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Fast pyrolysis of industrial waste residues to liquid intermediates - experimental and conceptual study

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Summary		
<p>This report summarises the results of the research project “Sustainable high value products from low-grade residues and wastes”, known as WasteBusters. The overall goal of the project was to generate novel sustainable solutions for bio and circular economy meeting the research needs of the Finnish industry. In the project, the whole value chain from pretreatment of industrial feedstocks via pyrolysis to products was studied.</p> <p>Main results of the project were:</p> <ul style="list-style-type: none"> - Development of an improved waste pretreatment unit - New data on pyrolysis/thermolysis of industrial waste - Techno-economic assessment of chosen concepts - Information on climate impacts of the concepts. - New data on business and operational environment for pyrolysis of industrial plastic waste and used wood - Several presentations of project results and reference articles under processing - Several new projects were planned two of them already accepted. 		
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Executive summary

Business Finland WasteBusters (2017-18) project consisted of the VTT research project and three company projects by Lassila & Tikanoja (L&T), Neste, and Pohjanmaan Hyötyjättekuljetus (PHJK). Participating companies in the research project were L&T, Neste, PHJK, Fortum, Valmet, Borealis, Suomen Uusiomuovi, and Savosolar. Ministry of Environment had an advisory role. The overall goal of the project was to generate novel sustainable solutions for bio and circular economy meeting the research needs of the Finnish industry.

In the project, the whole value chain from pretreatment of industrial feedstocks via pyrolysis to products was studied. Based on interest of clients and the potential for business cases three specific concepts were assessed economically:

- Fast pyrolysis of recycled (used) wood for bio oil production with centralized industrial drying of raw material,
- Fast pyrolysis of recycled wood for bio oil production with de-centralized solar drying of raw material,
- Thermolysis of plastic waste

Main results of the project were:

- **Development of an improved waste pretreatment unit.** Modular extruder, “Modix” (VTT patent pending) was successfully used for grinding and homogenizing heterogeneous industrial plastic waste.
- **Data on pyrolysis/thermolysis of industrial waste.** VTT bench-scale bubbling fluidized bed reactor was modified for thermolysis of plastics. Experiments with industrial feedstocks from L&T and Fortum were carried out and mass and energy balances determined for techno-economic assessment. Both feedstocks and products were characterized to evaluate the potential use of products. The results showed that in the thermolysis of plastic waste the product was mostly in the form of wax. The best yield (92 w-%) in thermolysis was achieved with the packaging plastic waste at 575 °C.
- **Techno-economic assessment of chosen concepts.** The levelized cost of bio oil and wax was calculated based on a discounted cash flow over 25 years of operation. The cost of the bio oil from recycled wood based on industrial drying of raw material was 37 €/MWh, the cost of bio oil from recycled wood with solar drying was 39 €/MWh, and the cost of wax from plastic waste was 23 €/MWh. The levelized cost of bio oil and wax is most sensitive to capital investment and discount rate. The cost of bio oil and wax is comparable to current energy prices in Finland.
- **Information on climate impacts of the concepts.** The climate impacts related to thermolysis of plastic waste were studied using the life cycle assessment (LCA) methodology. The aim of the studied system was to use plastic waste as a raw material for diesel and polymer production. Thermolysis of plastic waste was compared to a current business-as-usual situation in Finland, in which plastic waste was either incinerated with electricity and heat production or recycled mechanically, and the reject from recycling was sent to incineration. The results from the assessments show that under the assumed conditions, thermolysis of plastic waste has a significantly lower carbon footprint compared to direct incineration. In addition, thermolysis could provide recycled materials to fuel and polymer production, and have the ability to reduce climate impacts related to the production phase. In the studied scenarios, the carbon footprint of the WasteBusters scenarios was 15 - 60% lower compared to the business as usual scenarios, but the results are sensitive to the applied assumptions and data. When climate impacts of sending the separately collected post-consumer plastics waste to incineration or to thermolysis were compared, the results from the two scenarios were

quite close to each other. However, sending the reject from mechanical recycling to incineration was a significant contributor to the carbon footprint in the business as usual scenario. Thus, it is assumed that a more favourable result could be received, in case the reject from mechanical recycling would be directed to thermolysis instead of incineration (even though such combination was not included in this study).

- **New data on business and operational environment for pyrolysis of industrial plastic waste and used wood** was created. A marketing survey was carried out. As a result more precise understanding of waste plastics thermolysis operational environment was reached. Thermolysis production concept vision, alternative operational and logistics concepts, clear business drivers and also challenging bottlenecks were identified. Key focus value chain actors were gathered together for sharing same understanding and business perspectives, enabling fruitful cooperation in the future. A working document on legislative framework for waste to products was written. This will be used in a public project with Ministry on Environment on chemical recycling and end-of-life status of plastics.
- **Several presentations of project results have been kept and reference articles are under processing. In addition, as exploitation of the results several projects were planned.** VTT coordinated EU NonTox will start in June 2019, the focus being on removing toxic compounds from ELV (End-of-Life Vehicles) and WEEE (Waste Electrical and Electronic Equipment) plastics. In Business Finland Co-Creation project MoPo, monomers from end-of-life polymers, started in April 2019 and will last for six months. A Co-Innovation project will be built with industry where the focus is on new value chain for PS waste to new products by integration of mechanical and chemical recycling. Another BF initiative is BioFlex, where the overall goal is to identify and develop a least-cost solution for the production of sustainable and storable liquid fuels that meet the specifications for both flexible power generation and marine transport with large diesel engines. Also an EU proposal to LC-SC3-RES-23-2019 (RIA) is under preparation.

Preface

The research project “Sustainable high value products from low-grade residues and wastes”, known as WasteBusters, was carried out by VTT during the years 2017-2018. This research benefit project was funded by Business Finland, and it included three parallel company project owned by Lassila & Tikanoja, Neste, and Pohjanmaan Hyötyjätekuljetus.

The overall goal for the project was to generate novel sustainable solutions for bio and circular economy meeting the research needs of the Finnish industry. In the project, the whole value chain from pretreatment of industrial feedstocks via pyrolysis to products was studied. Main effort was focused on thermochemical recycling of plastic waste streams. This report summarises the project results.

Senior Principal Scientist Anja Oasmaa worked as project manager at VTT, and was responsible for the research. Research Scientist Kirsi Korpijärvi assisted her in project management and acted as secretary of the steering group. Main contributions to the project were made by Muhammad Saad Qureshi, Joonas Lahtinen and Christian Lindfors (PTL technology & pyrolysis tests); Hanna Pihkola and Ivan Deviatkin (LCA); Kristin Onarheim (TEA); Ismo Ruohomäki (market study); Jutta Laine-Ylijoki and Malin zu Castell-Rüdenhausen (regulatory framework); Jyrki Raitila and Eemeli Tsupari (solar drying); Suvi Jokinen and Henna Punkkinen (characterization of waste samples). Almost 50 VTTiers participated in the execution of the WasteBusters project.

The steering group comprised representatives of the organisations and companies funding the project: Mikko Paasikivi, L&T Oyj; Jukka-Pekka Pasanen, Neste Oyj; Sara Kärki, Fortum Power and Heat Oyj; Joakim Autio, Valmet Technologies Oyj; Tuomas Ouni, Borealis Polymers Oyj; Mikko Lammi, Pohjanmaan Hyötyjätekuljetus Oyj; Kaj Pischow, SavoSolar Oyj, Vesa Soini, Suomen Uusiomuovi Oyj; Heikki Kutinlahti/Lassi Hietanen, Protech AD Services Oyj; Pia Salokoski, Business Finland; Anja Oasmaa and Kirsi Korpijärvi, VTT. Ministry of Environment had an advisory role and Kati Vaajasaari participated in the steering group work.

The authors would like to acknowledge all those who have participated and contributed to the project as well as steering group for active participation.

Espoo 30.4.2019

Authors

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Definitions

In this report following definitions are used:

In this context, word thermolysis is used instead of pyrolysis related to plastic to liquids conversion. They basically mean the same but thermolysis is more widely used for thermochemical conversion of plastics. Pyrolysis is used for thermochemical conversion of biomass.

Fast pyrolysis is a process in which organic material is rapidly heated to ~500 °C in the absence of air. The vapours are condensed to fast pyrolysis bio-oil (FPBO) with typical yields of 60-75 w-% of the feedstock. The process is self-sufficient in energy requirement and about 70 % of the original energy content is captured in the biofuel product.

Melting temperature of the wax was visually measured by heating the sample under microscope. The temperature at which the sample started to change into liquid was recorded as the melting temperature.

PTL means Plastic to liquids process

Thermolysis or **PTL process** is thermal or catalytic decomposition of plastics in an oxygen-free environment or in presence of steam into liquid product for chemicals or fuels.

Thermosets. A thermosetting polymer, resin, or plastic, often called a thermoset, is a polymer that is irreversibly hardened by curing from a soft solid or viscous liquid prepolymer or resin. Curing is induced by heat or suitable radiation and may be promoted by high pressure, or mixing with a catalyst. It results in chemical reactions that create extensive cross-linking between polymer chains to produce an infusible and insoluble polymer network.

Recovery process is used for processing stages aiming for production of i.e. plastic monomers, cracker feeds, or drop-in heating oil.

1. Introduction

A great portion of the municipal and industrial waste constitutes of plastic. Variety of waste plastic management strategies exist, including reuse, recycling, valorising into chemicals and fuels, incinerating and landfilling. Although reuse and recycling are the most preferred routes in the waste management hierarchy, they are not always feasible. In most cases, plastic products are made up of different types of materials including, but not limited to, plasticizers, additives, softeners, hardeners or laminates. Moreover, some composite make use of wood or metals. Therefore stringent separation techniques are needed to separate foreign materials from plastic wastes which consequently makes mechanical recycling non-viable economically and technically.

Thermochemical routes offer a wide variety of options to convert plastic refuse to chemicals and fuels. The choice of routes depends largely with the nature of feedstock and type of product required. Plastic waste can be gasified to syngas and further converted to chemicals through chemical processes, thermolysed to get liquid fuels and chemicals or combusted/incinerated to achieve direct thermal energy. Gasification and combustion, that are relatively mature technologies and have been the choice of waste management industries for decades, do not always offer the largest conversion of plastic waste into energy. Thermolysis on the other hand, by converting plastic waste in to liquids, offer maximum energy densification. Plastic refuse which could not be mechanically recycled such as plastic film laminates of incompatible polymers and would be incinerated or landfilled, can be processed to products by thermolysis.

There are efforts to produce end products directly from waste plastics with thermochemical processes but the conversion of waste fractions in a manner which enables their co-utilisation in petrochemical industry is considered both technically and economically viable. However, presently pyrolysis/thermolysis of plastics is not considered as recycling technology under current EU legislation. There are attempts to change this and also this project aims to provide data to support this attempt.

At least the following general boundary conditions for waste-derived feedstock for thermal conversion production can be set: 1) sufficient hydrocarbon content, 2) volume and availability, 3) price, and 4) location, but we also need to understand the needs of the potential markets and customers and identify the possible barriers related to the new product/service.

2. Preliminary feasibility study

2.1 Description of the PTL concept

Plastic to liquids (PTL) – process is a thermal or catalytic decomposition of a material in an oxygen-free environment or in presence of steam into liquid product intermediate. Figure 1 shows a general plastic to liquids concept (ORA 2015). Table 1 presents the general resin to product route in thermolysis.

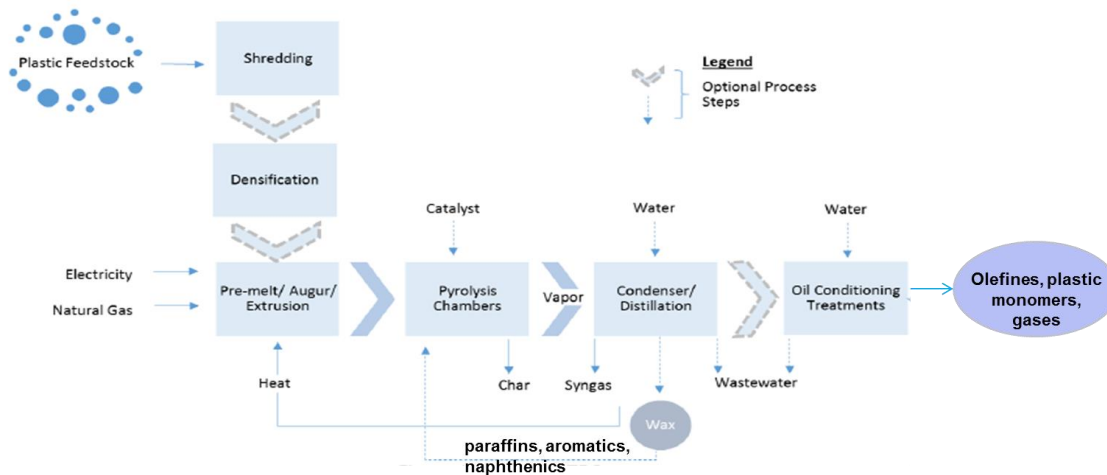


Figure 1. General plastics to liquids (PTL) concept (ORA 2015).

Table 1. Resins to products in non-catalytic thermolysis (VTT data).

RESIN	STRUCTURE	MAJOR ORIGIN OF WASTE	PYROLYSIS PRODUCT
PE	$\left(\begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ \text{---C---C---} \\ \quad \\ \text{H} \quad \text{H} \end{array} \right)_n$	Household, industrial plastic packaging, agricultural plastics	Waxes, paraffins, olefins -> Gases, light hydrocarbons
PP	$\left[\begin{array}{c} \text{CH}_3 \\ \\ \text{---CH---CH}_2 \\ \\ \text{H} \end{array} \right]_n$	Household and industrial plastic packaging, automotive	Waxes, paraffins, olefins -> Gases, light hydrocarbons
PS		Household, industrial plastic packaging, construction, demolition, WEEE (Waste Electrical and Electronic Equipment)	Styrene, its oligomers
PA-6	$\left[\text{---NH---(CH}_2\text{)}_5\text{---C(=O)---} \right]_n$	Automotive waste	Caprolactam
PVC	$n \left[\text{---CH}_2\text{---C(=CH}_2\text{)---Cl---} \right] \rightarrow \left[\text{---CH}_2\text{---C(=CH}_2\text{)---} \right]_n + n \text{HCl}$	Construction plastic waste	HCl (< 300C), benzene -> Toluene
PET	$\left[\text{---O---C(=O)---C}_6\text{H}_4\text{---C(=O)---O---CH}_2\text{---CH}_2\text{---} \right]_n$	Household plastic packaging	Benzoic acid, vinyl terephthalate
PMMA	$\left[\text{---C(CH}_3\text{)(COOCH}_3\text{)---} \right]_n$	Automotive, construction waste	MMA (methyl methacrylate)
PUR	$\left[\text{---NH---C}_6\text{H}_4\text{---NH---C(=O)---} \right]_n$	Construction, demolition, automotive	Benzene, methane, ethylene, NH ₃ , HCN

Thermolysis processes are broadly categorized into thermal and catalytic routes. Thermal thermolysis of plastics proceeds with random scission mechanism resulting in wide hydrocarbon distribution, which must be subsequently upgraded to achieve valuable products. However, narrower product distribution is possible with tuned process conditions such as the reaction temperature and residence time. At temperatures exceeding 650 - 700°C the quantity of aromatics and gaseous hydrocarbons increase whereas temperatures around 500°C favours the formation of oils with less aromatics. Low temperatures and short residence times favour wax formation. Light olefins are generally produced at high temperatures ($T > 800^{\circ}\text{C}$) and shorter residence times. However, care must be taken to avoid secondary reactions, which could lead to the formation of char. Several types of reactors, utilizing both batch and continuous operation modes, have been used in the thermal cracking of plastics.

The use of catalyst cracking has several practical advantages in the plastic thermolysis. Particularly in most cases, suitable catalyst makes the process economical by reducing the energy required for reaction and reducing the by-products formation by narrowing the product distribution and making the overall process efficient. Typically zeolites (HZSM-5, HY or HUSY), mesoporous (MCM-41) and silica alumina have been used. The catalysts are selected based on the product required and level of contamination in the feedstock if it is used in primary reactor. Catalyst with strong acidic sites primarily lead to short chain olefins whereas catalyst with wider pore size such as some zeolites favour more liquid hydrocarbons. Despite all the benefits catalyst cracking has to offer, deactivation of catalyst is an important challenge. Although deactivation is catalyst dependant (acidity and pore size), extreme operating conditions and level of contamination in the plastic waste i.e. the foreign material present in the feedstock often leads to the deactivation of the catalyst. Several remedies have been proposed in the literature to avoid the frequent deactivation of the catalyst such as the use of two stage cracking process. The first stage is essentially thermal cracking in the absence of the catalyst and the reactant or the melt comes into contact with the catalyst only in the second stage when the foreign materials and non-compatible plastics (such as PVC and PET) have already been stripped off in the first thermal cracking stage. Two catalysts in two stages can also be used in fixed bed settings. In fact, the gasoline obtained from a two stage catalytic process is better than with just one catalyst.

The most prominent reactor types are fixed bed, fluidized bed, kilns, microwave and free fall reactor. Normally the choice of the reactor is based on the feedstock available (the compositions can vary quite considerably) and the product required. For example, fluidized bed reactors have the advantage that operating parameters can be quite flexibly controlled, which gives direct freedom to achieve narrower and more valuable product distribution. Screw kiln reactors on the other hand under the same operating conditions, produce smaller content of gaseous hydrocarbons and bigger share of liquid hydrocarbons. Figure 2 presents the main pros and cons of various reactor technologies. As can be seen from Figure, fluidized bed reactors are most flexible in operation compared to other reactors. However, one major drawback is the cost of such system. The scale up of such requires piloting which renders the system expensive. From our experience with the fluidized bed system, the major advantage of such systems is the efficiency in heat transfer although the residence times can be not be easily manipulated or requires bigger installations. The reactor technology is described in more detailed in Appendix 1.

	Temp. profile	Heat exchange and transfer	Particle size	Residence time	Process flexibility	Non-catalytic thermolysis	Catalytic thermolysis	Value of obtained products	Scale-up	Costs
Fixed Bed	Red	Red	Yellow	Green	Red	Yellow	Yellow	Green	Red	Yellow
BFB	Yellow	Green	Yellow	Yellow	Green	Green	Green	Green	Yellow	Yellow
CFB	Yellow	Green	Yellow	Yellow	Green	Green	Yellow	Green	Yellow	Red
Rotary kiln	Red	Red	Green	Green	Yellow	Green	White	Red	Yellow	Yellow
Melting vessel	Red	Red	Yellow	Green	Yellow	Green	White	Yellow	White	Yellow
Extruder	Yellow	Red	Yellow	White	Green	White	Yellow	Green	Green	Yellow

Figure 2. Pros and cons on reactor technology for plastic thermolysis. (VTT summary from Arena & Mastellone 2006).

2.1.1 Description of the WasteBusters concept

The general purpose of WasteBusters project was to develop concepts for pyrolysis/thermolysis of plastic-containing waste to prove the possibility of effectively recover hydrocarbons in a form of marketable products for example plastic monomers, cracker feeds, or drop-in heating oils. Based on interest of clients and the potential for business cases three specific concepts were assessed economically:

- Fast pyrolysis of recycled/used wood for bio oil production with centralized industrial drying of raw material,
- Fast pyrolysis of recycled wood for bio oil production with de-centralized solar drying of raw material,
- Thermolysis of plastic waste

In the following the term recovery process is used for processing stages aiming for production of i.e. plastic monomers, cracker feeds, or drop-in heating oil.

2.1.2 Experimental results with used wood

The purpose of the research with used wood was to validate if the fast pyrolysis bio-oil (FPBO) from used wood would meet the specifications set by the standard EN 16900-2017 for industrial boilers. Commercial used wood Class C was used for fast pyrolysis. According to physical characterization studies, the dominant material groups were (virgin) wood (i.e. no visible coatings) (58 w-%) and chemically treated wood (41 w-%). The share of plastics was 0.7 w-%. The contents of heavy metals were not significant. No bromine was observed and the content of chlorine was ≤ 0.05 w-%. Prior pyrolysis studies, the sample was grinded, dried, and sieved. Plastic fraction was separated to over 0.98 mm sieve fraction. The main fraction having particle size of 0.55 – 0.98 mm containing wood was tested in one experiment and a mixture of plastic fraction (over 0.98 mm) and wood fraction (0.55 – 0.98 mm) was tested in

two other experiments. The fines below 0.55 mm were removed; Pb was found only in this finest fraction.

The pyrolysis experiments were carried out in a bench scale bubbling fluidized bed reactor (1 kg/h). Organic yields were lower (42 – 47 w-%) than with sawdust (62 w-%) but at the same level than those with stored forest residues (46 w-%). The side products char and gases are combusted for process energy in commercial integrated process. The liquid product had a high water content, which resulted in a spontaneous phase separation. The phases were mixed together, and a part of water was gently removed to obtain a single phase product with a water content of 21 w-%. The liquid product was a homogenous fluid, which in most cases met the demands of the EN standard and hence can be used in industrial boilers. All products based on the analyses made (nonpolar compounds were not analysed) met the specifications for REACH.

Solar enhanced drying

Sustainable biomass resources are limited, especially regionally. The energy content of sustainable woody biomass resources can be maximised through drying. On the other hand, there is an urgent need for low-cost energy storage applications, related to solar energy in particular. Biomass dried with solar energy could serve as a seasonal energy storage. It also improves the quality of biomass and helps preserve its quality.

VTT's experiments proved that solar heat energy can be well applied to biomass drying. Particularly, because moderate drying temperatures are favoured in order to ensure homogenous drying of wood particles, and to prevent changing the physical structure of biomass or losing volatiles with applying high temperatures. Ability to utilize low temperatures in drying extends efficient daily and seasonal drying times. Heat losses are also smaller when low temperatures are applied.

During the first experiment series, it appeared that there were some shortcomings of the used drying setting. With technical improvements and a better design, the efficiency of the drying system could be significantly improved. It should be remembered that this dryer was built primarily for different testing and measuring purposes and was never dimensioned for efficient drying or economic evaluations.

The sensitivity analysis, based on the experiment results, indicate that scaled-up dryers could be utilised in biomass drying with realistic payback times, such as 10-20 years. This seems to require several prerequisites. Natural drying outdoors should be utilised as much as possible before solar enhanced drying. The solar system investment is still high, calling for investment subsidies. It is as important to run the system at least as effectively as in the best experiments. It is also crucial to add monetary value to dried wood chips compared to wet biomass. Our experiments suggest that the wood chip price should increase at least €2/MWh after drying. Solar enhanced drying research is described more detailed in Appendix 2.

2.1.3 Experimental results in thermolysis of plastics

Thermolysis of plastics leads to the formation of products (oil/wax and non-condensable gases) rich in hydrocarbons which can be further upgraded into diesel like fuel. The purpose of thermolysis in this study of different plastic waste types was to carry out a thorough investigation on the yields and composition of the pyrolysis products at varying conditions to establish the optimum operational conditions. To accomplish this goal, thermolysis of one pure polymer (PP) and three different industrial plastic waste fractions were carried out at varying conditions in a 1kg/h bench scale fluidized bed reactor.

Feedstock composition

Three different types of mix plastic fraction (Figure 3) and one single pure polymer (PP) was used as a feedstock for thermolysis runs. Plastics separated from construction, demolition and energy waste (LTW) was delivered by L&T, while separately collected plastic packaging waste (F-SUM) and reject from plastic recycling (F-SRF) was delivered by Fortum. They constituted mostly of the polyolefin type of polymers. Other type of plastics include PET, PVC, PS etc. Also paper, cardboard and wood was present in the mixtures. The mixtures were sampled and analysed. Details on the feedstock composition can be found from Appendix 3.



Figure 3. Plastic waste feedstocks used in thermolysis tests. LTW on the left, F-SUM in the middle and F-SRF on the right.

Pretreatment with MODIX

The aim of the use of modular mixer (MODIX) was to enable organic waste/recycling material otherwise not suitable to be fed to thermolysis. These materials consisted of fluffy plastic films, plastic bottles, canisters and mixed plastic waste including paper, cartoon and pieces of wood. Also boundary assessment of process parameters, runability, and yield as well as energy consumption of MODIX-pretreatments was targeted. All planned materials were successfully pretreated to solid compounds and further crushed for thermolysis. With materials from Fortum the yield was in range of 12 kg/h and the calculated energy consumption in range of 0.7 kWh/kg in laboratory scale. Even though the energy consumption was quite reasonable it is not yet optimized and could be further decreased in next generation device. An example of feed to product in Modix is seen in Figure 4. The details of the MODIX experiments are presented in Appendix 4.



Figure 4. Reject from plastic recycling (F-SRF) going to feed zone of MODIX (left) and grains (right) after MODIX-treatment and crushing.

Experimental setup

Thermolysis experiments in a fluidized bed reactor (Figure 5) were carried out with four different feedstock at varying operating conditions. The aim was to find the best operating conditions for the maximum recovery of oil/wax. The experiments were carried out at temperatures varying from 550 to 650 °C with a vapour phase residence time of approximately 1 s. During the experimental trials, various configurations with the reactor were tested. The amount of sand was increased from 300 to 500 g which accomplished to a more stable temperature. By decreasing the particle size of the sand, it could probably be possible to have good fluidization with longer vapour phase residence time. The feed rate was close to 500 g/h in all the experiments. The details of the experiments are presented in Appendix 5.

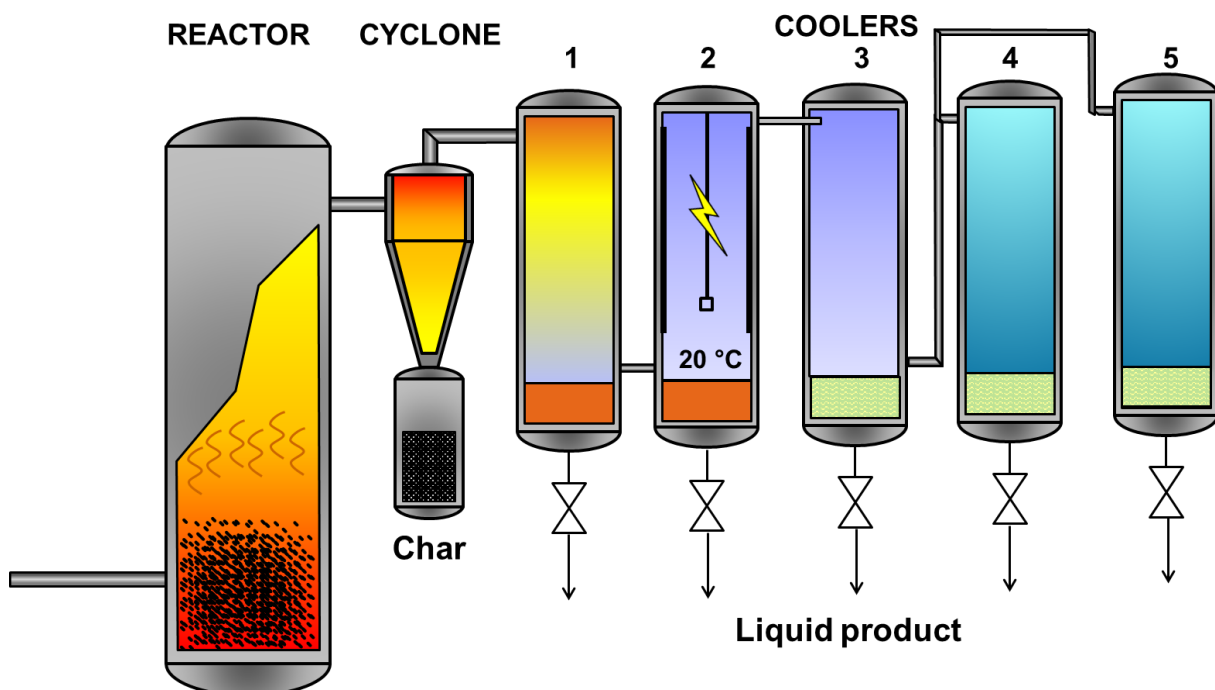


Figure 5. Bench scale unit used in the experiments.

Analysis of the products

Physical characterization of the feedstocks and products was carried out by employing modified standard methods (Oasmaa 2010). Elemental composition analysis (CHN) was carried out using an Elementar VARIOMAX CHN analyser (ASTM D 5291) and higher heating value (HHV) was determined using an IKA Werke C 5000 Control calorimeter (DIN 51900). The composition of the products was semi-quantitatively analysed using gas chromatography with mass selective (GC-MSD) and flame ionization detector (GC-FID). GC-MSD measurements were performed by using a Shimadzu GCMS-QP2010 Ultra gas chromatograph equipped with a mass selective quadrupole detector. A HP Ultra 1 fused silica capillary column (length: 50 m, inner diameter: 0.32 mm and film thickness: 0.52 μm) was used. GC/FID analyses were carried out using an HP series II (5890) gas chromatography with an on-column inlet and a CP-SimDist UltiMetal high temperature metal-capillary column (length: 10 m, inner diameter: 0.53 mm and film thickness: 0.17 μm). Samples were dissolved in THF and an internal standard decyclohexane was added before injection. Melting temperature of the wax was visually measured by heating the sample under microscope. The temperature at which the sample started to change into liquid was recorded as the melting temperature.

Results

Product Yields

Increase in the temperature led to the increase in gas formation and decrease in oil/wax formation (Table 2). Fast pyrolysis lead to the formation of wax at the expense of the oil. This is probably due to the fact that not enough residence time is provided to the hot vapours for continued cracking to lighter compounds. This could be adjusted by modifying the reactor and other unit operations to increase the residence time of the hot vapours in the hot sections of the reactor.

In the initial set of experiments, working at higher temperatures led to significant mass loss as can be seen from the mass balance Table 2. It can be expected that higher temperature led to the formation of lighter products thus, these experiments were repeated bearing in mind the change in product spectrum. The product collection was improved by

1. Stabilizing the temperature by adding additional bed material to the reactor
2. Modifying the condensing section by replacing the last CO₂ cooler with a bigger unit.
3. Splitting the gas flows in the condensers in the parallel mode to increase the contact time in the cooling section.
4. Carefully scrapping the products from the lines including all the bends and immediately weighing them before any volatiles could escape.

All these changes contributed to the better product recovery yet also, after a careful literature survey, we observed that this is a common problem and the lost compounds identified elsewhere constituted mainly C₅ hydrocarbons and aromatic hydrocarbons with various feedstock (Scott et al. 1990). To verify this, tar sampling technique was used in later experiments, where the gas was sampled before the condenser into a series of solvents. Subsequent GC analysis of the solvents revealed the presence of aromatic compounds.

Table 2. Product yields.

Feedstock	Temperature (°C)	Oil (w-%)	Wax (w-%)	Gas (w-%)	Char (w-%)	Total
PP	550	1.5	86.0	6.7	0.0	94.2
	600	18.6	38.7	18.5	0.0	75.8
	625	5.9	56.7	17.2	0.0	79.8
	650	8.9	17.2	19.6	0.0	45.7
F-SUM	575	0.0	72.5	11.6	7.7	91.7
	600	0.0	65.9	13.6	3.6	83.1
	625	0.0	60.9	18.8	4.4	84.1
F-SRF	575	0.0	65.4	12.6	6.7	84.6
	600	0.0	59.3	14.6	5.0	78.9
	625	3.0	50.3	17.7	8.0	78.9
LTW	575	0.0	64.3	6.0	10.0	80.3
	600	0.9	74.1	14.7	14.1	103.9
	625	1.2	56.1	15.0	14.3	86.7
	650	0.0	22.0	24.8	9.4	56.2
	650	0.0	58.7	25.2	6.8	90.7

Gas composition

The gases evolved from the thermolysis experiments were analysed in a gas chromatograph. Both online measurements and intermittent sampling in gas bags were carried out. It was observed that gas was mostly composed of the olefins since the primary feedstock component was polyolefins. A separate literature comparison was thus carried out and is presented in Appendix 6 to highlight the potential of extracting olefins from polyolefin feedstock. In Figure 6 below, only selected compounds are presented even though many others were analysed. Gas components with the highest share (more than 1 w-%) are selected. From the figures for mix plastics, it can be seen clearly that the gas was enriched in olefins as the temperature was increased. As much as 60 w-% of the gas consisted of ethane and propene in LTW thermolysed at 650 °C, besides other gases indicated in the figure 6. It must be noted here that not all the gases are graphically presented.

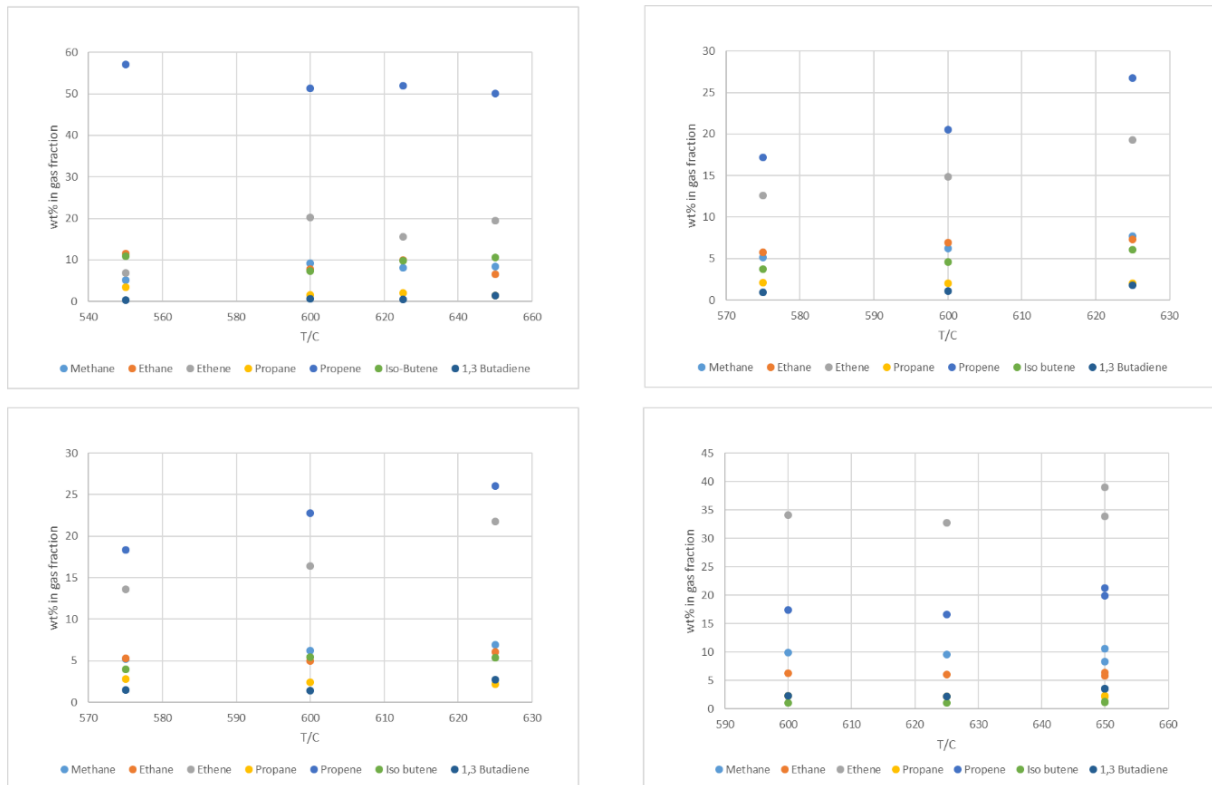


Figure 6. Gas composition from pyrolysis of polypropylene (PP) top left, reject from plastic waste (F-SRF) top right, separately collected plastic packaging waste (F-SUM) bottom left and plastic from C&D waste and energy waste (LTW) bottom right.

Wax analysis

The chemical composition of the products was analysed by GC-MS. The product from fast pyrolysis of PP contained mainly aliphatic hydrocarbons having methyl branches. Unsaturated and saturated aliphatic hydrocarbons were observed in the pyrolysis product of plastics from construction, demolition and energy waste (LTW). The product from separately collected plastic packing waste (F-SUM) and reject from plastic recycling (F-SRF) contained aliphatic hydrocarbons, but also aromatic hydrocarbons (styrene and alkyl benzenes) and aromatic hydrocarbons with heteroatoms. The hydrogen to carbon molar ratio of the products are in line with these observations from GC-MS.

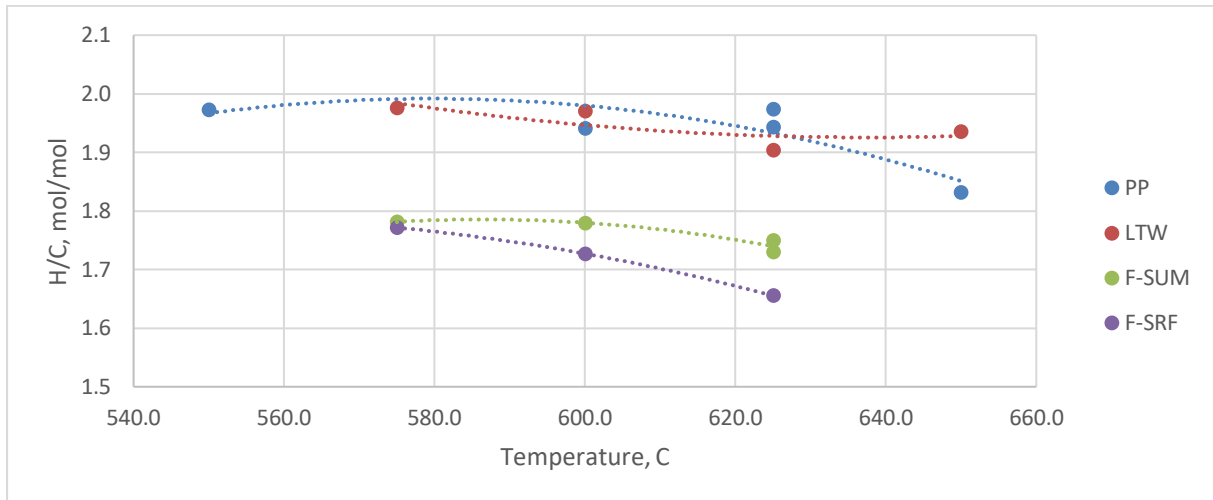


Figure 7. Based on the GC results, the product was divided into oil (C8-C16), light wax (C17-C37) and heavy wax (C38-C50) (Figure 8). The amount of oil and light wax increased with temperature. These observations can also be seen from the measured melting point temperatures.

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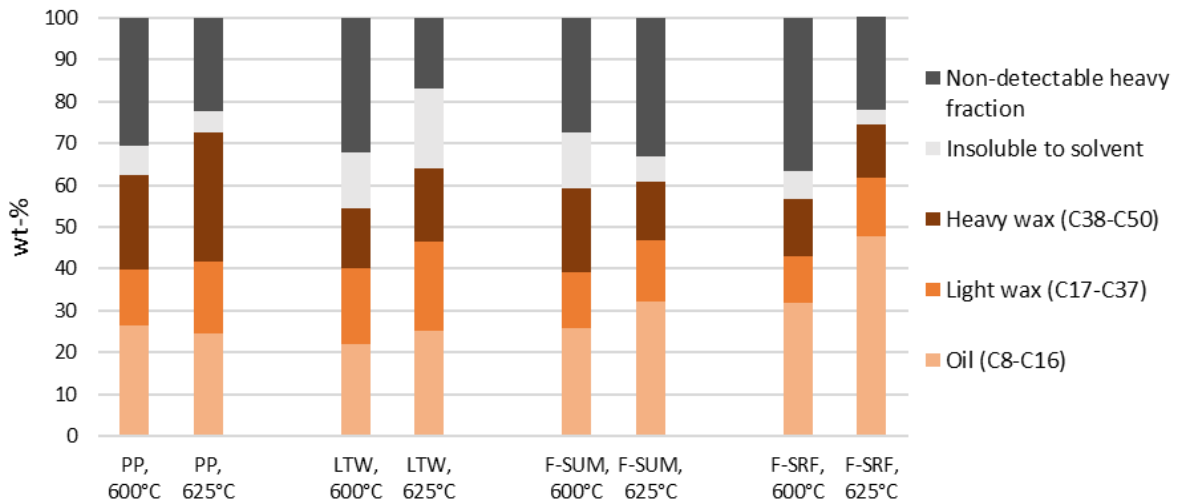


Figure 8. Different fragments in wax.

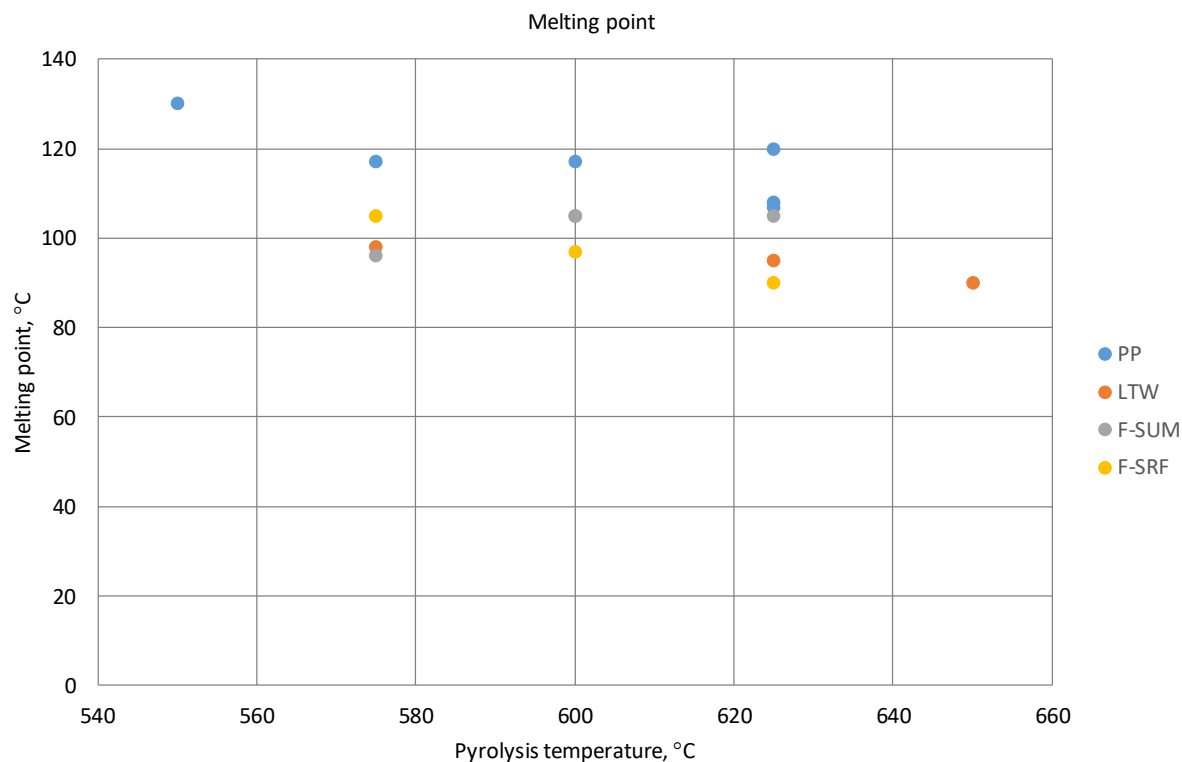


Figure 9. Measured melting point temperature (see definitions) for the wax products.

Char analysis

The char obtained from the experiments was analysed for moisture, CHN and ash content. Highest content of ash (almost 70 w-%) was found in LTW whereas F-SUM and F-SRF had almost 50 w-% ash. The carbon content was approximately between 30-40 w-% in all samples. Other components remained nearly negligible.

Conclusions

Pyrolysis experiments carried out with four different feedstocks confirms that the main product from the thermal degradation of polyolefins in fast pyrolysis is wax. The wax can be processed in the refinery, but the heavy nature of it makes its processing more difficult. The product contained also metals and heteroatoms, which are not accepted in a conventional oil refinery. Better solids removal and post treatment of the product is needed.

High temperatures significantly change the product spectrum by increasing the share of lighter compounds which consequently adds a considerable load to the product collection system. In practical terms, the condensing system should be designed and operated to cope up with the changes in product spectrum. Acknowledging this fact, we repeated the some experiments at higher temperatures but this time with improved product collection procedure, which significantly improved the mass balance, However, still part of the lighter products were lost in the experiments even if the last condensation units were cooled down to -50 °C. This was partly caused by the high amount of nitrogen needed for the fluidization. Better condensing system, able to comply with changing product spectrum or other reactor type is need to improve the yield and convert the heavy wax into oil.

As observed from the analysis carried out by Neste (Appendix 7) on the waxes derived from the plastic waste pyrolysis, though waxes can be co-fed directly to the conventional oil refinery. However, it must be ensure that the wax is free from solid precipitates and metals. Also Cl should be removed before processing the wax.

2.1.4 IP status

VTT has a patent family related to biomass pyrolysis, which has been licenced to a customer. However, these patents can be licenced to a third party related to thermolysis of plastics.

VTT has also a patent application concerning a new type of extruder, which may be used either a pre-treatment step in waste material handling (acting as densification unit reducing costs for handling and transporting solid fluffy wastes), or as a feeder for thermolysis unit without clogging (reducing cost of feeding systems by decreasing the size of feeding equipment needed). In addition, a novel thermolysis reactor is under design (patent pending) which combines waste pretreatment and thermolysis to one step and will correspond to the challenge of poor economics due to multi-step process.

2.1.5 Competition

Several commercial level activities are going on. These companies have mainly adapted conventional thermal or catalytic cracking techniques utilizing various reactor configurations although some companies have developed novel reactor systems. Despite all the technological advancements in the plastic thermolysis techniques, the economics of the PTL technologies rely largely on the needed pretreatment of the mixed plastic waste. The type of the feedstock directly relates to the end products (quantity and quality).

Commercial Scale PTL Systems in 2015 were 16 in India, 3 in USA, 3 in Europe, and 1 in Japan. 17 commercial Scale PTL Systems were in design-phase in 2016. Typical PTL systems size is 10 – 60 TPD. Main technology suppliers are Plastic Energy (former Cynar) in Europe, Agilyx in USA, Toshiba Corporation in Japan, and Pyrocrat Systems LLP in India.

2.2 Technical and operational feasibility

2.2.1 Potential challenges

Within the New_InnoNet - The Near-Zero European Waste Innovation Network (2015-2017) bottlenecks in the automotive, electronics and plastic packaging sectors were evaluated. Based on this work main bottlenecks were (www.newinnonet.eu):

- Limited source separation of plastic packaging waste
- 'Bad' product design
- Export of plastic packaging waste for recycling outside EU
- Performance of separation/sorting technology
- Performance of recycling technology
- Lack of common calculation methodology to calculate EU recycling targets, including more measuring points (collection, sorting & recycling) to efficiently measure the material flow
- Supply of highly heterogeneous and/or contaminated plastics from collection leading to downcycling and high rejection rates
- Lack of market trust in (products containing) recycled plastics; absence of quality requirement (end of waste criteria) for recycled plastic waste, both on supply and demand side
- Product standards limiting the use of recycled material
- Uneven level playing field for environmentally sound recycling plants because of not harmonized EU legislation in Member States and regions

Techno-economic challenges

The economics of the PTL technologies rely largely on the pretreatment of the mixed plastic waste. The type of the feedstock directly relates to the end products (quantity and quality). Some technologies offer processing of the mixed plastic waste as is, otherwise most technologies use only particular type of plastic waste. A general rule of thumb is that thermosets are not suitable feedstocks in PTL technologies. Commercial technologies are optimized to treat certain type of plastic mix. In most cases HDPE, LDPE, PP and PS are welcome. Acceptance of other plastics varies by the company. PVC and PET degrade to form chlorine and terephthalic acid, respectively. They are both corrosive and toxic and are therefore regulated in the feedstock to a minimum amount.

A consistent availability of feedstock with a consistent composition is another challenge and has deprived many PTL facilities worldwide to continue their operations economically. In lieu of these circumstances, many PTL companies have changed their focus from producing fuels to selling the technology. Besides the challenges with the pre-treatments of the plastic waste, post treatments of the products are also necessary in most cases the significant post treatments required are fractionation of the liquid into valuable streams, hydrotreating to stabilize and upgrade the fuel, blending in right proportions, and removal of particulates. Several other post treatments might be required depending on the end use of the product.

Post treatment methods are also necessary to meet the required fuel properties by the refineries. The economics of the whole chain needs optimisation of each unit operation.

Key challenges of PTL processes are described in Table 3 below. In order to overcome these obstacles the whole value chain from waste management to marketing the new products should be demonstrated. This demands both good co-operation within a strong consortium of different stake holders and flexible cost-effective process for processing waste to products. The economics of the whole chain needs optimisation of each unit operation.

Table 3. Key challenges of PTL processes and possible solutions.

Key challenge	Possible solution
Lack of feedstock	A consortium covering the whole value chain from plastic waste producers to liquid end-users Long-term binding agreements with feedstock suppliers Improve separate collection of plastics waste Active exploration of new sources
Feedstock quality	Securing access to consistently high quality feedstock Thermolysis processes having wider tolerance for different feedstock Further research for exploration and utilisation of cheap catalysts to reduce the process cost, improve product quality and overall process optimization
Expensive feedstock pretreatment	Development of cost-effective pretreatment techniques for heterogeneous waste streams Technology capable of dealing with significant amounts of contamination and variable feedstocks
Unknown thermolysis behaviour of plastic additives	Pyroprobe study on plastic additives to know their thermal behaviour Development of sustainable additives Information transfer along value chain (ecodesign)
Operational and business environment	Clarity to application of WID, REACH, End-of-waste, etc., also to side-products Harmonise legislation between European countries A comprehensive risk management plan Exploration of further applications of produced liquid oil, gases and char to make this technology more economically sustainable Comprehensive life cycle assessment (LCA).

In general, the interviewees (see Chapter 3) pointed out that the whole concept has to be economically viable and the legislative environment very clear before investments.

2.2.2 Initial production concept alternatives

The most critical issues, which needs to be solved related to thermolysis production concepts are:

- Economically viable logistics
- Densification of feed plastics materials
- Location for the thermolysis plants, and
- Location for further processing of the thermolysis products

The most economic thermolysis concept include distributed thermolysis production units and centralised refining of thermolysis oil/wax products. Based on available, appropriate and manageable waste handling systems, there could be a few – perhaps not more that 10 - plastics thermolysis plants. From these plants, produced thermolysis oil will be transported to one refinery. In the refinery, thermolysis oil is further processed centrally as co-feed. To achieve synergies the thermolysis units may be located in connection with either waste treatment plants, or heating plants, depending on which one of the options provides most favourable total efficiency. The interviewees (see Chapter 3) highlighted also that one potential production concept could include a feature, where a specific high value fraction could be taken apart from the main volume. This fraction could be refined elsewhere or at the thermolysis site.

"The Finnish thermolysis vision and production concept consists of distributed thermolysis plants that are optimally located for refining available plastics waste stream, from which the thermolysis oil is transported to refiner for further processing. Thermolysis plants are integrated in connection either with waste treatment or heating plants to gain synergies"



Figure 10. WasteBusters thermolysis vision and production concept.

Implementation of the thermolysis concepts should be based on long-term partnerships and value chains between necessary parties. All parties should have common long-term aims. Strategic partnering is needed between large and small companies and organisations on waste treatment, thermolysis, power production, plastic packaging, technology and service. Even large global players don't get along alone although they might have considerable resources and expertise on their own.

Key to increasing the recycling rate is the quality of recycling logistics, and how well consumers are able to employ existing recycling systems. Organizations for producer responsibility play a key role in improving recycling rates.

It is absolutely necessary to convince the financial sector on the viability of proposed schemes. Taaleritehdas is an example of funding technology companies related to circular economy in Finland. Service companies specializing in LCA computing, analysis and testing are also needed in the development of thermolysis technology to supply necessary data for investment decisions.

Examples of potential partners for building such consortium include:

- Companies providing waste management services like Lassila & Tikanoja, Fortum, Kuusakoski, SITA, Pohjanmaan Hyötyjätukuljetus, and Suomen Uusiomuovi Oy.
- Potential clients for purified products, including Borealis, Neste, St1, and Wärtsilä.
- Technology providers, including Valmet
- Providers of research and piloting and demonstration services, including VTT Bioruukki (Espoo), and Eco-3 (Tampere).

2.2.3 Regulatory framework

Various waste related EU legislation are already being implemented, but waste management and recycling still faces a number of challenges; such as finding balance between promoting recycling and protecting people and environment against harmful chemical substances in recycled materials; insufficient information and quality aspects related to recycling; energy recovery of waste; and waste prevention. The main legislative framework and its impacts on the operational feasibility is briefly presented in this section. The legislative environment is described in more detail in Appendix 8.

Plastic is one of the most common materials for toys and food packaging in Europe. The requirements imposed by the regulation limit the possibilities for using recycled plastics in e.g. toys and products in contact with food.

Policy framework

Major drivers for the development and implementation of European policies related to material resource efficiency, circular economy and raw material policies are:

- The **7th Environment Action Programme (EAP)** will be guiding European environment policy until 2020, and also gives a more long-term direction, a vision of where the Union should be by 2050.
- **Closing the loop - An EU action plan for the Circular Economy** (2.12.2015 COM(2015) 614 final) sets out a concrete and ambitious EU mandate to support the transition towards a circular economy. The aim is to ensure that the right regulatory framework is in place for the development of the circular economy. The proposed actions support the circular economy in each step of the value chain.
- The **European Strategy for Plastics in a Circular Economy** (COM(2018)28) aims to transform the way plastic products are designed, used, produced and recycled in the EU.

Legislation related to waste management

EU waste policy is built on a thematic strategy, a series of overarching directives and legal acts. The “Circular Economy Package” under adoption by the European Commission includes revised legislative proposals on waste to stimulate Europe's transition towards a circular economy, but waste management still faces a number of challenges, such as finding balance between promoting recycling and protecting people and environment against harmful chemical substances in recycled materials. Increasing targets for recycling and recovery results in a demand for a more versatile range of technologies for the recovery of waste. Main EU directives promoting the recovery of waste are:

- **The Waste Framework Directive (WFD)** (2008/98/EC) contains no specific recycling targets on plastic waste, but on recycling in general. The WFD states that by 2020 the preparing for reuse and recycling of municipal solid waste shall be minimum 50%, by 2025 55%, by 2030 60% and by 2035 65%; and 70% for C&DW by 2020.
 - o The WFD includes so-called **End-of-Waste (EoW) criteria**; if these criteria are fulfilled, the material will no longer be classified as waste, but will instead be-come a product subject to free trade and use. This “end-of-waste” status is reached when the waste has undergone recycling, and complies with specific criteria:
 - a) the substance or object is commonly used for specific purposes
 - b) a market or demand exists for such a substance or object
 - c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
 - d) the use of the substance or object will not lead to overall adverse environmental or human health impacts.
- Criteria related to the classification of waste as non-hazardous or hazardous are regulated in the WFD, while classification criteria related to the waste source and waste type is regulated in the **European List of Waste (LoW)**.
- **The Directive on packaging and packaging waste** (94/62/EG) sets up recycling targets for packaging in general, and specific targets for packaging of different materials, e.g. a minimum of 50% for plastic and 25% for wood by 2025, as well as 55% for plastics and 30% for wood by 2030.
- **Directive 2000/53/EC on End-of-Life Vehicles** states the reuse and recovery of all ELVs shall be 95% (reuse and recycling rate is set to a minimum of 85%).
 - o It is stated that it is not recommended to recycle plastics from ELV due to relatively low volumes and high number of hazardous substances. However, in other contexts recycling of plastics from vehicles has been concluded to have an important role to play in order to fulfil the 95% reuse and recycling target.
- **The Directive on Waste Electrical and Electronic Equipment** (Directive 2012/19/EU) aims at preventing the generation of WEEE, as well as promoting recycling and recovery. Plastics containing Bromated Flame Retardants (BFRs) must be removed from separately collected WEEE.

Legislation related to recycling

The aim of the policies is to ensure that all substances are manufactured and used safely; the requirements imposed by the regulations limit the possibilities for using recycled plastics in new products. The aim of the following regulation is to protect people and environment against harmful chemical substances in (recycled) materials:

- **The regulation of Persistent Organic Pollutants** (EU No 850/2004) is the EU tool of limiting substances listed in the Stockholm convention, the POP-protocol of the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) and the Basel Convention provisions for POP-waste. The regulation prohibits the use of POPs in new products and states that waste containing POPs over specified limit values must be destroyed or irreversibly transformed.
- **The REACH regulation** (EU No 907/2006) concerns use of substances in products manufactured in EU or imported to EU. It aims to restrict the use of certain substances, e.g. in food packaging, toys and childcare articles. It states that manufacturers and importers must register chemical substances to ECHA, the European Chemical's Agency; unregistered chemical substances cannot be marketed on the EU market.
- **The RoHS directive** (2011/65/EC) on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic equipment (EEE) aims to limit the use of hazardous substances in electrical and electronic equipment. This applies for both imported and domestically manufactured products put on the market in the EU.
- Food contact materials must be evaluated since chemicals may migrate from the material into the food, they cannot cause any safety concerns, or have negative effects on the food quality.
 - o **The Regulation on recycled plastic materials and articles intended to come into contact with food** (No 282/2008) sets up a framework specific to recycled plastics.
 - o **Regulation on good manufacturing practice for materials and articles intended to come into contact with food** (2023/2006/EC) aims to regulate the different materials, which food may get in contact with during production, distribution and selling, in order to avoid hazardous contamination of the food.

Legislation related to recovery as fuel or energy

When the recovered waste is used as a fuel, then requirements included in the Renewable Energy Directive (RED) and especially in the proposed new REDII regarding sustainability criteria and greenhouse gas emissions should be considered. Requirements for fuel quality and GHG emissions savings are also included within the Fuel Quality Directive. The increasing targets for renewable and waste-derived fuels promote the development of thermal conversion technologies for waste into fuels. Main EU directives promoting the recovery of waste as fuel are the Renewable energy directive (RED) and the proposal for a revised Renewable Energy Directive (REDII). However, the inclusion of recycled carbon fuels within the Renewable energy directive has also been criticised, due to use of fossil raw materials for energy purposes. While they are considered as an option for decarbonising the transport sector, the revised Renewable Energy Directive underlines that use of waste as fuels should adhere to the principles of the waste hierarchy. No support for renewable energy from incineration of waste can be granted, in case separate collection obligations of the Waste directive have not been met. According to the notes from the Parliament, use of recycled carbon fuels should not be included when assessing the achievement of the overall renewable energy target.

- **The Renewable energy directive (RED)** (2009/28/EC) sets a binding target of 20% final energy consumption from renewable sources by 2020. Also, each member state is required to have at least 10% of their transport fuels come from renewable sources by 2020. Fuel suppliers are also required to reduce the greenhouse gas (GHG) intensity of the EU fuel mix by 6% by 2020 in comparison to 2010.

- As part of the EU's energy and climate goals for 2030, EU countries have agreed on a new renewable energy target of at least 27% of final energy consumption by 2030.
- The proposal for a **revised Renewable Energy Directive (REDII)** (European Parliament 2013) contains a binding target of 32% final energy consumption from renewable sources by 2030.
 - REDII proposes that latest by 2030, at least 14% of the final energy consumed in the transport sector (minimum share) should become from renewable sources. Member states may include the use of recycled carbon fuels when calculating the required minimum share.
 - Within REDII, recycled carbon fuels means “liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations”
 - Starting from January 1st 2021, liquid and gaseous transport fuels produced from other than biological origin should achieve a 70% reduction in greenhouse gas emissions.
 - No threshold for the required minimum GHG emission savings for the recycled carbon fuels is included in the current proposal. The directive should be complemented with a delegated act by January 1st 2021 including specific criteria describing required life cycle GHG emission savings and calculation rules for the recycled carbon fuels.

3. Market status, challenges, trends and commercial vision

Mechanical recycling of industrial and pre-sorted post-consumer waste has been successful, but the recovery of value from low-grade mixed plastic waste has always presented technical and economic challenges. The conversion of plastic into oil/wax products requires that long polymer chains, characteristic to plastics, are broken into shorter chains that are typical compounds in crude petroleum. This depolymerisation can be achieved by heating raw materials to moderate or high temperatures. The basic processes of depolymerisation of plastic waste are thermolysis/pyrolysis and gasification. These processes have been used in the fossil refining industries for decades, and for those feedstocks they can be considered mature technologies for traditional fossil feeds. The use of plastic residues as a feedstock for these processes has also been studied for decades, but the uptake of plastic has been limited. This is due to the relatively low price of oil, and the lack of a credible collection infrastructure for this low-density and miscellaneous feedstock.

Demand for liquid products from thermolysis of plastics waste has been so far low. Industrial interest towards thermolysis oil and further processing routes is presently significantly increasing. There has been several projects and development plans announced by companies. Thermolysis technology companies have signed agreements with large petrochemical operators, other end-users, and operators. Remarkably, companies share lavishly information about their intentions, agreements and development initiatives in the media.

The greatest interest of thermolysis products currently is for direct use (?) as fuels, plastics, or other petrochemicals (e.g. solvents). The wax route hasn't gained as much interest, although there are some recent examples of potential market changes (Greenmantra 2018). Carbon residue is currently the most challenging thermolysis fraction with no efficient recovery and use.

Development and investments of new fuels and products are dependent of crude oil prices. As a rough estimate, based on company interviews, alternative fuels will hardly be competitive when crude oil market prices are below \$30 for a barrel. Together with technical viability of thermolysis technology, these two factors dictate the industrial implementation of thermolysis facilities. However, prospects of plastics waste utilization have improved due to advanced waste treatment policies, and low feed material prices. National policies are possible in order to secure own country climate strategies. Yet an increase in the recycling rate is needed to increase the waste plastic volume. The keys are recycling logistics, and efficiency of utilisation of existing recycling systems.

Mechanical recycling as a mature technology, is the primary option for recycling waste plastic streams. However, mechanical recycling technologies have some critical constraints. One is the difficulty of processing multi-layer packaging materials, and the other a need for complicated pre-sorting and cleaning. Hence, mechanical recycling alone is not capable of treating all plastics streams to reach EU recycling targets. Additional technologies, such as chemical recycling, are needed. Business environment is now changing because of the growing interest of large petrochemical companies. Their activity in chemical recycling seems to open up new options for plastics recycling.

The markets of the PTL technology is dependent on the future market expectations of PTL derived products. It also depends on both the availability of waste feedstock at fairly constant quality and price, and the operational and business environment of chemical recycling.

The market analysis in this study is based on the description of the solution, expert interviews of participating companies, review of market reports and other literature related to production and current situation of plastic-containing wastes. Results are summarised in Table 4. The main target products are liquid and gaseous products. Char is considered waste and is used for process energy.

Table 4. Commercial markets of PTL products modified from Table 1 to include results of the survey.

MAJOR ORIGIN OF WASTE FEEDSTOCK	MAIN RESIN COMPONENT	INTERMEDIATE PRODUCT FROM THERMOLYSIS	MARKET END-PRODUCT
Household, industrial plastic packaging, agricultural plastics	PE	Waxes, paraffins, olefins -> Gases, light hydrocarbons	Olefins
Household and industrial plastic packaging, automotive	PP	Waxes, paraffins, olefins -> Gases, light hydrocarbons	Olefins
Household, industrial plastic packaging, construction, demolition, WEEE	PS	Styrene, its oligomers	Styrene
Automotive waste	PA-6	Caprolactam	Caprolactam
Construction plastic waste	PVC	HCl (< 300C), benzene -> Toluene	benzene, toluene
Household plastic packaging	PET	Benzoic acid, vinyl terephthalate	Benzoic acid, vinyl terephthalate
Automotive, construction waste	PMMA	MMA (methyl methacrylate)	MMA (methyl methacrylate)
Construction, demolition, automotive	PUR	Benzene, methane, ethylene, NH ₃ , HCN	Benzene, methane, ethylene

Experts from participating companies were asked to describe, what kind of thermolysis based industrial visions they would like to see materializing, and which are the expected elements of such systems? Thermolysis has clear potential in circular economy, but realizing the potential is by no means straightforward. The most optimistic vision goes along these lines:

"Plastic waste thermolysis will be introduced successfully to the market and it will become profitable business - at the moment we are quite close to it"

The interviewees underlined that thermolysis has many strengths, and many of the identified challenges can be tackled. However, some challenges are not easily overcome. Diverse thermolysis related research activities, piloting, and even small scale demonstrations have been on-going for decades. So far no commercial industrial scale solution has appeared. Thermolysis is now promoted as a part of circular economy, most recently by the EU plastic strategy, the Finnish plastic roadmap, bans of transporting plastic waste to the Far East, incineration taxes, publication of the IPCC Assessment Report, and Neste's announcement of development projects for the use of liquefied waste plastic as a co-feed for refining purposes (Neste 2018a & Neste 2018b). In addition, Scotland's only oil refinery is a willing partner in introducing plastic-derived crude oils, mixed distillates or diesel blend components to the fuel supply chain (Haig et al. 2016).

Companies see that now the time for thermolysis may have arrived. They see that

"Right now the rationale of utilizing thermolysis looks more promising than ever"

Global interest towards liquefying plastic waste for refinery co-feed is particularly noteworthy. The construction of new thermolysis plants are underway, thermolysis investments receive funding, and mutual deals revealing routes and thermolysis products are published. One considerable implementation option could be thermolysis integration with mechanical recycling value chains. The interviewees emphasized that the full potential of mechanical recycling has not been reached yet. Mechanical recycling should be utilised for plastic waste fractions where it is most useful, for easily recoverable fractions.

"Smart waste plastics liquefying into thermolysis oil should be introduced into those fractions where it is best suited based on techno-economical and LCA-calculations"

The thermolysis plant should be located logistically related to the exploited plastics waste feed streams. A preferred location is close to waste management operations. In an alternative concept, the plastics feed is compressed into granulates reducing costs in handling, transportation, and thermolysis. The integration of thermolysis into existing CHP plants yields in improved utilization of different fractions for improved overall economics. A downstream refinery offers several routes into fuels, new plastic materials, or chemicals.

Partnering, long-term value chains, and strategic co-development are essential components of the thermolysis vision. It is probably not possible for any individual actor to dominate the whole value chain. Therefore, thermolysis solutions calls for relatively specialized roles for partners to establish the entire value chain.

Reactors, recovery systems, waste material pre-treatment systems, and compactor solutions together with existing boiler technology, enable new technology export opportunities. Export opportunities require successful technology demonstrations. . Finally, the success of any approach will depend on the final product cost. Finland could become a domestic market for thermolysis development, testing and demonstration. The summary report of the interviews is in Appendix 9 and the interviewees' key points are illustrated in Figure 11.

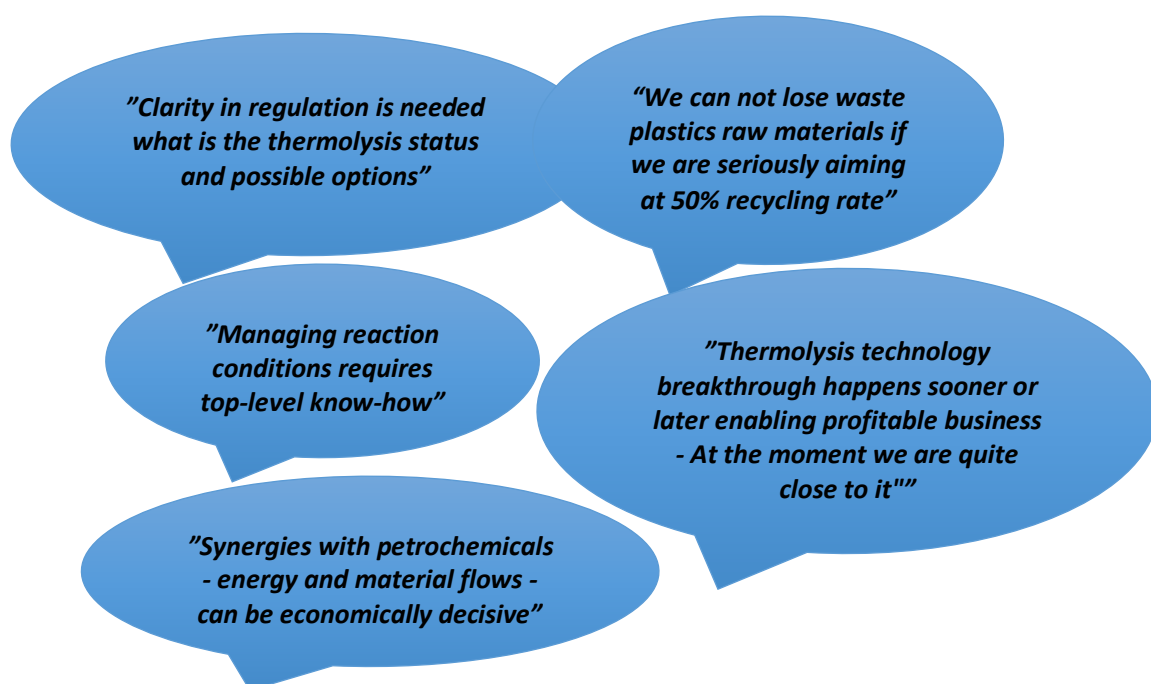


Figure 11. Summarised interviewees' key points.

4. Climate impacts

The climate impacts related to thermolysis of plastic waste were studied using the life cycle assessment (LCA) methodology. The aim of the studied system was to treat plastic waste and to use it as a raw material for diesel and polymer production. The functional unit used in the study was treatment of 1 kg of plastic waste, and production of diesel and polyethylene (PE) in the amounts equal to those produced during thermolysis process. Thermolysis of plastic waste was compared to a current business-as-usual situation in Finland, in which plastic waste was either incinerated with electricity and heat production or recycled mechanically, and the reject from recycling was sent to incineration.

Studied systems are presented in Figure 12 for the baseline scenarios and Figure 13 for the alternative WasteBusters scenarios.

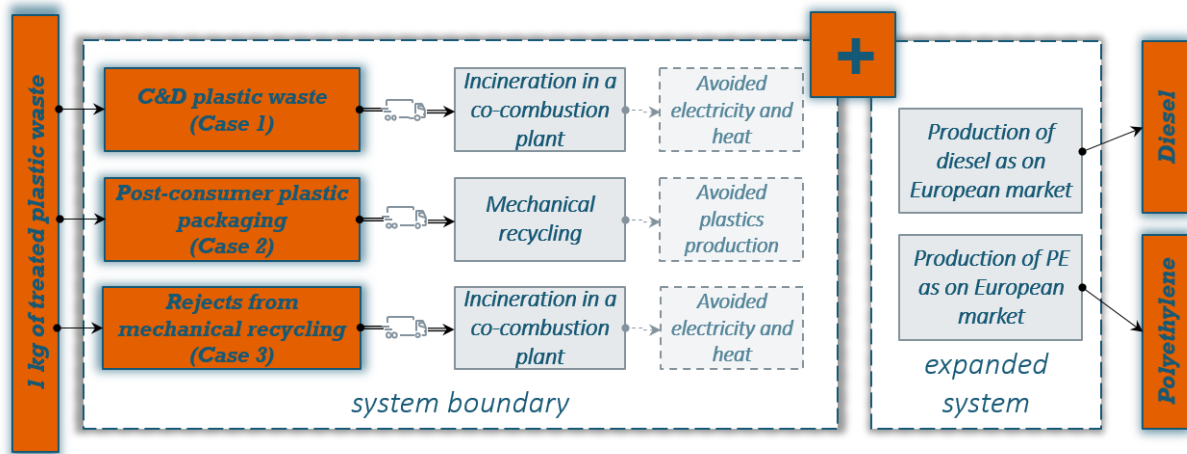


Figure 12. System boundaries for the baseline scenario.

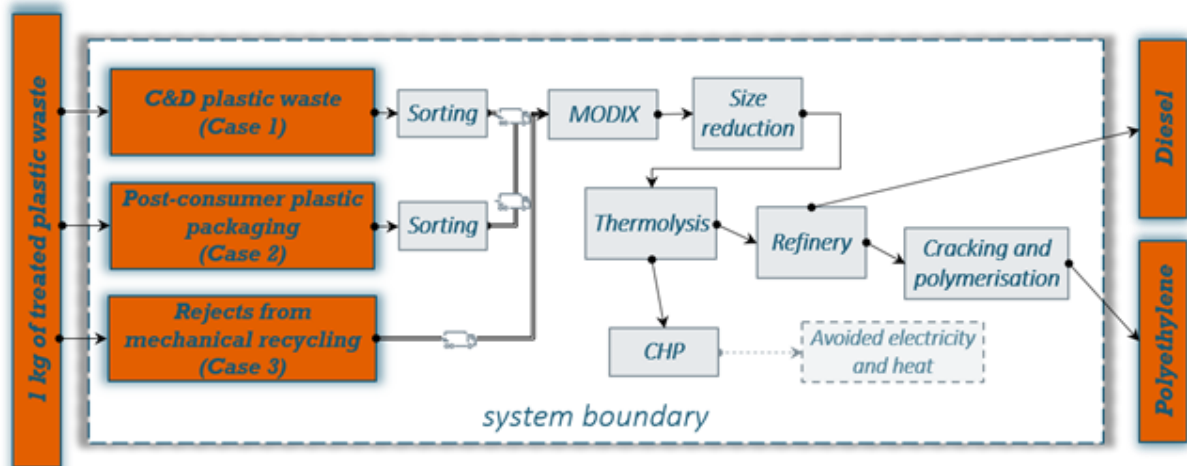


Figure 13. System boundary for the alternative WasteBusters scenarios studied within this project.

Collection of plastic waste from consumers was not included in the study, because the collection system is expected to be the same in all scenarios. Thus, the system boundaries begin with the transportation of plastic waste to either incineration (baseline) or their separation from impurities and transportation to pre-treatment before thermolysis (alternative WasteBusters scenarios). Environmental impacts from the preceding life cycles of collected plastic were not included in the study, due to lack of proper data. In the LCA methodology, this

so called zero-burden approach (or cut off allocation) may be applied if the raw material is considered as waste with no other value or use. Data for thermolysis and pre-treatment was collected from the test runs conducted during the project and from available literature.

The study consisted of a screening carbon footprint study, and the results are partly based on assumptions and experimental data. Thus, some uncertainty is related to the results. However, the results show that under the assumed conditions, thermolysis of plastic waste has a significantly lower carbon footprint compared to incineration of plastics. In addition, thermolysis could provide recycled materials to fuel and polymer production, and have the ability to reduce climate impacts related to the production phase. In the studied scenarios, the carbon footprint of the WasteBusters scenarios was 15 - 60% lower compared to the business as usual scenarios, but the results are sensitive to the applied assumptions and data.

When climate impacts of sending the separately collected post-consumer plastics waste to incineration or to thermolysis were compared, the results from the two scenarios were quite close to each other. However, sending the reject from mechanical recycling to incineration was a significant contributor to the carbon footprint in the business as usual scenario. Thus, it is assumed that a more favourable result could be received, in case the reject from mechanical recycling would be directed to thermolysis instead of incineration (even though such combination was not included in this study). Comparison between the case studies showed that the quality of the plastics directed to thermolysis has an impact on the outcome, since better yield from thermolysis leads to more output per studied functional unit (and a smaller carbon footprint per kg).

The sensitivity analysis showed that a large variation in the results is possible depending on the modelling approach used, e.g. the type of electricity and heat replaced, or depending on the accuracy of the data. Future studies should focus on considering the alternative best case and worst-case scenarios and their combinations. In addition, future studies should aim for collecting and applying more accurate data for the processes studied. Available data for the production of primary plastics and substitution of primary plastics with recycled plastics is currently on a very generic level, which might affect the conclusions made. Testing and developing appropriate allocation methods and factors for plastics recycling would be an important topic for future research. This would be needed in order to better understand the environmental impacts and benefits from plastics recycling. In addition to climate impacts, the future studies should be extended to cover other emissions and impacts to the environment, starting from air emissions and resource depletion categories. In case the raw material is expected to include harmful substances, potential impacts related to toxicity should be considered.

If the product from thermolysis would be used for transport fuel production, it should comply with the GHG reduction requirements set out in the recast of the Renewable energy directive (REDII) for recycled carbon fuels. Related calculation rules were not available by the time of this study.

5. Economic feasibility

5.1 Economic feasibility

5.1.1 Process concepts

Based on interest of clients and the potential for business cases three specific concepts were assessed economically:

- Fast pyrolysis of recycled wood for bio oil production with centralized industrial drying of raw material
- Fast pyrolysis of recycled wood for bio oil production with de-centralized solar drying of raw material
- Thermolysis of plastic waste (F-SRF)

The pyrolysis plants have a capacity of 230 000 t/a (wet) for the recycled wood concepts and 100 000 t/a for the plastic waste concept. The capacities reflect the availability of the raw material in Finland. The techno-economic assessment (TEA) included the raw material grinding, drying and thermolysis into bio oil. Transport of raw material to the distributed pre-treatment plants and transport of bio oil to user site were not considered in the TEA.

Recycled wood with centralized industrial drying:

Recycled wood is grinded to a particle size of approximately 5 mm. Moisture as received for recycled wood is 20 w-%. The raw material is dried to a moisture content of 8 w-%. Grinded, dried raw material particles are fed into the fast pyrolysis reactor where they are rapidly heated to 520°C in the absence of air and under atmospheric pressure. The particles are thermo-chemically decomposed to organic vapours, non-condensable gases, char and pyrolytic water. Sand from an integrated combined heat and power boiler is used as heat transfer medium to the fast pyrolysis reactor. Sand and char are separated from the vapours and gases in subsequent cyclones and sent to the CHP where char is combusted and the sand is reheated. The organic vapours and water fractions are quickly cooled and condensed to around 35°C in a counter-current spray tower. Condensed bio oil is used as spraying medium in the condenser. Non-condensable gases are sent to the CHP for combustion.

The integrated CHP plant is fuelled with char and non-condensable gases from the fast pyrolysis reactor. The CHP plant generates power and heat to the bio oil production process. As a result, the process is self-sustained in terms of energy, and depending on the raw material type and moisture content, the process can even produce excess electricity and district heating to surrounding facilities.

The concept of the recycled wood with centralized industrial drying is based on distributed collection points for recycled wood that is transported to a central bio oil processing facility. The concept is visualized in Figure 14. The mass and energy balances for the recycled wood with centralized industrial drying concept are illustrated in Appendix 11.

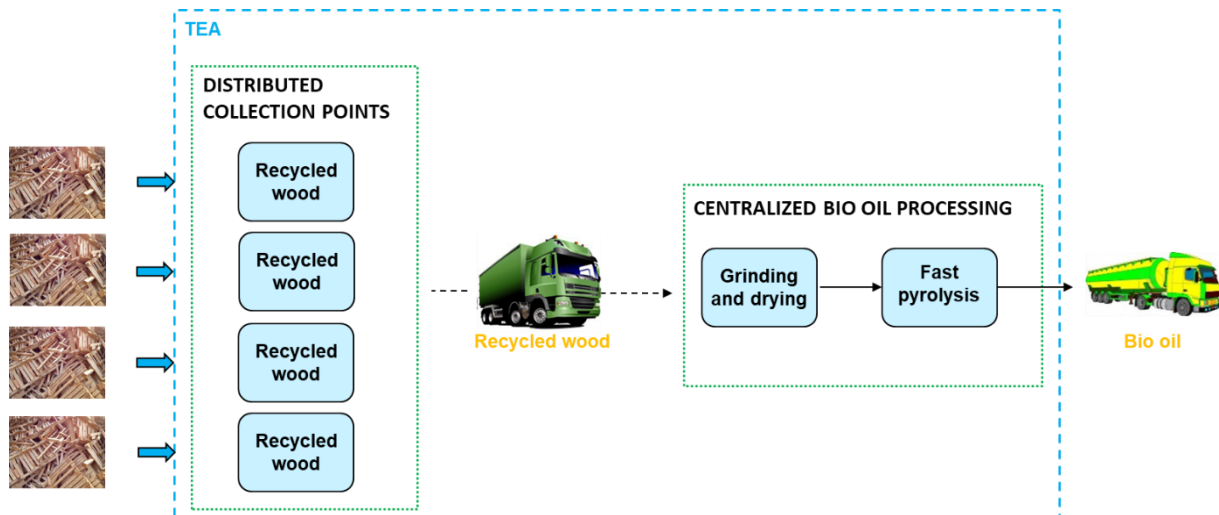


Figure 14. Recycled wood with centralized industrial drying.

Recycled wood with distributed solar drying

The raw material dryer is the most energy intensive process unit in bio oil production. In the concept featuring solar drying of raw material, the centralized industrial belt dryer was replaced with de-centralized solar drying units located in closer proximity to the raw material. The dried raw material is then transported to a centralized bio oil processing plant. Drying the raw material in de-centralized locations lessens the cost and environmental burden of transporting the raw material to the bio oil processing plant. The recycled wood with distributed solar drying is visualised in Figure 15. The mass and energy balances for the recycled wood with centralized industrial drying concept are illustrated in Appendix 11.

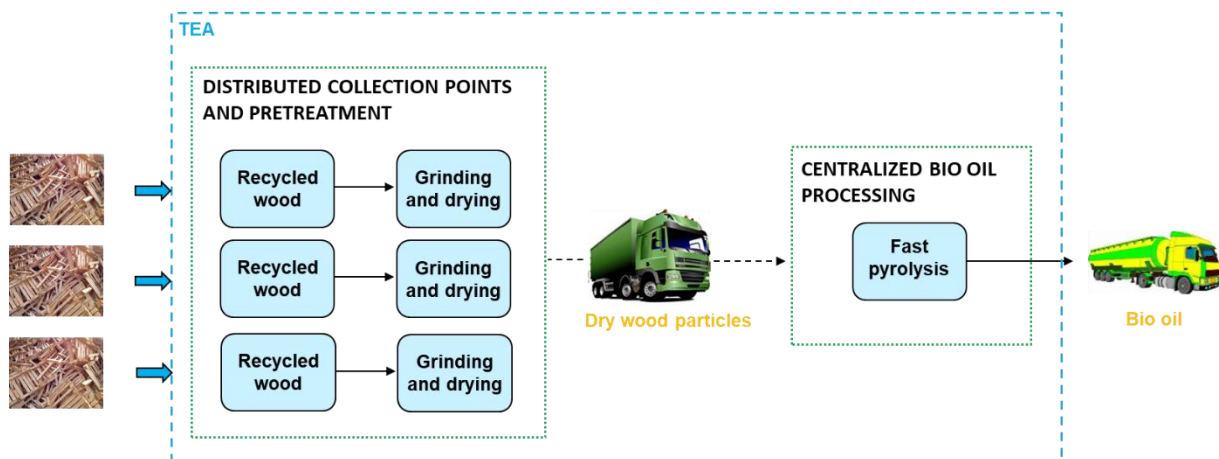


Figure 15. Recycled wood with distributed solar drying.

Plastic waste recycling

Separately collected plastic waste for thermolysis does not require drying in most cases, only grinding. Consequently, the concept is modelled as a centralized unit as visualized in Figure 16. In this concept, the feedstock stream consisted of rejects from plastic recycling namely F-SRF (Solid recovered Fuel). In a separate task (Appendix 3), a thorough feedstock characterization revealed that the stream consisted of mainly poly-olefins (ca. 71%) beside 5% PET, 5% PS, almost 10% multilayer plastics and almost 7% non-plastics. The amount of PVC was fairly low (ca. 0.3%). The thermolysis of plastics is fairly different from wood pyrolysis. The pyrolysis products are entirely different and consequently different collection procedure is

necessary. This also implies to storage and transport of the product. The plastic waste concept is visualised in Figure 16. The mass and energy balances for the plastic waste concept are illustrated in Appendix 11.

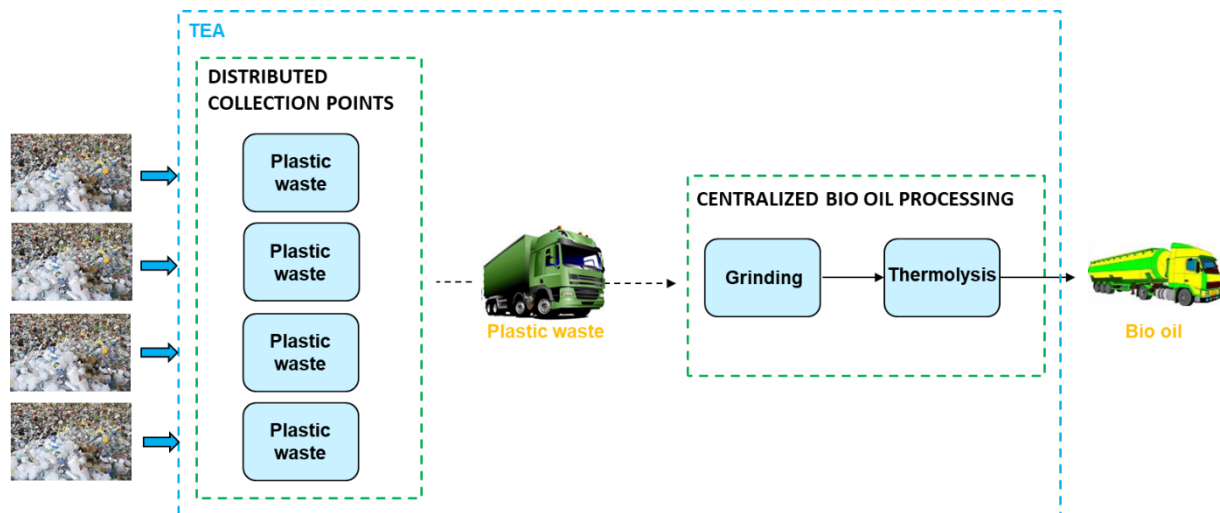


Figure 16. Plastic waste recycling with thermolysis.

5.1.2 Economic evaluation

The TEA was based on process modelling by Aspen Plus® to generate detailed mass and energy balances of the different concepts. Input to the Aspen model simulation was obtained from pilot and lab scale test runs performed at VTT. A discounted cash flow analysis was applied for the three different concepts in the evaluation of the break-even price per tonne of bio oil.

The economic evaluation includes both capital investment and operating costs. The pyrolysis plants are assumed to be located in Central Finland. The economic evaluation includes transport of raw material to the processing plant. Standard raw material trucks of 60 tons were assumed. The total investment costs for the three evaluated concepts are reported as Total Installed Costs (TIC), Total Plant Costs (TPC) and Total Capital Requirement (TCR). The pyrolysis plants are assumed to be operating 7 446 h/a. The integrated CHP plants operate when the pyrolysis plants operate, but district heating is only produced during the cold season at a rate of 5 500 h/a. Fluctuations in availability of raw material is assumed to be compensated for by raw material storage to ensure continuous supply of raw material to the process when operating. Reasonable available flows for the selected raw materials are based on mapping of waste flows in Finland. The plant capacity for the recycled wood concepts is 230 000 tons wet raw material per year, while the capacity for the plastic waste concept is 100 000 tons raw material per year. The main product from the industrial wood pyrolysis is bio oil, while the main product from the plastic waste pyrolysis is wax. Excess electricity and district heating is assumed to be sold to the national electricity grid and local district heating networks and represent additional sources of income to the bio oil and wax.

The TPC includes Total Installed Cost (TIC) and project contingency. TIC include direct equipment costs, construction and installation costs, engineering and procurement costs, management fees, insurances, temporary construction facilities, construction equipment, etc. The total plant costs are reported on a plant turnkey basis. TIC is based on in-house knowledge and open sources. The cost report year was 2017 and the costs are reported in euro.

The Total Capital Requirement (TCR) includes TPC, spare parts, start-up and commissioning costs including start-up capital expenses and operating and maintenance costs, additional fuel,

owner's costs, interest during construction and working capital corresponding to 30 days of feedstock and 15 days of finished product.

The investment costs including TIC and TPC are listed in Table 5. Input to the techno-economic assessment is listed in Appendix 12.

Table 5. Capital investment costs for the three assessed concepts.

Cost	Unit	Recycle wood + industrial drying 230 000 t/a	Recycle wood + solar drying 230 000 t/a	Plastic waste 100 000 t/a
Total Installed Costs (TIC)	MEUR	108	112	73
Project contingency (10%)	MEUR	11	11	7
Total Plant Costs (TPC)	MEUR	118	123	81
Total Capital Requirement (TCR)	MEUR	164	171	110

Annual operating and maintenance costs (O&M) include fixed costs (direct and indirect labour costs, annual maintenance costs, insurances, taxes, etc.), variable costs (raw material, chemicals, utilities, waste processing, fuel, etc.) and other operating costs such as marketing, logistics, distribution and delivery. The production cost of oil from pyrolysis and thermolysis was calculated as the levelized cost of production over 25 years of plant lifetime, plus a two-year process plant construction period. The levelized cost of oil product is the cost that enables the present value of product to equal the present value of all the costs of construction, maintenance and operation of the process plant over the plant life time (= breakeven price of product when net present value (NPV) is set to zero). The Internal rate of Return was set to 10%. The levelized cost of product is given in Table 6.

Table 6. Levelized cost of product for the three assessed concepts calculated with base input.

Unit	Recycle wood + Industrial drying bio oil	Recycle wood + Solar drying bio oil	Plastic waste wax
€/t	301	301	286
€/MWh	37	39	23

The production cost of the bio oil from the recycled wood cases based on industrial drying and solar power drying are similar. The only difference between these two concepts is the raw material receiving and pre-treatment. The solar drying concepts has the advantage of not requiring an industrial dryer to dry the raw material. However, the cost of the solar panels for raw material drying outweighs this advantage and thus the total investment costs for the solar drying concept becomes higher than for the industrial dryer concept. Notwithstanding, the total production cost of bio oil based on industrial drying is slightly higher. This is mainly due to slightly higher fixed cost associated with labour and raw material transport. Labour costs associated with transport of raw material have been taken into account, but it should be noted that expenses associated with personnel for the de-centralized drying units have not been taken into account. The process for the plastic waste concept is largely similar as the recycled wood concepts, with the exception that there is no need for drying the raw material. The

significantly lower investment costs are, however, mainly due to the smaller plant capacity. Compared to the recycled wood concepts, the production cost of wax in the plastic waste concept suffers from economies of scale and high fixed costs associated with shift-based labour rotation.

As can be expected from a thermochemical process, the levelized cost of product is highly sensitive to the capital investment and the cost of raw material. For the mixed SRF, the cost range is 0 - 40 €/t, which could result in a LCOP increase of more than 20% from 258 €/t wax to 313 €/t wax, respectively. The base cost used for SRF was 20 €/t. The effect of the raw material cost of recycled wood is more pronounced due to the larger flow of raw material to the process. The corresponding LCOP increase for recycled wood is more than one third, with LCOP of bio oil increasing from 225 €/t at raw material cost 0 €/t to 301 €/t at raw material cost 40 €/t. The base cost for recycled wood was 40 €/t. Sensitivity analyses for total capital investment (TCR) and raw material cost are illustrated in Figure 17 and Figure 18, respectively.

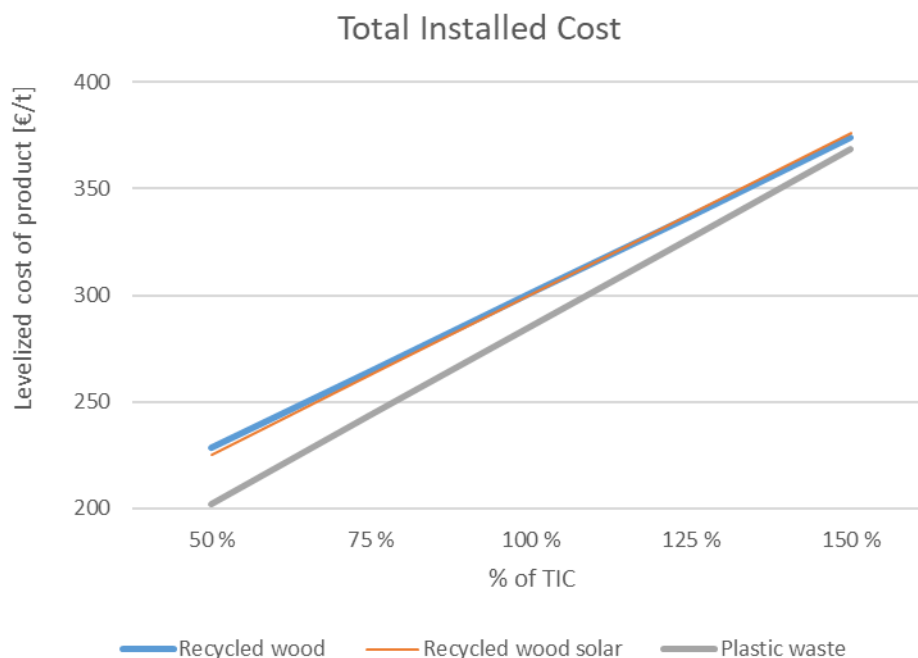


Figure 17. Levelized cost of product as a function of Total Installed Cost (TIC) for the raw material processing plant.

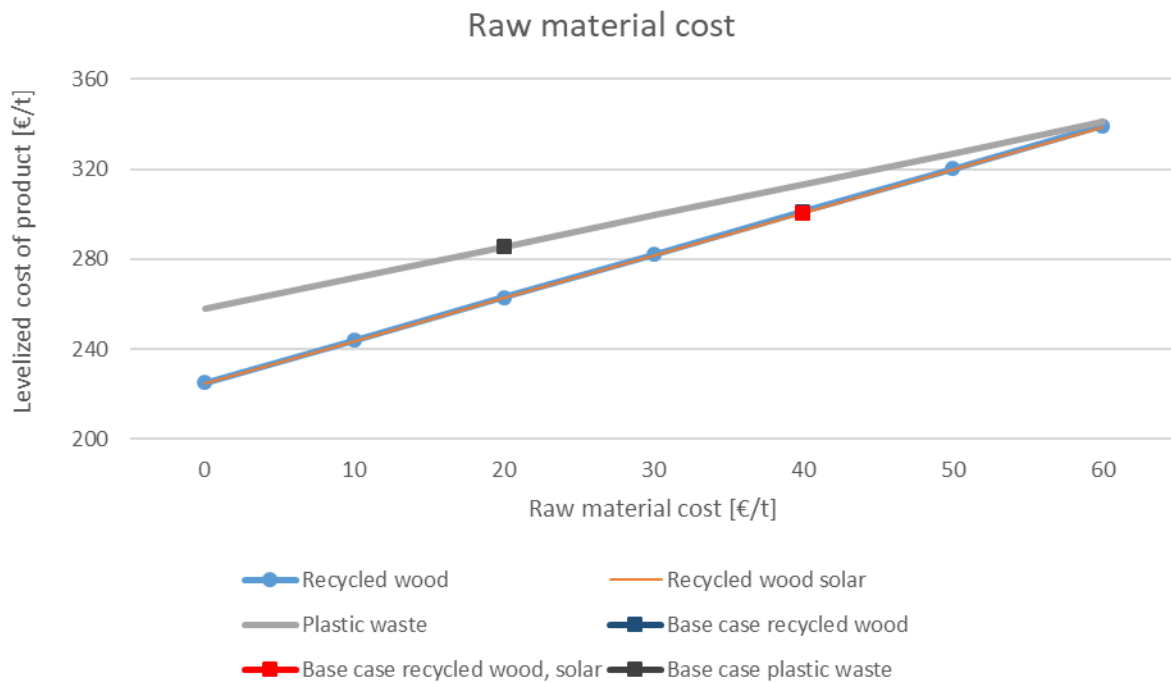


Figure 18. Levelized cost of product as a function of (wet) raw material cost.

Sensitivity analyses for discount rate, raw material transport distance and the price of electricity and heating are illustrated in Appendix 12. The base case transport distance one way was 100 km and it was assumed that outbound trucks have no load. The raw material transport distance will increase the operating cost of the transportation in terms of fuel costs, wear and administrative costs including ao. vehicle service. However, the effect of increasing the transport distance will be minor, with around 13% increase in LCOP between minimum and maximum distance for the recycled wood concepts, and 6.5% increase between minimum and maximum transport distance for the plastic waste concept. The difference between transporting wet raw material compared to transporting raw material dried de-centrally is small in this case as the initial moisture of the wood is only 20 w-%.

The effect of the electricity and district heating selling price is minor. The effect of the electricity price is higher for the recycled wood cases as these concepts have more excess electricity that can be sold to the grid. The higher electricity production rate for these concepts is due to the higher amount of char from the pyrolysis process combusted in the CHP plant. A drop in electricity selling price of 25% will increase the LCOP of the recycled wood concepts by around 2% and less than 1% for the plastic waste concepts. The effect of a 25% drop in the district heating selling price will increase the LCOP by 1.8% for the industrial recycled wood concept, 2.1% for the solar recycled wood concept and by 2.5% for the plastic waste concept.

For the concepts and raw material assessed it is clear that the option of de-centralized solar drying does not make a significant difference in the overall production cost. For a raw material with higher moisture content the benefit of decentralized solar drying would be more pronounced. The overall production cost, as listed in Table 6 above, is comparable to the prevailing energy prices in Finland, with the wax produced from plastic waste being in the lower end. This is mainly due to the high energy density of the wax.

6. SWOT analysis

SWOT-analysis (presented in Table 7) provides an overview of the potential Strengths, Weaknesses, Opportunities and Threats related to the studied plastic to liquids concept. SWOT is commonly applied in strategic management and as part of foresight studies. It can be used for analysing the operational environment of a company or a technology. Proposed strengths and weaknesses refer to the characteristics of the studied technology, while opportunities and threats relate to the surrounding operational environment, which may affect the success of the technology.

Table 7. SWOT analysis of the plastic to liquid concept.

STRENGTHS	WEAKNESSES
<ul style="list-style-type: none"> • Ability to reuse waste plastic streams for which no end-use currently exists (other than incineration) • May reduce the use of fossil fuels and (primary) fossil raw materials and enable moving towards “closed loops”. Potential end-use applications include intermediate products for petrochemical industry, heating, traffic fuels and plastics. • Offers possibilities for greenhouse gas emission savings compared to direct incineration • Capable of processing several kinds of raw materials (hydrocarbons), incl. mixed sources (plastics containing small amounts of wood & paper) • Synergies with mechanical recycling of plastics • Low CAPEX and OPEX • Process is scalable according to the input volume → Future possibilities for local, small scale processing plants (close to source) & decentralised energy production • Ability to re-use process-energy (heat) → energy self-sufficiency may be achieved • Solid recovered fuel (SRF) is already a product for CHP – output from thermolysis could offer a sulphur-free source for traffic fuels, especially for marine fuels 	<ul style="list-style-type: none"> • Heterogeneous material stream entering the system leads to uncertain yield • Price of collection & sorting vs. price of the recycled raw material is not in balance/tempting enough • Competitive situation between SRF and thermolysis oil – which case is competitive enough? • Separate collection of plastic packaging is still under development → raw material supply not yet stable • Raw material volumes are still quite low – economy of the process (economies of scale) difficult to prove/achieve • Evaluation of potential benefits and burdens is challenging, and differences between cases may be significant • Fuzzy evaluations and data gaps related to plastic life cycles may lead to misleading conclusions
OPPORTUNITIES	THREATS
<ul style="list-style-type: none"> • Ability to remove hazardous substances from recycled plastics → Possibilities for new end-use applications and upscaling of recycled plastics? • Policy framework is putting pressure in removing hazardous substances • In the long term, thermolysis may contribute in the move towards closed loop recycling of hydrocarbons • Refineries need new raw material sources from asset management and resource efficiency point of view • Development of more efficient collection & sorting systems & improved identification of hazardous substances may increase the volume of recyclable waste plastics • Many customers are interested in waste feedstock • Amount of packaging waste is increasing globally • Recycled carbon fuels may be included as part of the national targets related to decarbonisation of traffic under the REDII directive • Possibilities for high-level brand and value products from recycled plastics (“recycled sneakers” and wax products replacing scarce animal and plant-based waxes)? 	<ul style="list-style-type: none"> • Cheap oil price makes new raw material sources unprofitable. • Bad reputation of plastics (consumer attitudes) → Acceptability of plastics recycling & new products? • Plastics considered as a fossil raw material • Ownership of the waste streams may be unclear – networking needed for organizing supply • Not enough plastic waste is currently created/collected in Finland for feasible production, existing gaps in statistics related to plastic waste • Competing products or routes using the same feedstock? • Status of new recycling methods is unclear in legislation, thermolysis is often considered as energy use • Legislation is unpredictable and can be confusing – waste, energy & chemical legislation should all be considered together • Strict legislation regarding use of recycled raw materials narrows down the markets and end-uses (but may become an advantage in case hazardous substances may be safely removed via thermolysis) • European policy framework favours material recycling, but definitions related to recycling are unclear - Will thermolysis be accepted as recycling? • Narrow national (Finnish) opportunities to influence and change EU-level policy framework

The need to increase volumes of recycled plastics creates growing interests towards thermolysis technology. Substantial synergies with mechanical recycling and promising prospects in utilizing thermolysis products as refinery feeds are strong drivers for thermolysis development. We have plenty of emerging knowledge in tailoring thermolysis technology and waste plastics pre-treatment operations suitable for specific plastic fractions. We do have all the necessary value chain parties, and initial routes to build up profitable businesses.

There are two major challenges to overcome. The first one is the regulatory status of thermolysis, since currently thermolysis is not considered as recycling technology under EU legislation. This status should be changed before anything can happen. Another important step would be the establishment of End-of-Waste-criteria to thermolysis oil (See section 2.2.3 related to regulatory framework). What is also challenging to overcome in here, is our national abilities to influence future EU legislation. Experts believe that large European companies are reluctant to change existing regulation, or changing the status of thermo-chemical recycling. This change could potentially take a major portion away from the volumes currently directed to the mechanical recycling of plastics. However, thermolysis could especially target those waste streams that are not suitable for mechanical recycling, but which would need to be recycled in future, if we want to achieve the European recycling targets for plastics. Thermolysis promoting and resisting forces are summarised in Figure 19.

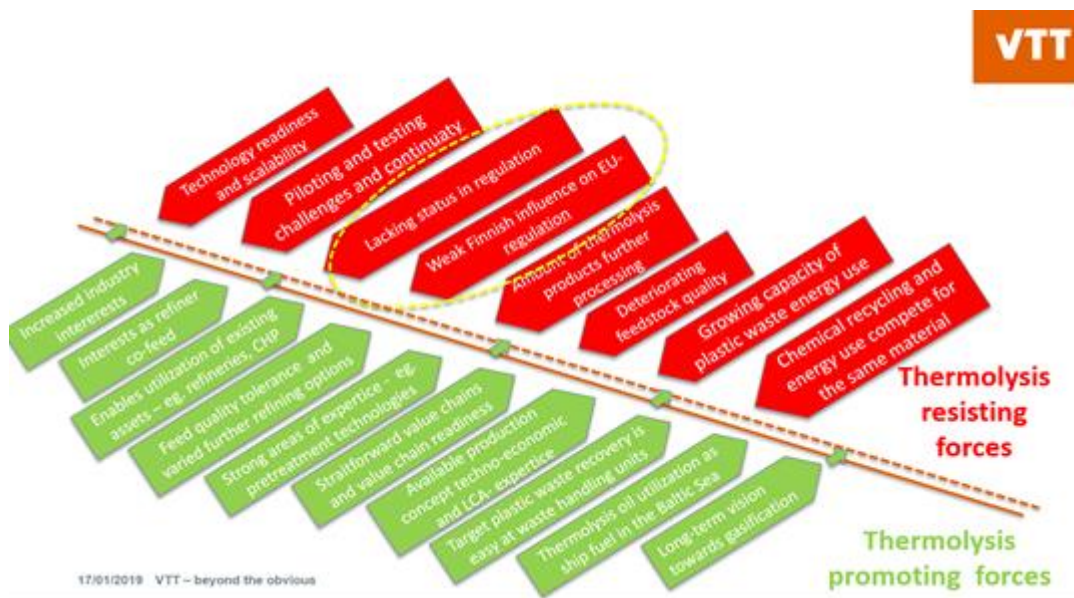


Figure 19. Thermolysis promoting and resisting forces.

7. Dissemination and exploitation

Presentations in the conferences and seminars on the field were kept and are coming. Several reference papers from project results are going on. The publication list is in Appendix 14.

As exploitation of the results for example several projects were planned:

- NonTox (2019-23, VTT coordinator), Removing toxic compounds from ELV and WEEE plastics, EU H2020 CE-SC5-01-2018, Developing methods to remove hazardous substances and contaminants from secondary raw materials. To be started in June 2019.
- MoPo, New life for polystyrene waste, monomers from end-of-life polymers (MoPo), BF and VTT (Co-Creation), Creation of new value chain for PS waste to new products by integration of mechanical and chemical recycling. Started in early April 2019 and to be finished in early October 2019. A Co-Innovation project proposal to be prepared.
- BioFlex, Production of Sustainable Storable Liquid Fuels for Flexible Power Generation and Marine Transport, BF (Co-Innovation), The overall goal is to identify and develop a least-cost solution for the production of sustainable and storable liquid fuels that meet the specifications for both flexible power generation and marine transport with large diesel engines. Wärtsilä, AuraMarine, Polartek, Valmet and Fortum have their company projects linked to VTT's research project. Other companies involved are St1, Neste, and PHJK.
- CleanMarine (VTT coordination), Next generation, drop-in marine fuel from biogenic residues for clean & sustainable shipping, EU H2020 LC-SC3-RES-23-2019 (RIA).

8. Conclusions

In the project, the whole value chain from pretreatment of industrial feedstocks via pyrolysis/thermolysis to products was studied. Based on interest of clients and the potential for business cases three specific concepts were assessed economically:

- Fast pyrolysis of recycled (used) wood for bio oil production with centralized industrial drying of raw material,
- Fast pyrolysis of recycled wood for bio oil production with de-centralized solar drying of raw material,
- Thermolysis of plastic waste

An improved waste pretreatment unit, modular extruder, "Modix" (VTT patent pending) was further developed and successfully used for grinding and homogenizing heterogeneous industrial plastic waste. New data on pyrolysis/thermolysis of industrial waste was gathered. VTT bench-scale bubbling fluidized bed reactor was modified for thermolysis of plastics. Experiments with industrial feedstocks were carried out and mass and energy balances determined for techno-economic assessment. The results showed that using the fast pyrolysis unit the product was mostly in the form of wax. The best yield (92 w-%) was achieved with the packaging plastic waste at 575 °C.

The cost of bio oil and wax was calculated to 37 €/MWh, 39 €/MWh, and 23 €/MWh for the recycled wood with industrial drying, recycled wood with solar drying and SRF plastic waste, respectively. These costs are comparable to current energy prices in Finland. As the processes are fairly similar, with the exception of the raw material pre-treatment, the difference in cost is mainly due to economies of scale. The difference in cost between industrial and solar drying results negligible, mainly because of the low initial moisture content of the raw material (20 w-%).

The climate impacts related to thermolysis of plastic waste were studied using the life cycle assessment (LCA) methodology. Thermolysis of plastic waste was compared to a current business-as-usual situation in Finland, in which plastic waste was either incinerated with electricity and heat production or recycled mechanically, and the reject from recycling was sent to incineration. The results from the assessments show that under the assumed conditions, thermolysis of plastic waste has a significantly lower carbon footprint compared to direct incineration. In addition, thermolysis could provide recycled materials to fuel and polymer production, and have the ability to reduce climate impacts related to the production phase. In the studied scenarios, the carbon footprint of the WasteBusters scenarios was 15 - 60% lower compared to the business as usual scenarios, but the results are sensitive to the applied assumptions and data. When climate impacts of sending the separately collected post-consumer plastics waste to incineration or to thermolysis were compared, the results from the two scenarios were quite close to each other. However, sending the reject from mechanical recycling to incineration was a significant contributor to the carbon footprint in the business as usual scenario. Thus, it is assumed that a more favourable result could be received, in case the reject from mechanical recycling would be directed to thermolysis instead of incineration (even though such combination was not included in this study).

As a result of the marketing survey more precise understanding of waste plastics thermolysis operational environment was reached. A working document on legislative framework for waste to products was written. This will be used in a public project with Ministry on Environment on chemical recycling and end-of-life status of plastics.

Several presentations of project results have been kept and reference articles are under processing. In addition, as exploitation of the results several projects were planned. VTT coordinated EU NonTox will start in June 2019, the focus being on removing toxic compounds from ELV (End-of-Life Vehicles) and WEEE (Waste Electrical and Electronic Equipment) plastics. In Business Finland Co-Creation project MoPo, monomers from end-of-life polymers, started in April 2019 and will last for six months. A Co-Innovation project will be built with

industry where the focus is on new value chain for PS waste to new products by integration of mechanical and chemical recycling. Another BF initiative is BioFlex, where the overall goal is to identify and develop a least-cost solution for the production of sustainable and storable liquid fuels that meet the specifications for both flexible power generation and marine transport with large diesel engines. Also an EU proposal to LC-SC3-RES-23-2019 (RIA) is under preparation.

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