg/m^{3}n (dry gas)	112	12	2.0
Ammonia, mg/m^{3}n (dry gas)	n.m.	348	313
Fuel N-to NH_3	n.m.	58	56
Wet gas flow rate after reformer, m3n/h	10.8	10.0	11.3
H2O content in wet gas, vol-% (calculated)	13.0	24.4	25.2
H2O content in wet gas, vol-% (measured)	20.4	24.4	25.4
Oxygen balance closure, out/in	1.08	1.00	1.03
Kp-shift from gas analysis	1.13	1.01	0.99
Kp-shift calculated at reformer temperature	0.93	1.11	1.03
Ammonia, mg/m^{3}n (dry gas)	n.m.	348	313
Reformer conversions			
Tars, %	99.5	100	100
Benzene, %	72.5	92.2	99.4
Methane, %	-71.1	63.3	83.5
C_2-C_5Hy, %	95.3	98.3	100

[a] S/C ratio = steam input divided by the carbon input in hydrocarbon gases and tars, mol/mol, [b] STP at 273.15 K and 101.325 kPa

Appendix H: Photos of filter dust, bottom ash, and other findings (WP3).

Figure H1. Filter dust

Figure H2. Bottom ash

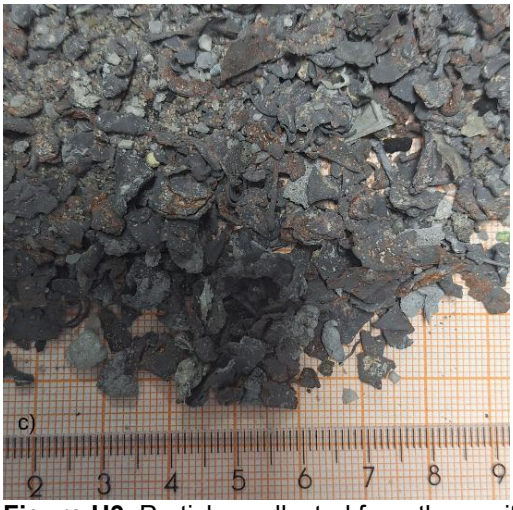


Figure H3. Particles collected from the gasifier plate distributor after

Appendix I: Poster: Fluidized-Bed Gasification of Aluminium-containing Plastic Waste

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Fluidized-Bed Gasification of Aluminium-containing Plastic Waste

Minna Kurkela, Ilkka Hiltunen, Esa Kurkela & Sanna Tuomi
VTT Technical Research Centre of Finland Ltd

Introduction

Research was focused on gasifying plastic waste that contains aluminium, with the goal of producing synthesis gas (syngas). The syngas can then be further processed to make methanol, and then olefins - chemicals that serve as raw materials for manufacturing new plastics and polymers.

Materials and Methods

- Gasification experiments were performed using a steam/O2-blown bubbling fluidized bed (BFB) gasifier equipped with a hot filter and catalytic reformer.
- The temperature for gasification was 650-660°C to avoid aluminium melting in the gasifier.
- Tests used plastic waste pellets containing 12% aluminium as feedstock.
- Particulates were removed and aluminium recovered through high-efficiency filtration.
- Hydrocarbons and tars were reformed via a catalytic single-stage fixed-bed reformer.

Table1. Feedstock analyses.

Aluminium, wt% (d.b.)	12
Moisture	0.5
Volatile matter, wt% (d.b.)	84.3
Fixed carbon, wt% (d.b.)	~ 0
Ultimate analysis, wt% (d.b.)	
C	68.6
H	11.0
N	0.2
O (as diff.)	3.92
S	0.02
Ash	15.8
Cl	0.46
LHV, MJ/kg (d.b.)	35.0
HHV, MJ/kg (d.b.)	37.2

Table 2. Ash composition (maximum).

Al metallic	65
Al_2O_3	19
CaO	6.1
SiO_2	4.3
TiO_2	2.6
Fe	0.6

Fig 1. Pelletized feedstock.

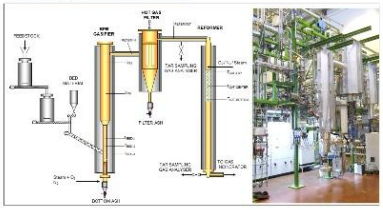
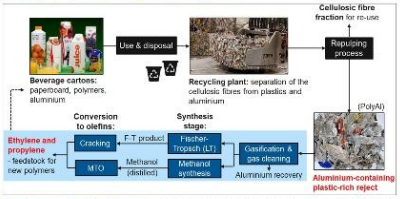


Fig. 2 BFB gasification test unit, VTT Bioruukki Pilot Centre (Espoo).

Chemical recycling of polymer barrier-coated board reject via gasification



Process evaluations: Fischer-Tropsch (FT) and methanol routes were studied to produce olefins from plastic-rich reject.

- The methanol route produced more olefins and was more selective than the FT route.

PDU-scale gasification of aluminium-containing plastic waste to syngas was successfully validated.

- Gasification tests confirmed stable gasifier operation, despite the raw gas contained particularly high concentrations of hydrocarbons and tars.
- High carbon conversion (>99%) was achieved with no bed sintering or deposit issues.
- Raw gas with high tar content was filtered at ~500 °C without filter blockage.
- Catalytic Reforming: Stable operation, full conversion of tars and C2–C5 hydrocarbons (>99%).
- 56–70% of feedstock aluminium was recovered in the filter ash, ~14% in the bottom ash → This demonstrates further potential for aluminium recycling.

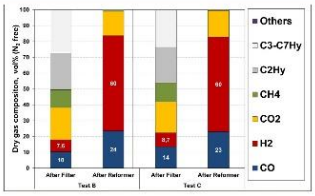


Fig. 3 Comparison of gas compositions after gasifier and reformer

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Series title and number

VTT Technology 447

Title	**Fiber and Polymer-Coated Barrier Material Recycling** Final Report of the VTT ReMatCh project
Author(s)	Minna Kurkela, Ilkka Hiltunen, Esa Kurkela, Sanna Tuomi, Christian Frilund, Marjo Määttänen, Ilkka Rytöluoto, Joonas Mikkonen, Kalle Kinnunen & Hanna Pihkola
Abstract	This report presents the results of the VTT ReMatCh project, which focused on improving recycling methods for fiber and polymer-coated barrier materials. The project involved collaborative research on the recyclability of polymer-coated board, mechanical and chemical recycling techniques, and the life cycle assessment (LCA) of recycling options. Stora Enso Oyj provided principal funding for the project, which was conducted between May 2023 and December 2025. The VTT ReMatCh project identified effective methods for recycling fiber and polymer-coated barrier materials, organizing the research into four work packages: WP1: Fiber and Polymer Separation address challenges in separating fibers, polymers, and aluminium from polymer-coated board waste. Using acid delamination, hydra pulping, and enzymatic hydrolysis, highly pure PE fractions were obtained. WP2: Mechanical Recycling of Polymer Coating focused on melt filtration and upgrading of polymer coatings to produce reusable materials. WP3: Chemical Recycling via Gasification validated a low-temperature BFB gasification, followed by filtration and catalytic reforming, for converting aluminium-containing plastic reject (PolyAl) into a hydrogen-rich synthesis gas. A techno-economic analysis evaluated two alternative pathways, Fischer–Tropsch and methanol, for producing olefins from plastic-rich reject material. WP4: Life Cycle Assessment (LCA) evaluated the potential environmental impacts of manufacturing Liquid Packaging Board (LPB), with a particular focus on the end-of-life options for the PolyAl fraction, that is separated from fibres during recycling. The end-of-life scenarios compared were incineration and gasification. The project findings provide a foundation for advancing recycling technologies for polymer-coated board materials and contribute to packaging circularity efforts.
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Final Report of the VTT ReMatCh Project

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