



4.1.5b

RECYCLING OF REJECT STREAMS FROM CARDBOARD RECYCLING VIA THERMAL CONVERSION

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PREFACE

This report is a continuation of project 4.1.5 and includes results taken forward within the framework of the project “4.1.5b Återvinning av rejektströmmar från kartongåtervinning via termisk omvandling” focused on the thermochemical conversion of the reject fraction obtained after cardboard recycling. This project was conducted within the framework Climate-leading Process Industry funded by Vinnova, VGR and the Chemicals and material cluster of Western Sweden. The contribution of the project participants including fruitful discussions, practical support in form of analyses and the willingness to supply the material needed is acknowledged.

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SUMMARY

As an extension of the previous project “4.1.5 Recycling of reject flows from textile sorting and cardboard recycling through thermochemical recycling”, this project aimed to follow up and scale the completed initial research of batch experiments at lab scale with trials in a continuous way in the Chalmers pilot plant. The work performed in the context of this project aimed to investigate to what extent the waste stream comprising polymer blends and leftovers of cellulose could be used as raw materials for new material production by means of thermochemical conversion. For that purpose, this project was taking forward mass balances and yields of the main products from the thermochemical conversion in a dual fluidized bed system of the reject fraction from cardboard recycling. In this kind of product, both natural and synthetic polymers are blended which makes it not a first choice for feedstock recycling.

As expected from the molecular structure of the different materials being part of the waste mixture, the evolution of permanent gases and more importantly carbon oxides depend heavily on the oxygen bound to carbon, being the content of cellulose a driver in this sense. For the same reason, olefins such as ethylene and propylene are only formed in larger quantities if the parent material comprises a considerable amount of polyolefins, which are characterized by alkane structures with saturated C-C bonds.

Monoaromatics, more specifically benzene, toluene, xylene and styrene make up 7-10% of the mix being the origin and reaction route twofold: (a) the decomposition of a polymer containing an aromatic ring, e.g., polyester; (b) a cyclization/aromatization reaction based on primary decomposition products which can stem from both natural as well as synthetic polymers. An increase of the temperature from 740 °C to 805 °C induces a growth towards the formation of polyaromatic hydrocarbons (PAH) such like naphthalene which is more pronounced for route (b).

Keeping in mind the complex composition, steam gasification presents a viable option for feedstock recycling. Especially in the light of a circular use of carbonaceous materials, it is a less energy intensive way to re-use all the carbon in the material blends, compared to combustion and carbon capture and utilization.

In summary the product yields analyzed in the framework of this project lead to the following main conclusions:

1. Valuable chemicals like monoaromatics and light olefins can be extracted directly by separation.
2. The amount of carbon in the gases lighter than ethylene comprising carbon oxides and methane is relatively large and to reach a circular material usage a conversion of this stream is required. Here catalytic synthesis processes like methanol or syngas fermentation processes are an option.
3. The results from the experimental trials show that the yield of light olefins per kg polyolefins in the waste is of the same magnitude as for pure polyolefins. Based on

that it can be concluded that a prior separation or sorting of such blended waste fractions is an unnecessary effort if the downstream gas separation dimensioned accordingly.

4. The operation in the large scale seems to have a beneficial effect preventing aromatization and polymerization reactions

The industrially relevant experimental data obtained from this project can be used to provide a better basis to evaluate steam gasification as recycling route for mixed materials. Specifically, to what degree further processing, separation of the distribution and synthesis of base chemicals, are economically viable.

1. PROJECT DESCRIPTION

BACKGROUND

Many of the products we use daily, like packaging, consist of blends of materials of both biogenic and syntetic origin. The blending of such materials is often required to achieve the desired product properties and gives freedom to design resource-efficient products with high functionality. However, from a recycling perspective, blended materials are very challenging as the different parts are usually difficult to separate from each other. This makes energy recovery the main recycling process used nowadays for this kind of material. If ending up in recycling schemes, the remaining part of such products can be found in rejected fractions after sorting or separation as for example residual fractions after cardboard recycling. This fraction consists of the remaining of the plastic-coated cardboard with a possible aluminum layer. These materials with their composite nature, pose a major challenge for traditional mechanical or fiber recycling. From a thermochemical recycling perspective, however, many of the contained materials are of high value. Especially the combination of high-quality cellulose fibers and pure polymers.

For example of the 35-40.000 tons of beverage carton packaging that are used in total in Sweden, around 14.000 tons are collected for recycling, of which approximately 75%wt. is recovered as fiber while the reject, around 25%wt., is incinerated [1]. Nonetheless, the reject, consists of a plastic-rich residual fraction which also contains fiber residues (mainly remaining cellulose) and aluminum traces. The strong link between fibers, plastic and aluminum indicate that the effort needed for further mechanical separation is uneven.

Nowadays, the above-mentioned rejected fraction is not further recycled into materials. Thus, this project investigated the possibility to thermochemically recycle this material via steam gasification in the temperature range of 700-825 °C. Steam gasification is indifferent of the source of carbonaceous fuel, therefore it can convert materials of both biogenic origin or fossil origin into primary raw materials. This means that this recycling path could act as a future way of phasing out fossil primary raw materials and replacing these with bio-based raw materials to produce synthetic carbon-based materials and chemicals.

Particularly, the biogenic part of the feed could be a very valuable resource, considering the limited amount of biogenic carbon sources available for material production. This carbon being part of a blend can create a flow of renewable raw material to produce new synthetic materials and/or chemicals.

PROJECT AIM AND STRUCTURE

As an extension of the previous project “*4.1.5 Recycling of reject flows from textile sorting and cardboard recycling through thermochemical recycling*”, this project aimed to follow up the initial set of batch experiments at lab scale with trials in a continuous way in the Chalmers pilot plant. Thus, this project aims to investigate to what extent the existing waste

fractions from cardboard recycling could be used as raw materials for new material production by means of thermochemical conversion at large scale (>50kg/h). The main objective of the project was to create experimental data for the products obtained via thermal gasification of this reject fraction at industrial scale in a steam atmosphere in the temperature range of 700-825 °C. The industrially relevant experimental data obtained from this project can be used to provide a better scientific basis to evaluate different recycling routes of mixed materials and convert them into high-quality materials and chemicals via steam gasification.

The project was connected to two basic goals in the framework of “Klimatledande Processindustri”: (1) to ensure the efficient recycling of materials for high-quality products to minimize the need for primary raw materials in general; and (2) to replace fossil primary raw materials in the processes with a recycled raw material.

In this project the reject fraction obtained from cardboard recycling from the Fiskeby’s Fiber Recycling process was investigated. As the experiments are aiming at an industrial scale (50-100 kg/h), challenges linked to pre-treatment and to the efficient feeding of materials for thermochemical recycling processes were also considered in the project. Experience and knowledge of how plastic-rich material mixtures can be chemically recycled will also help to broaden the requirements specification for raw materials for chemical recycling and thus to reduce further sorting and separation requirements for similar fractions.

The specific goals for the project were:

1. To close the mass balance for the thermal gasification of the blended reject fraction in a steam atmosphere in the temperature range of 700-825 °C and provide analysis of the product yields for industrial scale trials.
2. To provide insights and gain practical experience on how materials of this type can be upgraded for an efficient logistic and to facilitate feeding in an industrial thermochemical recycling process.

The report is organized as follows. First, the description of the problematic of this reject fraction is exposed in the project description section. Then, the upgrading and characterization results are presented in the second chapter. In the third one, the industrial scale trials are described including both the methodology followed and the results obtained. In this section a comparison with the results obtained in the first project (at lab scale) is also included. The fourth chapter shows the conclusions obtained and proposals or future works.

2. UPGRADING AND CHARACTERIZATION

The upgrading presented in this section includes grinding, classifying and pelletizing. The experience gained in the previous project “4.1.5 Recycling of reject flows from textile sorting and cardboard recycling through thermochemical recycling” was used in this project. The objective of the grinding and pelletizing tests was to evaluate the mechanical properties that the pelletized waste will present during transport, handling and feeding in gasification tests. In this section a description of the process and the characterization of the pelletized batches is presented.

To be able to pelletize this reject fraction, a first shredding step is needed, followed by a purification step to remove inert materials. Then, the pelletizing takes place in a rotating ring matrix according to the same principle as wood material is pelletized.

1. The comminution was performed in a slow-moving shredder (*Lindner Micromat 2000*) coupled with a 15 mm sieve. From this step the resulted material was finely ground, and it was able to be pelletized without further grinding.
2. The separation of inert parts took place in a separation table coupled with a suction nozzle (*Franssons Lift-Sep LS60-420*) with a capacity of 100 kg/h. Here, the light fraction was separated from the heavy one by removing impurities like metals or stones.
3. The pelletizing was performed in a pellet mill (*Buhler DPCA*) using two different press channel lengths (50 and 55 mm). The capacity was 100 kg/h, which is considered very reduced compared to the usual rate for wood (around 500 kg/h), but it was needed due to the low bulk density of the material.

The test material consisted of two batches taken out at different days from the process and where pelletized separately the first batch 165kg with a 50 mm press channel length and the remaining 100kg with 55 mm press channel length. Around 50 kg remained unpelletized for further testing. The two batches are named *50mm* and *55mm* and display differences in composition unrelated to the pelletizing process.

The characterization techniques used for this material are described below along with the outcomes obtained from them. This characterization allows to have an overall idea of the homogeneity of the batches, their composition in terms of contaminants and/or the expected behavior during the thermal treatment. Thermogravimetric and ultimate analysis were carried out for both batches of samples. Here the comparison with the results from the previous project (where the press channel length was 45 mm) is also included.

Thermogravimetric analysis (TGA) allows to investigate the thermal decomposition of the samples and have a preliminary idea of the possible composition of the different batches used in terms of the ratio between cellulosic and polymeric materials. The analyzer used in this project was a *LECO TGA701*. This furnace allows to analyze 19 samples at the same time, measuring the weight loss of the different samples when a heating rate is applied in a specified atmosphere. A maximum of 5 g can be added in every crucible, and the balance

resolution of the TGA is 0.0001 g. The samples were heated up in a nitrogen atmosphere with a heating rate of 5 °C/min from 25 to 700 °C.

Different repetitions taking random samples of both batches of pellets were analyzed. In figure 1, some of them are represented. From the results here obtained, we consider that the repeatability is good since all the profiles are similar and within a narrow range, and therefore, the further decomposition of larger volumes of fuel via steam gasification should report similar values as the small batches used in the bench scale trials.

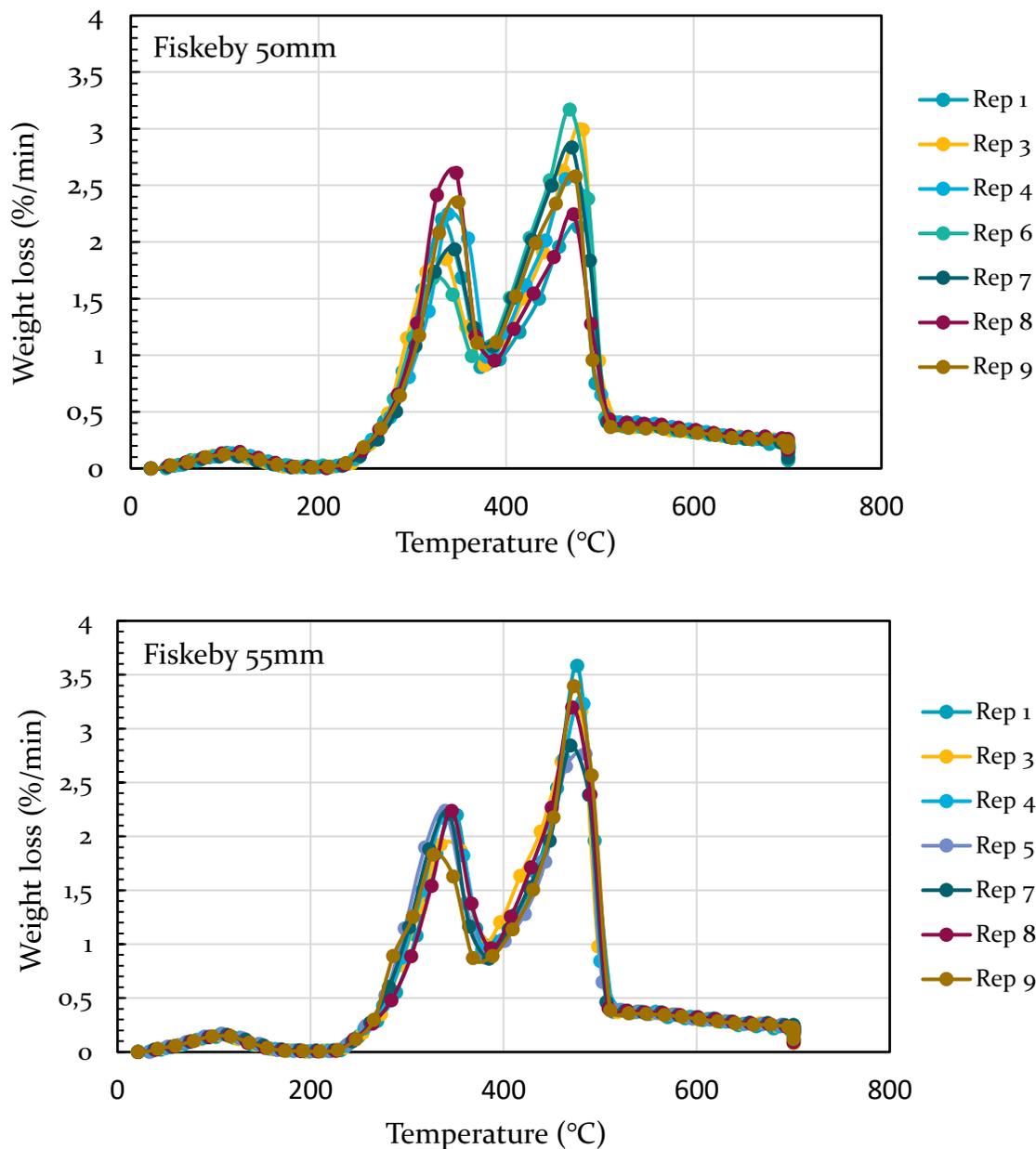


Figure 1: Thermogravimetric analysis of random samples from cardboard recycling samples. This analysis shows the thermal decomposition of the samples.

From this analysis a clear decomposition of cellulosic and polymeric materials is observed. At lower temperatures (around 300°C) the first peak of devolatilization can be related to cellulosic materials decomposition (paper, cardboard, etc.). The second peak can be associated to synthetic polymer decomposition. Based on this, a ratio of ca. 30-40 %wt. cellulosic materials/60-70 %wt. polymers (linear polymers like polyethylene or polypropylene) was estimated. We also observed that most of the components present in the pellets can be devolatilized in an inert atmosphere. Less than 10% of the materials represent the ash fraction. In this category can be included pieces of metal, glass or aluminum.

For the sake of a better view of the differences in the composition for the two batches used in this project and the one used for the laboratory trials (pellets of 45 mm matrix), a chart with the average values obtained from all batches is included in Figure 2.

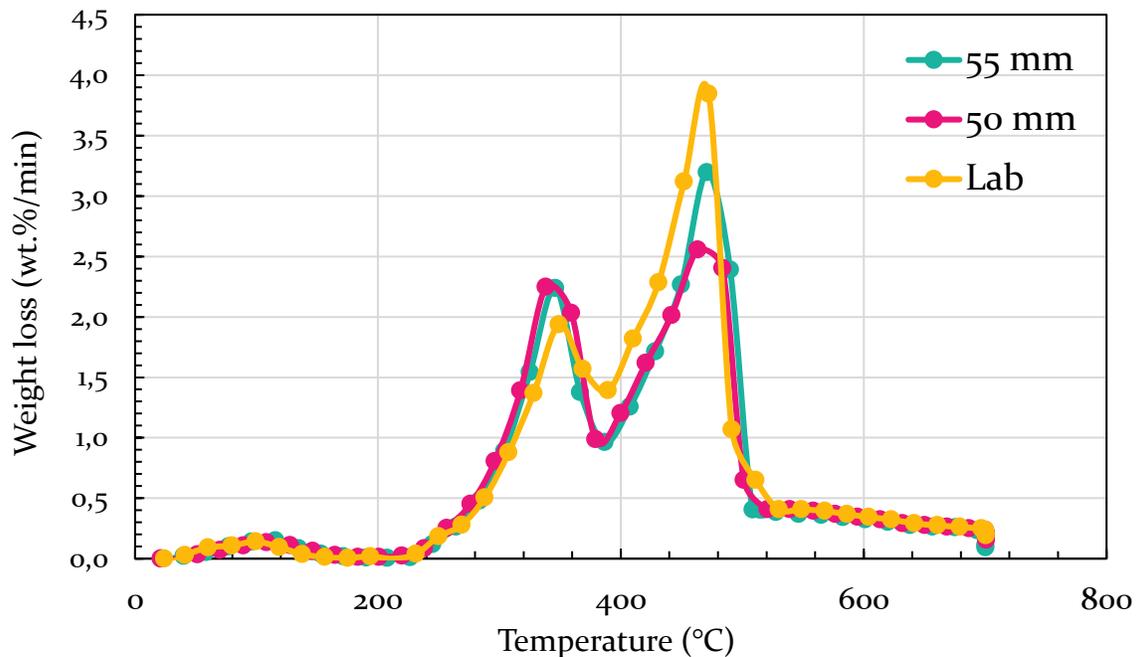


Figure 2: Average values of the thermogravimetric analysis for the different batches used in this project (50 & 55 mm) and the reference value used in the previous project (Lab)

Along with the thermogravimetric analysis, the ultimate analysis of the different batches gives a preliminary idea of the composition of the reject fraction. Also, this analysis provides insights on the products that can be the outcomes of the steam gasification step. In table 1, the elemental analysis for the different batches is shown.

We can draw similar conclusions based on the elemental analysis. Results obtained from the three batches are alike but the slight differences that we can see here can lead to different yields of the products after steam gasification. All batches showed a major share

in carbon (~60%) followed by oxygen (~20%). The remaining compounds are hydrogen, nitrogen, sulphur and chlorine (which altogether account for ~10%). Regarding chlorine and sulphur content, these elements represent a weight average percentage between 0.2 – 0.3% Cl and between 0.06 – 0.24% S. This indicates the presence of plastic materials like PVC and other impurities that mainly remained in the ash.

Table 1. Ultimate analysis of the different batches used in the project. The comparison with the batch from the previous project (45 mm) is also included

Analysis	Unit	45 mm	50 mm	55 mm
Moisture	%	1.8	2.8	1.9
Ash	% db	7.34	9.36	8.75
Carbon (C)	% db	65.9	59.5	60.6
Hydrogen (H)	% db	10.0	8.6	9.0
Nitrogen (N)	% db	0.30	0.29	0.35
Oxygen (O)	% db	18.0	22.0	21.0
Sulfur (S)	% db	0.24	0.06	0.07
Chlorine (Cl)	% db	0.31	0.24	0.20
Calorific value	MJ/kg db	-	28.44	29.36
Net calorific value	MJ/kg db ash free	-	29.42	30.14

Based on the elemental analysis and focusing on the C/H/O ratio, a preliminary estimation of the polymer composition was obtained. Some assumptions were considered such as: (a) no other polymers are present in the mixture beside the ones here considered; (b) ashes do not contribute to the oxygen content; and (c) other impurities do not contribute to the content of chlorine and nitrogen. In table 2, the estimated polymer composition can be found in a dry ash free basis.

As can be seen from table 2, the percentages of each compound vary depending on the batch used. Based on this estimation, the percentage of olefins in the produced gas from the batch at 45 mm should be higher than the other two batches. Similarly, the percentage of carbon oxides should be lower in this batch (45 mm) due to the lower content in cellulosic materials. These assumptions can be confirmed by the results obtained from the steam gasification of the different batches.

Table 2. Estimated polymer composition based on ultimate analysis

Analysis	Unit	45 mm	50 mm	55 mm
Cellulose	% daf	36.2	42.5	42.4
Polyolefins	% daf	56.1	44.1	47.8
PVC	% daf	2,6	2.1	1.7
PET	% daf	2.5	8.8	5.3
PA	% daf	2.6	2.4	2.8

3. INDUSTRIAL THERMOCHEMICAL RECYCLING TRIALS

In this section the experimental tests performed at industrial scale for the different batches are presented. First the methodology followed is described, and then the results obtained are shown. A comparison with the lab-scale results is also included for a better understanding. At this point it is interesting to note that lab-scale experiments were performed for the reject fraction of cardboard recycling pelletized at 45mm, but for sake of clarity in the graphs it is labelled as Lab, whereas industrial-scale results are labelled as 50mm and 55mm. Three reaction temperatures of steam gasification were selected to evaluate the influence of this parameter in the product distribution. Those temperatures were selected close to the ones chosen at lab scale for a better comparison.

METHODOLOGY FOLLOWED

For this project, industrial scale experiments (50 kg/h) were performed during the experimental season in the Chalmers power plant. These experiments allow to evaluate opportunities and risks associated with the use of blended materials at industrial scale. The Chalmers power plant is a dual fluidized bed (DFB) which consists of a 12MWth circulating fluidized bed (CFB) boiler coupled with a 2-4 MWth bubbling fluidized bed (BFB) gasifier. In Figure 3, a schematic description of the power plant is shown. The gasifier is entirely fluidized with steam and heated by the bed material (silica sand) circulating through the system. At Chalmers the boiler is dimensioned after the heat demand of the Campus with an own fuel feed and not as in a general constellation in an indirect DFB gasifier after the heat demand of the gasification. To assess the amount of gas produced 35 l/min of helium were added as tracer gas to the gasifier. As helium can be detected later by GC analysis the measured concentrations can be converted into mass flows.

To establish the mass balances based on the measurement of permanent gases and relevant condensable hydrocarbon compounds, the following procedure was employed. The raw gas was sampled from the gasifier and then it was filtered to remove particulate matter and split into two streams for further analysis. The first stream is quenched with isopropanol, to condense the tar and water, while the permanent gases were analyzed in a *Varian CP4900* gas micro-GC. A sampling port before the quenching point allowed for the sampling of tar compounds using the solid-phase adsorption (SPA) method. The adsorbed hydrocarbons are eluted afterwards and analyzed in a *Bruker-430 GC-FID* system. The second raw gas sample stream is further reacted in a high-temperature reactor, where it is cracked down to H₂, CO, CO₂, and H₂O, at 1700 °C. It is then analyzed to quantify the overall amount of carbon in the raw gas in a micro-GC similar to the one used for the first sample stream. The amount of unconverted fuel (or char) leaving the gasifier is obtained by difference of the carbon content of the raw gas given by this high temperature reactor and the carbon content of the fuel.

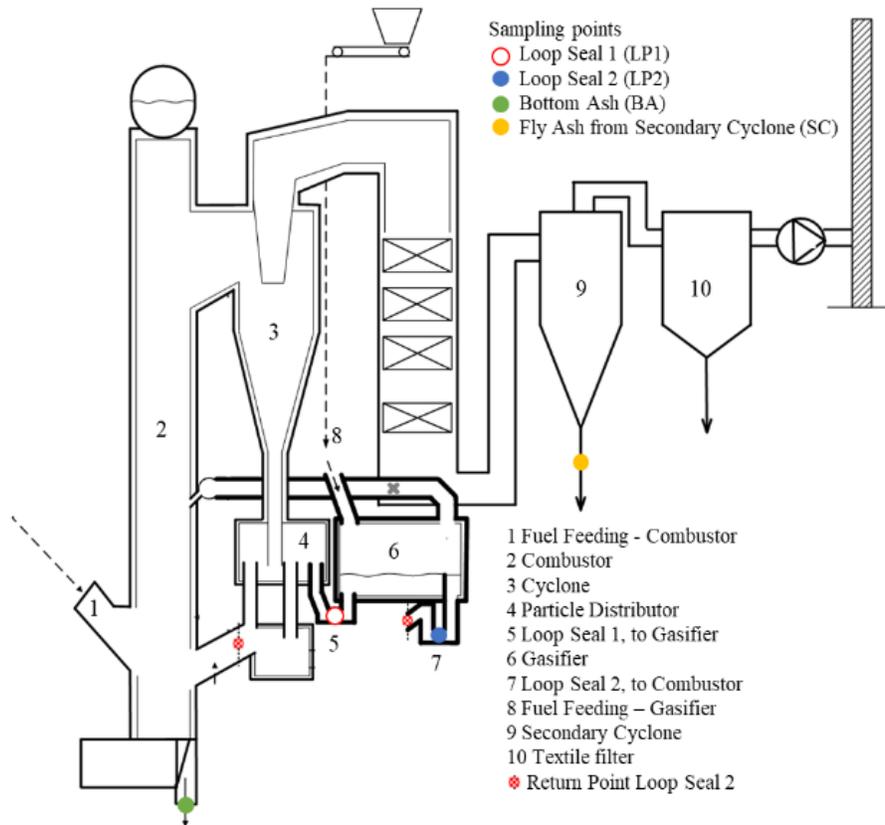


Figure 3. Schematic of the Chalmers power plant used for the gasification of the reject fraction of cardboard recycling.

Based on the results from the lab trials three different gasification temperatures (740, 770 and 805 °C) were selected for the experimental tests of the samples. The temperatures of the large scale are aimed at the temperature range around 750 °C which had displayed the best distribution in the lab experiments. Experiments in the range of 700 °C were not possible to adjust during the limited time of the trial as the waste character of the fuel requires to follow the environmental obligations to maintain 850 °C and a gas residence time of 2 s in the furnace. To still reach such a large temperature stretch between the combustion and the gasifier is possible but requires a longer start-up period.

The batch obtained at 50 mm was tested at 770 °C and the batch of 55 mm was used for the experiments at 740 and 805 °C. This gives an idea of not only the effect of the temperature but also the effect of the different composition of the feedstock. The feeding of the pellets during these tests was done at ca. 36kg/h for some hours of stable operation during a two-days period.

The feeding was performed via an extruder system that melts the pellets before coming into the gasifier. This feeding scheme acts also as a way to seal the system, preventing air to come in the gasifier and allows the feeding of the material in a more continuous way. In figure 4,

the extruder is shown in the left hand, while the appearance of the melted product can be seen in the right hand. The feeding to the extruder was done by hand to supervise that no blockage or failure happened during it.



Figure 4. Feeding system via extruder used for this project in the left hand. Appearance of the melted material in the right hand.

Although the feeding seems to be more stable using a extruder as feeder, there are still some issues regarding the amount of fuel that reaches the bed in the gasifier. This unstable control of the feeding could be observed during the experiments with the batch of 50mm pellets. The continuous measurement of the produced gases during the gasification step showed ups and downs during the operation, indicating that the feeding was not steady, most likely related to the intake of the material, which is designed for granules. This was confirmed by observing the flowing melt through a small window. For the 50mm, the melt of material coming into the gasifier had not a continuous appearance, falling in pieces, which explains the variability on the results. As a matter of fact, the results from the trials will be presented separately but the numbers do not have the required reliability to draw conclusions from those trials.

RESULTS OBTAINED

Industrial scale trials

The product distribution obtained in the gasification of the two batches at industrial scale is presented below (Figure 5). To have a better view of the results, the two batches are shown separated inside a dotted box labelled with the size of the pellets in each batch.

As mentioned earlier the experiments suffered of fuel feeding issues which provides the quantification of some values with a relative uncertainty. By means of the helium tracing the overall flow of carbon can be derived from the analysis downstream of the high temperature reactor. When the mass flow is known accurately the difference between the two measurements is attributed to the char formed in the process. In this case, as the fuel feeding measurement was not reliable the values of char obtained from the laboratory experiments were used as reference.

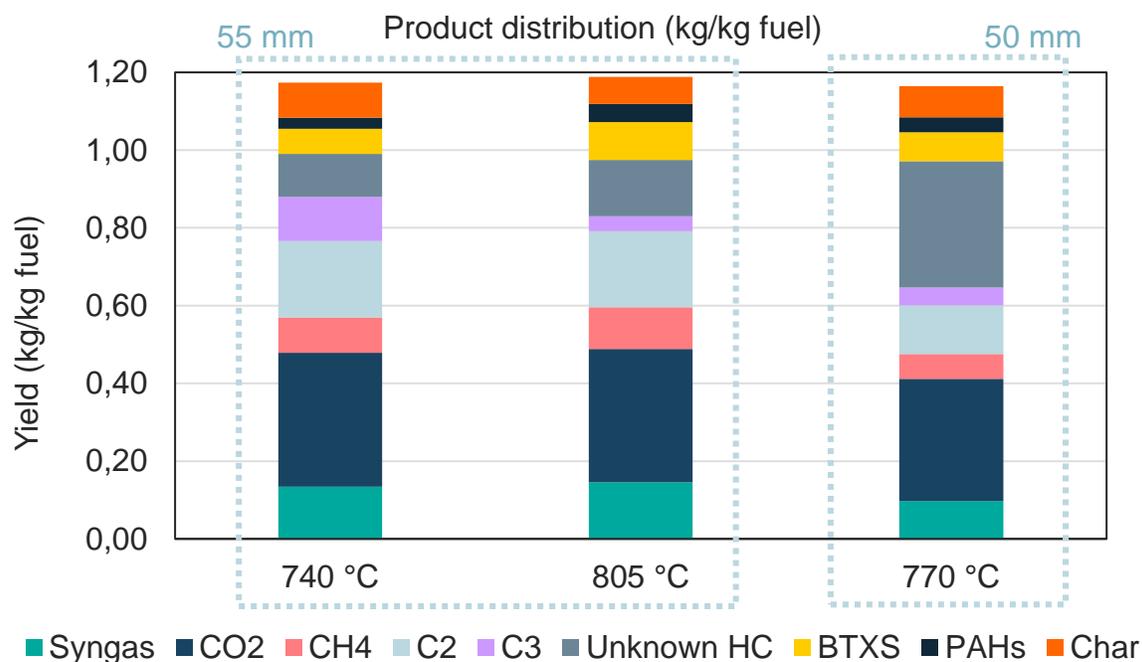


Figure 5: Product distribution in kg/kg fuel obtained through the large-scale gasification of the two batches (55 mm and 50 mm pellets)

Typically, when higher temperatures are applied, the values of CO₂, CH₄ and syngas increase. Similarly, aromatic hydrocarbons tend to form more likely when the temperature increases. Besides, the yield of produced olefins which would be the main product aimed at from this raw material is the lowest at the higher temperatures. As expected from the chemical structure of the feed, the amount of CO₂ produced is very high stemming from the decomposition of cellulosic material. The yield of C₂ and C₃ compounds is acceptable for such a waste fraction due to the presence of plastic materials (mainly polyolefins). The main share of the aromatic fraction is benzene, toluene, xylene and styrene (BTXS) as can be observed in Figure 6. With the increase of gasification temperature, the overall formation of aromatics increases but the fraction of BTXS decreases slightly, from approximately 69.4% to almost 66% in the total aromatic fraction. This indicates that higher polyaromatic compounds are produced at higher temperatures. Both observations are in line with trends observed in experiments with pure polyolefin materials. Regarding the unknown HC share, this represents mainly the amount of C₄-C₅ hydrocarbons that are out of the scope of the analytical techniques used for this project. This value is calculated as the difference between the carbon content measured in the high temperature reactor and the carbon identified both in the gaseous and the aromatic fractions. This is the reason why the yield of unknown HC for the batch of 50mm at 770 °C is so high. In this case, the carbon in both the gas and the aromatic phase is very low, probably due to not only the variation in the feeding, but also due to errors in the sampling and measurements. Therefore, those results do not present an adequate reliability to draw any conclusion in this sense.

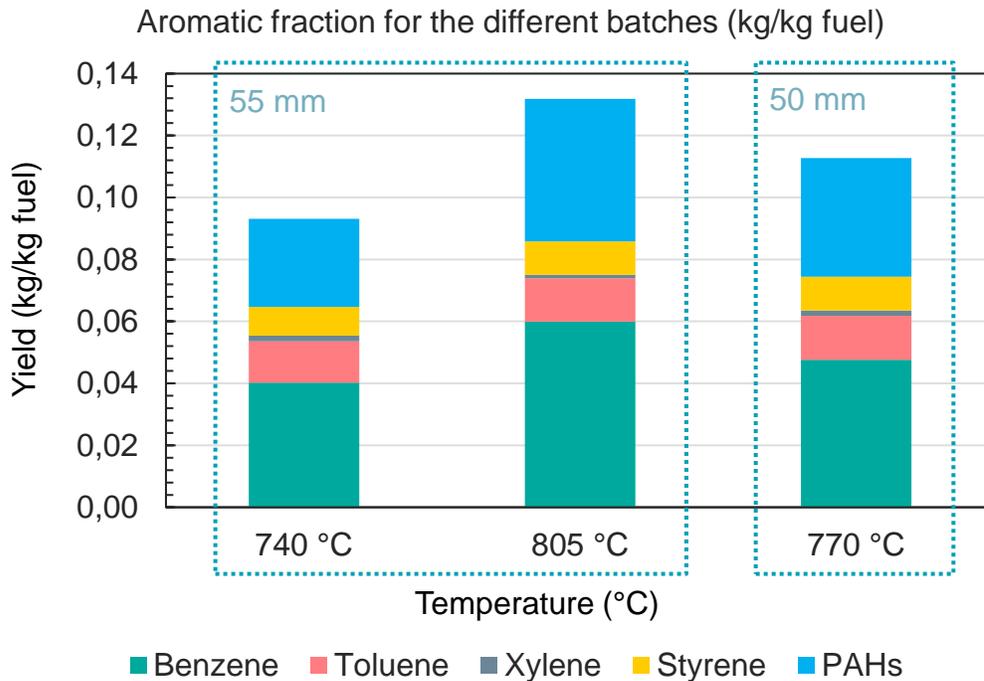


Figure 6: Aromatics distribution in kg/kg fuel obtained through the gasification of the different batches: 55 mm (740 °C and 805 °C) and 50 mm (770 °C)

In a process aiming at carbon utilization, CO, CO₂, H₂ and CH₄ should be used to gain further carbon as feedstock. Based on the raw material properties and the knowledge of the decomposition patterns, a large share of the carbon in this fraction will stem from the decomposition of the cellulosic part and present therefore a biogenic carbon source which could be utilized in further synthesis. In figure 7 the different values obtained within this fraction are shown as mols/kg fuel to give a better representation of the eventual hydrogen demand in a downstream synthesis process. As can be observed, a clear increase in hydrogen production is seen when the gasification temperature is higher. A similar trend is observed with the methane production. Both trends are in line with the decrease in light olefins and the increase in aromatics where CH₄ is an alternative product to light olefins and hydrogen a side product of aromatization. CO and CO₂ show a slight increasing trend when the reaction temperature is increasing, but the trend is not very pronounced.

In this case, the syngas percentage is very high due to the chemical structure of the initial products in the samples. Mainly cellulose – but polyester as well - contain high shares of oxygen and do inevitably yield carbon oxides during thermal decomposition.

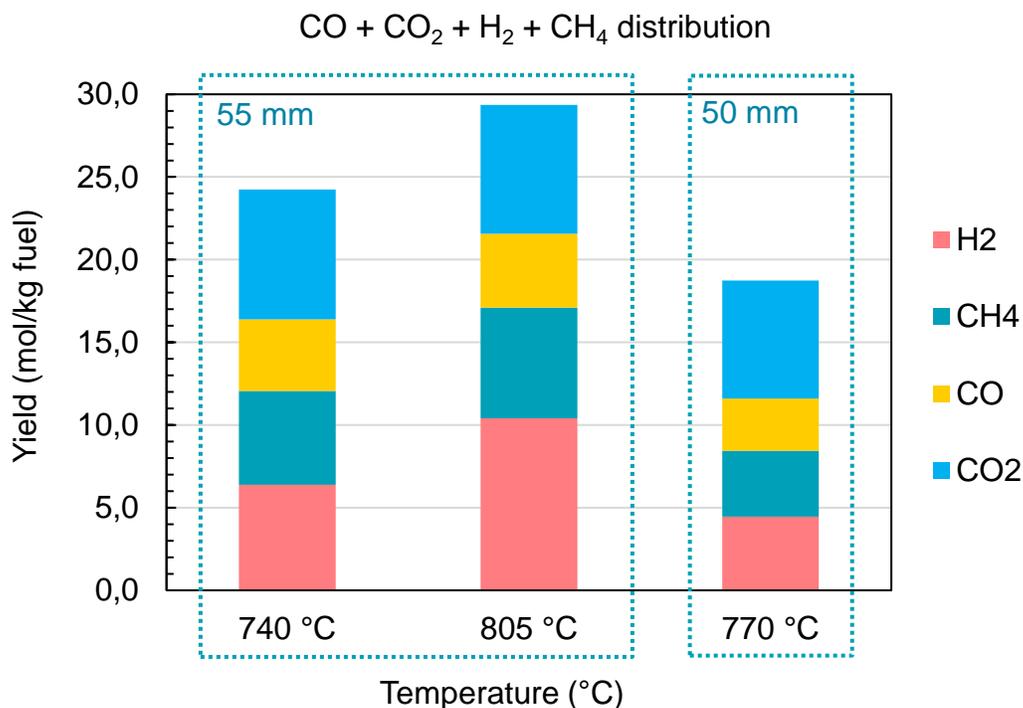


Figure 7. Distribution of syngas (CO+CO₂+ H₂+CH₄) produced at the different reaction temperatures for both batches

From the facts here exposed, it can be concluded that a lower temperature (e.g., 740°C) is more convenient to valorize this reject fraction because: (1) the yield of olefinic compounds is higher at this gasification temperature; (2) less polyaromatic hydrocarbons are produced at lower temperatures, which favors the recovery of BTXS; and (3) less syngas is formed, which requires more effort to be valorized as feedstock for new material production.

Comparison between lab-scale and industrial-scale trials

For a better view of the outcomes found, the comparison between the results obtained at laboratory scale for the project “4.1.5 Recycling of reject flows from textile sorting and cardboard recycling through thermochemical recycling” and the ones obtained at industrial scale are shown in this section. Although the comparison between the different scales is difficult due to the variation in composition, similar trends in the product composition are observed.

Figure 8 shows the comparison of the product distribution of the different batches at industrial scale, and lab scale. In line with the oxygen content of the feedstock more carbon oxides are generated during the industrial trials. This can be explained by the different composition of the batches, where 50mm and 55mm present a higher share of cellulosic materials. Similarly, the lower share in polyolefins in the 50mm and 55mm batches compared to the one used in the lab (45mm) led to a lower percentage in olefins in the product gas.

Even more interesting is the trend towards lower aromatization in industrial scale preventing extensive creation of PAH's. The reason for this tendency is not fully understood but residence times and dilution effects could be the reason.

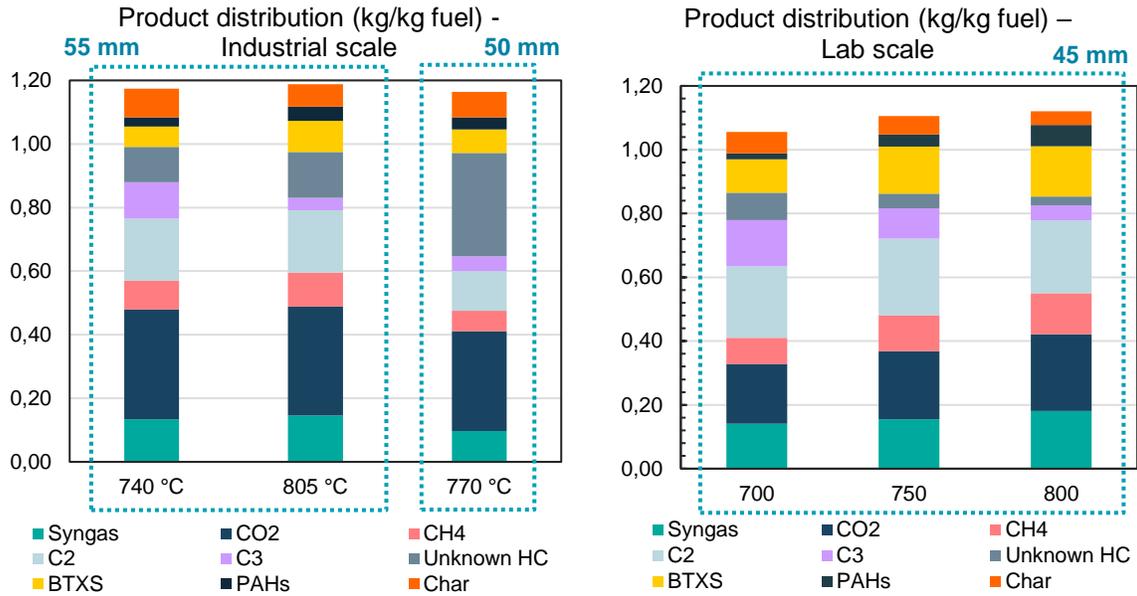


Figure 8. Comparison between both scales in terms of product distribution (kg of product per kg of fuel)

In figure 9, the comparison in terms of syngas, CO₂ and CH₄ distribution is shown. As can be seen all the experiments besides the one at 770 °C (50 mm batch) follow the same increasing trend with the temperature. As mentioned previously, these differences can be ascribed to the different composition mainly in terms of cellulose content. Nonetheless, what is clear is the increasing trend of the values of the different gases when the temperature of gasification is higher.

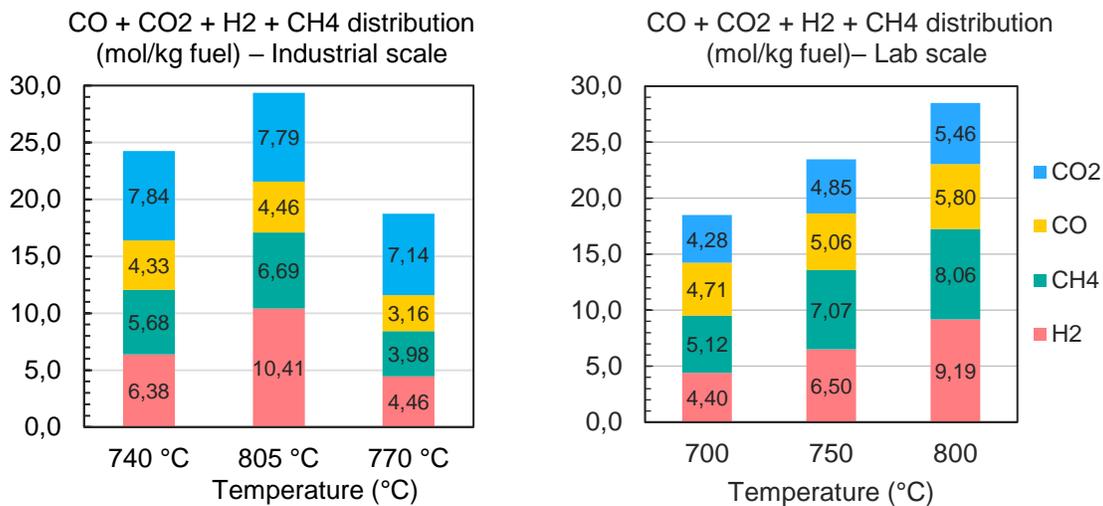


Figure 9. Comparison between both scales in terms of syngas, CO₂ and CH₄ (mol of product per kg of fuel)

When it comes to the aromatics' distribution, the trend is the same in both lab- and industrial-scale (Figure 10). As the temperature increases, also does the quantity of tars produced. However, in this case, larger differences between the lab and the industrial plant can be observed. First, at industrial scale, the total amount of tars is almost reduced to the half of what was obtained at lab scale, mainly BTXS compounds. More interesting is the clear trend towards lower aromatization in industrial scale preventing extensive creation of PAH's at such scale.

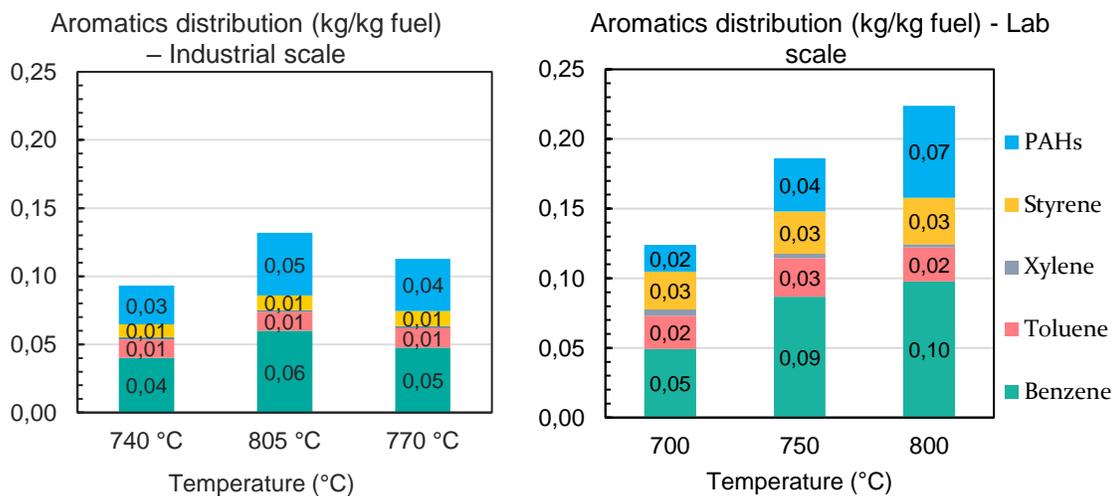


Figure 10. Comparison between both scales in terms of aromatics distribution (kg of product per kg of fuel)

4. CONCLUSIONS AND FUTURE WORKS

The industrially relevant experimental data obtained from this project can be used to provide a better basis to evaluate steam gasification as recycling route for mixed materials with the aim to convert them into high-quality materials and chemicals via steam gasification. For that purpose, the project was taking forward mass balances and yields of the main products for the reject fraction obtained after cardboard recycling.

The common characteristic of this waste fraction was the presence of both naturally and synthetic polymers in a blended material. As expected from the molecular structure of the materials in the waste mixture, the evolution of permanent gases and more importantly carbon oxides depends heavily on the oxygen bound to carbon. As a matter of fact, the content of cellulose and polyester to some extent, is an important point in the production of carbon oxides from the feedstock. For the same reason olefins such like ethylene and propylene are only formed in larger quantities if the parent material comprises a considerable amount of alkane structures with saturated C-C bonds (e.g., polyolefins such as polyethylene and polypropylene). Monoaromatics, more specifically benzene, toluene, xylene and styrene make up 7-10% of the mix in all cases and the origin and reaction route is twofold: a) the decomposition of a polymer containing an aromatic ring, e.g., polyester. b) a cyclisation/aromatization reaction based on primary decomposition products which can stem from both natural as well as synthetic polymers. An increase of the temperature induces a growth towards the formation of polyaromatic hydrocarbons (PAH) such like naphthalene which is more pronounced for route b).

In summary, the product yields analyzed lead to the following main conclusions

1. The material prepared by shredding and pelletizing is suitable for feeding if melted previously through an extruder.
2. The intake of this extruder requires some further modifications to allow unsupervised and stable feeding.
3. The differences between the batches used were mainly due to the cellulose content which affects the yields of products from the conversion, mainly syngas from cellulose.
4. The comparison between the different scales is difficult based on the conducted experiments due to the variation in the composition of the different batches.
5. Valuable chemicals such like monoaromatics and light olefins are present in the products in relatively large quantities and can be extracted directly.
6. The yield of light olefins in relation of the estimated polyolefin content is comparable to the yield from pure polyethylene cracking, with a tendency to be slightly higher as even other polymers contribute to the yield of those desired components.
7. The relatively large gas yield requires further conversion to achieve the goal of circularity. Catalytic or biological synthesis processes are required for production of basic chemicals.

8. Sorting or further separation of reject streams is an unnecessary step before the thermochemical conversion. The products are separated more easily afterwards, e.g., in existing equipment at the cracker plant.

To sum up, the industrially relevant experimental data obtained from this project can be used to provide a better basis to evaluate steam gasification as recycling route for mixed materials. Specifically, to what degree further processing, separation of the distribution and synthesis of base chemicals, are economically viable.

As further should include the following activities:

- Reproduction of lab trials with the test material from the large scale trials for better comparison
- Inclusion of the analysis of the unknown hydrocarbons
- Assessment of the value chain, with a specific perspective on the effort for gas separation and the utilization of the gases
- Comparison with a two-step process of a decentral pyrolysis for an oil production and a centralized high temperature pyrolysis to generate high value chemicals