MUSIC

Market Uptake Support for Intermediate Bioenergy Carriers

WHITE PAPER:
FAST PYROLYSIS BIO-OIL (FPBO)

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List of Acronyms

FCC – Fluid Catalytic Cracker
FPBO – Fast Pyrolysis Bio-Oil
GFN – Green Fuel Nordic
GHG – Greenhouse Gases
IBC – Intermediate Bioenergy Carrier
LCA – Life Cycle Analysis
NCG - non-condensable gases
NG – Natural Gas
RED – Renewable Energy Directive
RTP^{TM} - Rapid Thermal Processing
SPO – Stabilised Pyrolysis Oil

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1 Introduction

Intermediate bioenergy carriers (IBCs) are formed when biomass is processed to energetically denser, storable, and transportable intermediary products analogous to coal, oil and gaseous fossil energy carriers.

The EU H2020 MUSIC project will support market uptake of Intermediate Bioenergy Carriers (IBCs) by developing feedstock mobilisation strategies, improved cost-effective logistics and trade centres.

IBCs can be used directly for heat or power generation or further refined to final bioenergy or bio-based products. IBCs lead to wider implementation of renewable energy, thus contributing to energy security, reduced greenhouse gas emissions, thus providing a sustainable alternative to fossil fuels in Europe.

Pyrolysis oil is one example of an IBC. When organic materials, such as wood, are heated in the absence of oxygen, vapours are formed which can be condensed to a liquid, called Fast Pyrolysis Bio-Oil, (FPBO).

This document provides an overview on the FBPO process, technology status and implementation, applications, and outlook. Attention is paid to current as well as emerging applications of pyrolysis oil, in particular beyond direct energy production.

2 Pyrolysis oil production

2.1 Biomass feedstocks

Fast pyrolysis of biomass (hereinafter: "pyrolysis") is a flexible process with respect to feedstocks. In principle, all lignocellulosic biomasses can be converted to pyrolysis oil, including primary residues[1], like chips, stumps, roadside grass; secondary residues, such as sawdust, sunflower husks, and tertiary residues and wastes, for example wood waste; as well as dedicated lignocellulosic energy crops like miscanthus and poplar.

The most important feedstock requirements are:

- Particle size (penetration depth max. 3 mm)
- Moisture content (< 6-8 wt% wet basis)
- Ash content (preferably as low as possible)

When particles are too large, sizing is required. If the moisture content is too high, the feedstock needs to be dried before processing. This is often the case. Higher ash contents reduce pyrolysis oil yield, both directly and because of the influence of this ash on the pyrolysis reactions.

Currently, commercial applications of pyrolysis oil production use clean wood fractions, specifically sawdust. Sawdust becomes available as a by-product in sawmills. In European sawmills, approximately 11% of the input ends up as sawdust, 28% as woodchips and 5% as shavings (FAO 2020). All these by-products are suitable feedstock for pyrolysis. With a total production of 109 million m^3 of sawnwood in the EU (2019 data)[2], this would mean 95 million m^3 of by-products. If we assume that between 25% and 33% of these woody by-products are available, this implies opportunities for an increase in the European pyrolysis oil production capacity of a factor 60 to 100, to a total of 7 to 12 million tonne of pyrolysis oil per year.

Actual implementation of pyrolysis plants will depend on the specific local feedstock availability and competition with other uses for the biomass. However, this calculation shows that there is for the short and medium term enough biomass to support rapid expansion of pyrolysis oil production capacity.

[1] Primary residues become available during harvesting of forests and agriculture. Secondary residues become available during processing/manufacturing. Tertiary residues (waste) become available after end-use of products.

[2] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_products_-_production_and_trade#:~:text=The%20total%20output%20of%20sawnwood,%2C%20respectively%20(Figure%204).

2.2 Process and final product

Fast pyrolysis is a process in which organic materials are rapidly (in seconds) heated to 450 - 600 °C in the absence of air. Under these conditions, the structure is broken down and organic vapours, non-condensable gases and charcoal are produced. In a next step, the vapours are condensed, and fast pyrolysis bio-oil (FPBO) is formed. If woody biomass is used as feedstock, typically, 60-75 wt% of the feedstock is converted into pyrolysis liquid. See Figure 1 for a schematic overview of the process.

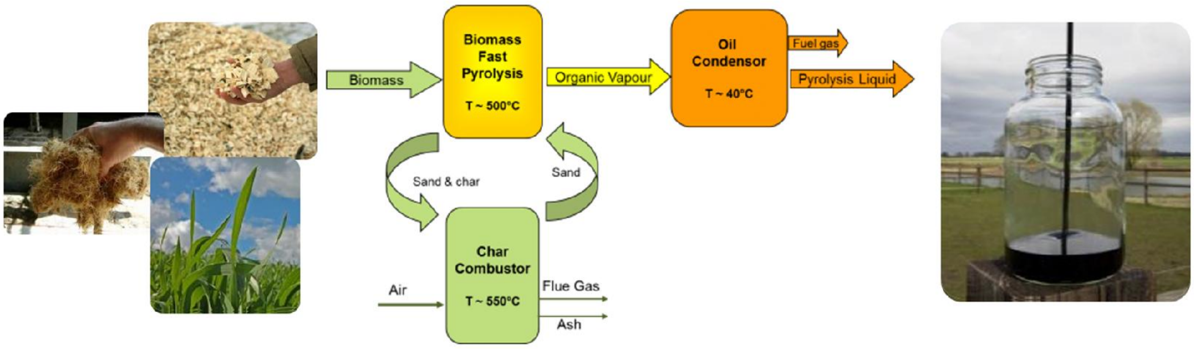


Figure 1: Fast pyrolysis process (Vos, J. et al. 2020)

To achieve maximum yield and high quality of FBPO, rapid heat transfer to the biomass and quick condensation of the formed organic vapours are essential. This can be done by using small, homogeneous feedstock particles (approx. 3mm) with a moisture content of less than 6-8 wt% and a carrier material for ensuring sufficient supply of heat (e.g. sand). The sand is heated by combusting char in a combustor. The energy generated during the combustion can be used to power the plant and/or to produce process heat for other applications. The quality of the pyrolysis oil is influenced by several factors, such as type of reactor used, operating conditions and feedstock properties, like ash content (Venderbosch and Prins 2010). Some advantages of pyrolysis oil compared to raw biomass are:

- Pyrolysis oil is easier to store, transport and use than raw biomass.
- Biomass residues becomes available in many forms. With pyrolysis these can be converted to a homogeneous liquid.
- Energy density of pyrolysis oil is 4-20 times higher than of raw biomass.
- Biomass contains minerals that are almost absent in the pyrolysis oil, this reduces the emissions during usage.
- Pyrolysis oil can be upgraded to transport fuels, chemicals, and materials; in other words: it is an Intermediate Bioenergy Carrier (IBC) – as covered in the scope of MUSIC (Vos, J. et al. 2020).

The final product, fast pyrolysis bio-oil (FPBO), is a dark brown, acidic liquid which can be used in different forms, e.g. as bioliquid for direct energy production, feedstock to be processed to advanced biofuels, feedstock for co-processing in mineral oil refineries or as feedstock to produce chemicals and materials (Buffi et al. 2020).

Pyrolysis oil may have a similar appearance as fossil oil, but chemical/physical properties are quite different. Besides the already mentioned aspect of acidity, the energy density of pyrolysis oil is roughly half of the energy density of fossil transport fuels like diesel and gasoline, and it is also not miscible with these fuels. To utilise pyrolysis oil as transport fuel, it is necessary to upgrade it. Technologies to accomplish this are discussed in section 4.2.

In Figure 2 the various envisaged product applications for pyrolysis oil are shown: via various secondary processes, chemical products, biofuels, and heat and power can be produced. This is called the Bioliquids Refinery concept.

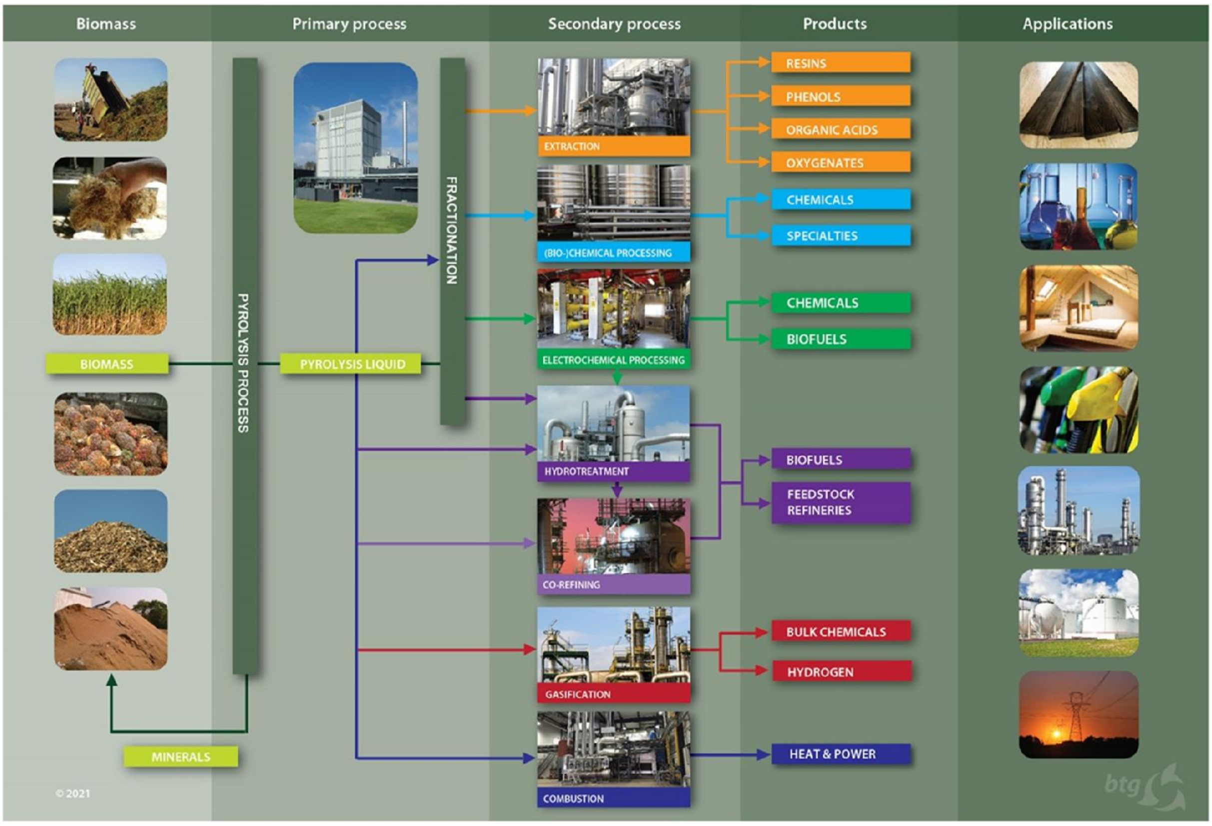


Figure 2: The pyrolysis Bioliquids Refinery concept

3 Technology status and sustainability

3.1 Fast Pyrolysis technology status

Significant progress in developing of pyrolysis oil technology for bio-oil production dates from the 1980s. A variety of reactors were investigated (Wang and Brown 2017). Since 2007 the pace of research and development in fast pyrolysis has accelerated considerably: the number of scientific publications increased from a dozen or so per year in the early 1980s to over 600 per year in the period 2014-2016. This rapid growth in research and development has been translated into notable successes in the commercial deployment of fast pyrolysis technologies in the last few years.

Anno 2022 pyrolysis oil is produced at scale at a growing number of industrial plants. The bio-oil produced is mainly used for heat - or combined heat and power (CHP) production. A pyrolysis plant that was recently constructed in Sweden is the first one in the world to produce pyrolysis oil for co-refining at an existing refinery.

In Finland, Fortum[3] has implemented a fast pyrolysis plant in Joensuu integrated with its own CHP plant. The pyrolysis reactor is a circulating fluidised bed using local forest residues, wood chips and sawdust as feedstock. Heat is provided by the CHP plant. The reactor was designed and delivered by Valmet. This first industrial pyrolysis plant in Europe (annual capacity 42 million litres output) was commissioned in 2013. The plant is now owned by Savon Voima Joensuu.

Figure 3: The Fortum (now: Savon Voima Joensuu) pyrolysis plant in Finland.

In the Netherlands, a 20 million liters/year pyrolysis plant (the Empyro plant) was developed by BTG Bioliquids[4] in 2015, and operated by the company Empyro. After three years of successful operation the plant was acquired by the local utility company Twence in 2018. Twence uses

[3] https://www.fortum.com/

[4] https://www.btg-bioliquids.com/

residues from wood pellet production ("crumbles" – residues from broken wood pellets) that are brought to the plant with a pellet truck that pneumatically feeds the residues to the storage vessel. Currently, the plant also uses other feedstocks, such as sawdust. An additional silo was implemented for that.

Figure 4: The Twence pyrolysis plant in Hengelo, the Netherlands.

From the storage vessel, the residues are conveyed to the pyrolysis reactor and converted to pyrolysis oil, which is subsequently combusted in a dual-fuel burner at a nearby dairy plant (owned by FrieslandCampina) to produce process steam. The pyrolysis plant has a high thermal efficiency of nearly 90%, also because waste heat is used in the next-door salt production process of Nobian Industrial Chemicals.

In Finland, the first Green Fuel Nordic (GFN) pyrolysis plant has been implemented in Lieksa, in the east of the country. This plant was also developed by BTG Bioliquids. Here sawdust from the nearby sawmill is used as feedstock. The pyrolysis oil is used for direct energy generation in a district heating plant. The plant was commissioned in early 2021.

In Sweden, the Pyrocell plant, located at Setra's Kastet sawmill in Gävle at the east coast, was commissioned recently (October 2021). The plant is very similar to the one in Lieksa. It is also based on BTG Bioliquids technology and also uses sawdust as feedstock. The plant is owned by Pyrocell, a joint venture of Setra and Preem, the largest fuel company in Sweden. The pyrolysis oil is further processed into renewable diesel and petrol at Preem's refinery in Lysekil in southwest Sweden.

Besides these plants in Europe, several industrial plants are established outside Europe. The Ensyn/Honeywell UOP joint venture – called Envergent Technologies - has developed their own technology for pyrolysis, referred to as Rapid Thermal Processing or RTP™. Ensyn was established in 1984 based on research carried out by University of Ontario, Canada. In 2007, Ensyn commissioned a plant in Renfrew Ontario, with a capacity of 11.3 million litres of renewable fuel oil, RFO™ per year. This plant was upgraded in 2016. More recently (2018), another, larger scale - 38 million liters/year - plant was realised by Envergent in cooperation with Arbec Forest Products and Groupe Rémabec in Port Cartier, Quebec. Actual production data are not publicly available.

Figure 5: The Côte-Nord pyrolysis plant in Port Cartier (Canada).

The total operational and planned pyrolysis oil production capacity in Europe stands at 122,000 tonne per year, or 100 million liters per year. In energy terms this amounts to 2 PJ/year. FPBO production capacity in Canada adds about 33% to these numbers (see Table 1).

Table 1: Commercial-scale pyrolysis plants installed capacity (as of early 2022)

Plant name/owner	Location	Main technology provider	Volumetric capacity (million liters/y)	Capacity in tonne (t/y)	Capacity in energy (PJ/y)
Twence	Hengelo (NL)	BTG Bioliquids	20	24,000	0.38
GFN	Lieksa (FI)	BTG Bioliquids	20	24,000	0.38
Pyrocell	Gävle (SE)	BTG Bioliquids	20	24,000	0.38
Savon Voima Joensuu	Joensuu (FI)	Valmet	42	50,000	0.80
Kerry Group plc	Renfrew (CA)	Envergent Technologies	11	13,200	0.21
AE Cote-Nord Bioenergy	Cote North (CA)	Envergent Technologies	38	45,600	0.73
Total			**151**	**180,800**	**2.9**

3.2 Sustainability

Sustainability focuses on meeting the needs of today without compromising the needs future generations may have. In broad sense sustainability can be viewed in terms of economy, society, and environment. In regards of using biomass as a feedstock for energy and fuel applications the sustainability is evaluated in terms of greenhouse gas (GHG) emissions, biodiversity, carbon stock change and land use change.

RED II refers to the European directive that succeeded the RED I regulation. In December 2018, the recast Renewable Energy Directive 2018/2001/EU entered into force. The recast directive moves the legal framework to 2030 and sets a new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023. It also comprises measures for the different energy sectors to make the transition to significantly higher shares of renewables happen.

RED II includes requirements on the sustainability of biomass used for renewable energy or fuel production. It specifies the feedstocks that comply with specific sustainability and greenhouse gas emissions reduction criteria. Only bioenergy or biofuel that fulfils these criteria qualify for financial support and can be counted towards national climate and renewable targets.

Other RED II criteria take into account impacts on soil quality, biodiversity, carbon stock, indirect land use change (ILUC) and cascading use of biomass. Compliance to the RED II scope needs to be proven through certification. Qualifying certification scheme include for instance Roundtable of Sustainable Biofuels EU RED (RBS EU RED) and Biomass Biofuels voluntary scheme (2BSvs). Biofuel certification schemes approved by the EC are published online[5].

When residues / wastes are used as main feedstock for pyrolysis oil production, it is relatively easy to demonstrate compliance with sustainability criteria under RED II. This is because emissions in the upstream value chain do not have to be considered when using residues.

Pyrolysis oil and RED II

The SmartCHP[6] project assessed greenhouse gas reductions of several pyrolysis oil production routes, based on different types of biomass feedstocks. (Vis and Davidis 2020) have calculated the GHG emissions associated with pyrolysis oil-based heat production at 4 to 11 gCO_2-eq/MJ pyrolysis oil (see Figure 5). This translates into GHG emission reductions of 86 - 95% vis-à-vis the mandated RED II 'fuel comparator' (e.g. 80 for heat).

Besides being used for heating, pyrolysis oil can also be processed further into transport biofuels. The process needs to meet a minimum level of greenhouse gas reductions to qualify for meet the RED II mandate. For plants starting operation after 1 January 2021, the minimum GHG reduction level is set at 65% compared to the fossil fuel comparator

When biofuels are produced from certain kinds of residues, such as lignocellulosic residues, the resulting biofuels are labelled 'Advanced Biofuels'. They may attract a premium as they qualify for double counting towards national RED II obligations. Complying residues are listed in Annex 9a of RED II.

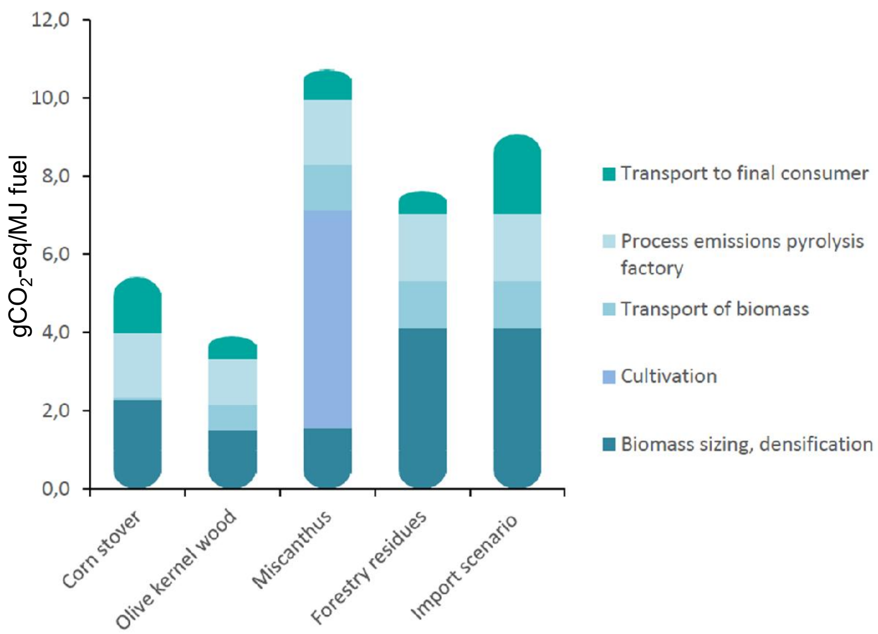


Figure 6: Calculated emissions from several supply chains

[5] https://ec.europa.eu/energy/topics/renewable-energy/biofuels/voluntary-schemes_en
[6] https://www.smartchp.eu/

4 Pyrolysis oil energy applications

4.1 Pyrolysis oil use for heat, steam, and power production

4.1.1 Energy production in boilers and furnaces

FBPO can be used for the production of heat, steam, and power. Good quality pyrolysis oil can be used in traditional boilers and furnaces. Redesign of the burner and its operation mode are usually required for smaller units. Corrosion resistant materials are also needed for the equipment that is contacted with the pyrolysis oil, due to its acidity.

In medium or large-scale boilers, furnaces and turbines that operate on natural gas, coal or heating oil to produce heat, pyrolysis oil can be (co-)combusted already today. Retrofitting these systems for operation on pyrolysis oil requires limited investments.

Since 2015, a dairy factory in Borculo, the Netherlands co-fires FBPO in a natural gas (NG) boiler to generate process steam for milk powder drying (Van de Beld and Toussaint 2020). The steam boiler (29 MW_{th} capacity, 95.5% efficiency) is a water-tube boiler with a furnace made from cooled membrane walls. A dual fuel double register burner allows the boiler to operate on a combination of pyrolysis oil and natural gas, and on natural gas only.

Figure 7: Supply of Pyrolysis oil from the Empyro plant to the end user for heat production

In the past, the co-firing of FBPO in large electric power stations had been demonstrated, i.a. in Wisconsin USA (370 hours, 5%, co-fired with coal in a 20 MW_e plant, (Sturzl 1997)) and in Harculo, The Netherlands (15 tons of pyrolysis oil, co-fired with natural gas, (Wagenaar, B.M.; Gansekoele, Florijn, and Venderbosch, R.H.; Penninks, F.W.M.; Stellingwerf 2004)). Likely due to unfavourable economics and limited availability of pyrolysis oil at that time, these tests have not led to follow-up.

4.1.2 Energy production in engines and turbines

Use of pyrolysis oil in engines and turbines would enable co-generation of heat and electricity at variable scale and allow for more flexibility than co-firing or simple combustion in a burner. Use of pyrolysis oil in stationary engines and turbines is possible with some modification but use of pyrolysis oil in automotive engines is not possible without extensive modification of the pyrolysis oil. The required pyrolysis oil upgrading for automotive applications is discussed elsewhere in this White Paper.

Due to the specific properties of pyrolysis oil, compared to diesel fuel or gasoline, the combustion of untreated pyrolysis oil in stationery internal combustion (IC) engines or turbines is a challenge. FPBO is acidic, has a lower heating value and is difficult to ignite.

Despite these difficulties, there have been successes. Recently, BTG completed successfully a 500 hour run on a modified diesel engine[7], and Opra turbines offers a modified turbine running on FPBO[8].

4.2 Upgrading and processing into transport fuels

4.2.1 The need for upgrading of pyrolysis oil to transport fuels.

Research is ongoing to use FPBO as a fuel component that can be blended with common transport fuels such as diesel, gasoline, and kerosene. Before "raw" FPBO can be used as a fuel "drop in" it requires chemical upgrading.

The FPBO upgrading can take place in two ways: in an existing fossil refinery or in a stand-alone installation (see Figure 8).

- FPBO upgrading in an existing fossil refinery involves co-feeding FPBO in a Fluid Catalytic Cracker unit at an existing fossil refinery. After upgrading (stabilisation), a higher share of FPBO can be processed in the refinery than is the case with "raw" pyrolysis oil.
- Stand-alone upgrading of FPBO involves the hydrotreatment of pyrolysis oil in a 2-step process. This process yields Hydrotreated Pyrolysis Oil (HPO), which can be blended with fossil fuels such as diesel, for use in e.g., the maritime sector.

[7] https://content.yudu.com/web/442ay/0A444rp/MPS0122-Pros/html/index.html?page=30&origin=reader
[8] https://www.opraturbines.com/

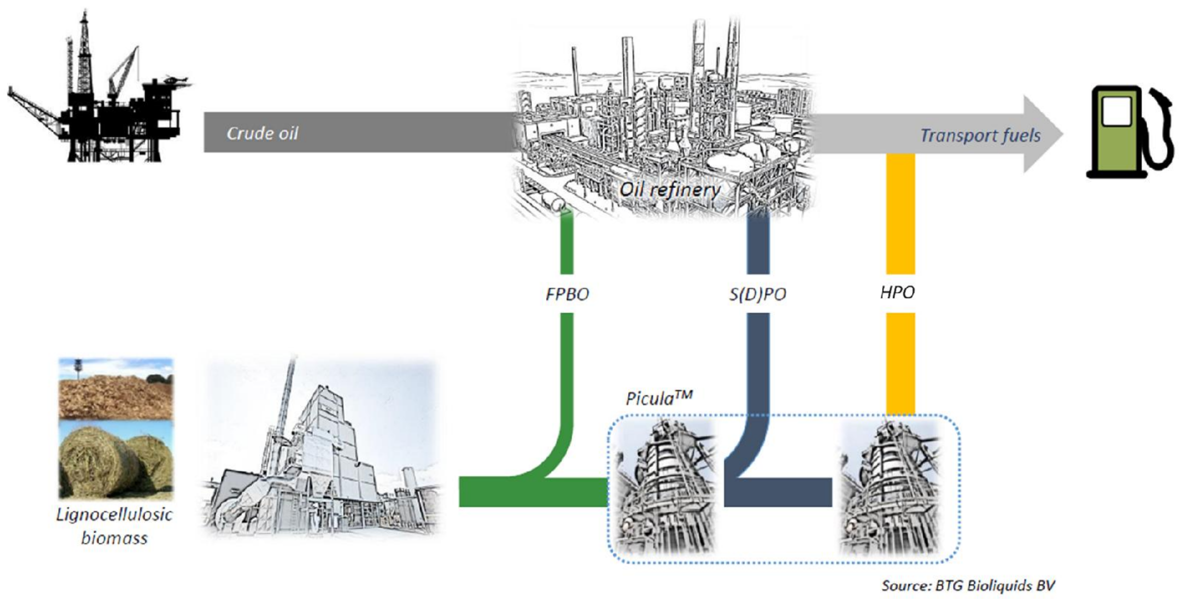


Figure 8: Pyrolysis oil transport fuel production routes

4.2.2 Co-refining of pyrolysis oil

Fossil refineries are large and capital-intensive installations that convert crude oil into final products. With a crude refining capacity of about 13.2 million barrels per day, representing 13% of total global capacity, the EU is the second largest producer of petroleum products in the world after the United States. In the EU's 90 refineries, direct employment is provided to 120,000 persons, and indirectly to 1.2 million people (Rutz et al. 2020).

Co-feeding of pyrolysis oil in a fossil refinery involves injecting it in the Fluid Catalytic Cracker (FCC) unit of a refinery. This type of equipment is available in many – more complex – refineries, and its function is to upgrade Vacuum Gas Oil (VGO) – a 'heavy' product - into a spectrum of lighter products. An FCC is essentially a circulating fluidised bed, where the catalytic conversion takes place (see Figure 9).

The pyrolysis oil can be co- injected in the FCC reactor, and catalytically cracked to a spectrum of products. This is not without problems, most important one being the extra formation of coke on the catalysts. This can be burned off in the regenerator, but the carbon is lost. Part of the pyrolysis oil is also converted into water and gases such as CO and CO_2 (Rutz et al. 2020).

First published proof that pyrolysis oil could be co-fed in an FCC was published by Pinho (Pinho et al. 2014; 2015; 2017). Pinho showed that pyrolysis oil could be co-processed in the demo plant of Petrobras using a separate feed injector. Most notably, Pinho *et al.* not only showed that pyrolysis oil could be co-processed at 5, 10 and even up to 20 wt-%, but also that co-processing low volumes of pyrolysis oil (5 wt-%) gives an increase in FCC gasoline yield.

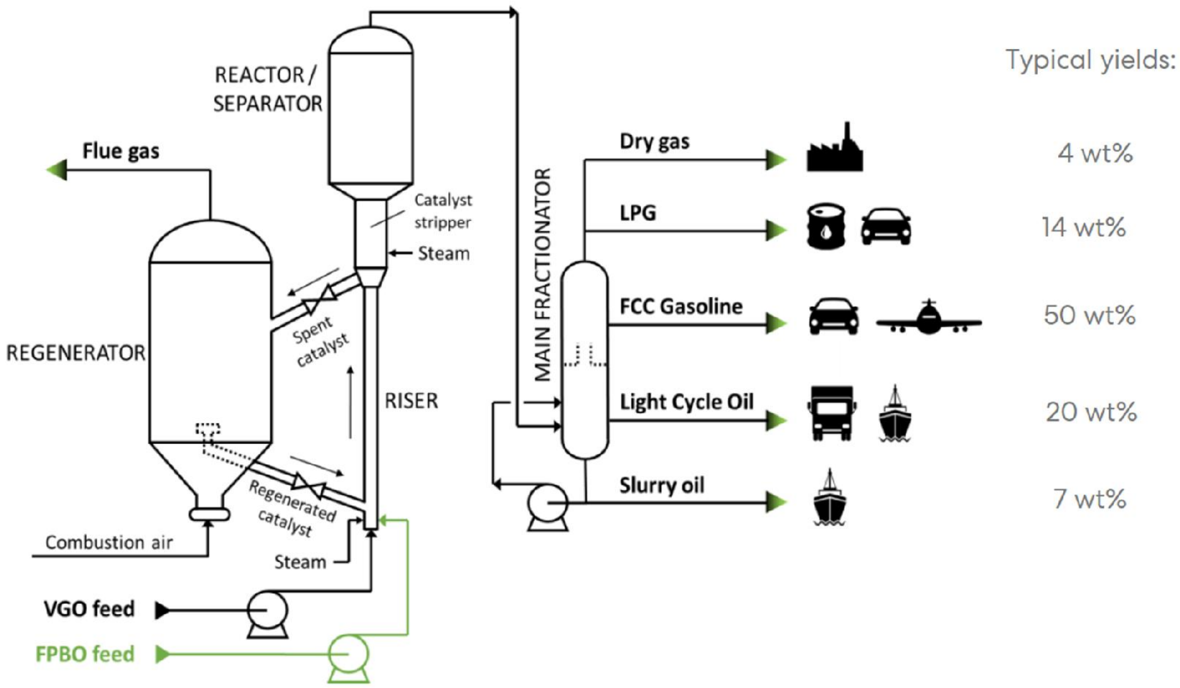


Figure 9: Principle of co-feeding of pyrolysis oil in an FCC

The economic feasibility of co-refining FBPO has been shown by the models of (Talmadge et al. 2021) and the environmental benefits have been proven by for example the LCA of (Shi et al. 2021). Commercial trials have also been executed successfully, of several days of continuous co-processing of up to 5% FPBO in refinery FCC's (Lammens and Talebi 2019). Commercial implementation of pyrolysis co-feeding has recently started at the Preem refinery in Lysekil, Sweden[9].

It is expected that in the coming years co-feeding of pyrolysis oil will increase, due to the need to produce advanced biofuels in Europe, and the technical and economic viability of co-feeding of pyrolysis oil compared to other solutions.

[9] https://bioenergyinternational.com/biofuels-oils/preems-lysekil-refinery-begins-producing-renewable-petrol-from-pyrolysis-oil

4.2.3 Stand-alone upgrading of pyrolysis oil

A stand-alone process for upgrading of pyrolysis oil is being developed by BTG. The process consists of two steps (Figure 10):

- Firstly, the pyrolysis oil is stabilised to convert the most reactive components. This is carried out using a dedicated catalyst, called Picula, under elevated pressures (200 bar) and temperatures ranging from 100°C to 300°C. The product – Stabilised Pyrolysis Oil (SPO) – contains less oxygen than the raw pyrolysis oil and can be used as input for refineries and fed to FCCs at higher shares than untreated FPBO.
- Secondly, a hydrotreatment step using commercial catalysts converts the SPO to a new product, HPO or Hydrotreated Pyrolysis Oil. This product is fully miscible with fossil fuels and can be distilled just as fossil transport fuels can.

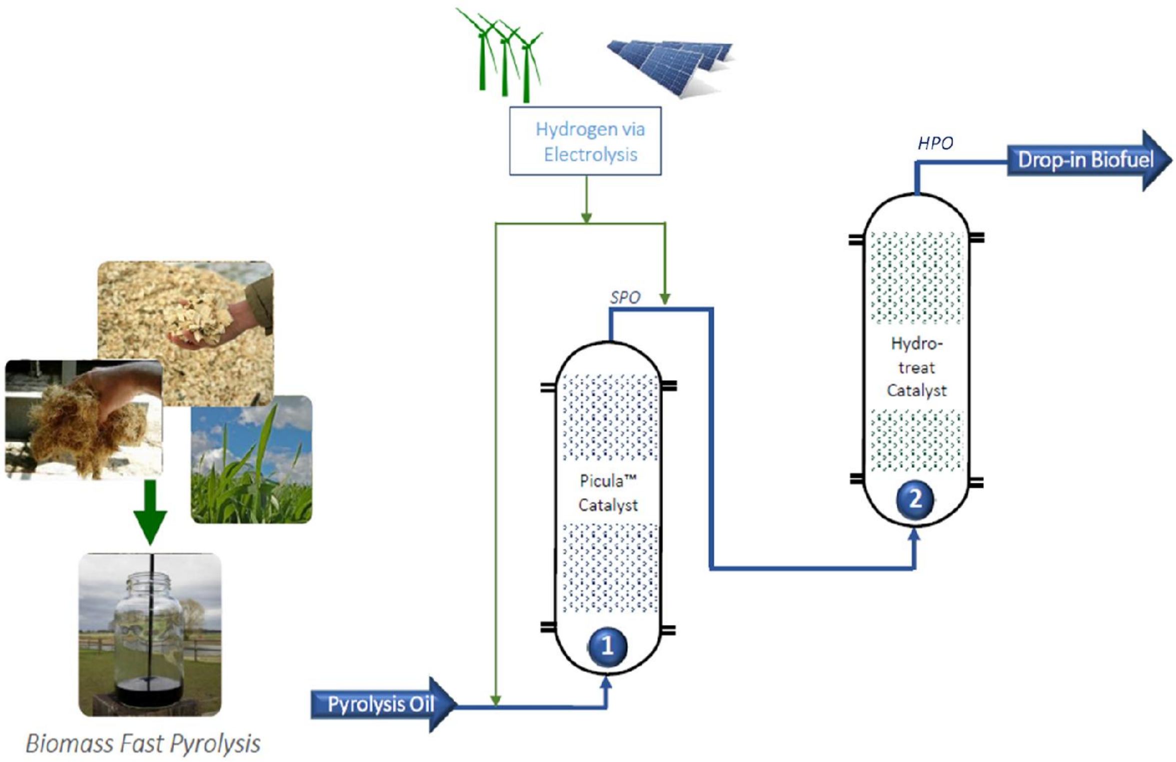


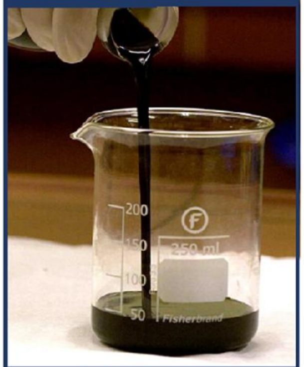
Figure 10: Stand-alone upgrading of pyrolysis oil to transport fuels: The BTG neXt process

A key input for both steps is hydrogen, needed at a rate of 0.05 kg hydrogen per kg of pyrolysis oil. For every kilogram of pyrolysis oil input, 0.4 kg of transport fuels can be produced. Thus, 0.125 kg of hydrogen is needed per litre of transport fuel. The overall energetic efficiency of the process is about 75%. To ensure RED II requirements (see Paragraph 3.2) are met, the hydrogen will have to be produced internally, from renewable resources, or the CO_2 released during steam methane reforming (the most common industrial method to produce hydrogen from natural gas) should be captured.

Product

Key composition parameters of pyrolysis oil and upgraded components are given in Figure 11. Initially, the focus of the technology development is on marine transportation fuels. This means that the Hydrotreated Pyrolysis Oil needs to be treated to produce an end product suitable for marine application (Marine Distillate Fuels). The acid number and the sulphur content are reduced significantly and the water is removed almost completely, whereas the heating value is significantly increased (Van de Beld 2020).

Water content	25	wt%
Density	1,170	kg/m³
LHV	16	MJ/kg
Acid Number	70	mg_{KOH}/g
Sulfur	< 0.5	wt%
FlashPoint	?	°C
Cetane Number	< 20	-



Crude Pyrolysis Oil

Water content	< 0.1	wt%
Density	870	kg/m³
LHV	> 40	MJ/kg
Acid Number	< 0.15	mg_{KOH}/g
Sulfur	< 0.05	wt%
FlashPoint	25	°C
Cetane Number	?	-

Hydrotreated Pyrolysis Oil (HPO)

Water content	-	wt%
Density	< 890	kg/m³
LHV	42	MJ/kg
Acid Number	< 0.5	mg_{KOH}/g
Sulfur	< 0.1	wt%
FlashPoint	> 60	°C
Cetane Number	> 40	-

Marine Distillate Fuel (DMA)

Figure 11: Change in composition of pyrolysis oil (left) when it is converted to HPO (middle), which is comparable to fossil DMA (right).

Technology status

The process is working at a pilot scale. In a 20-50 kg FBPO/day pilot plant HPO has been produced. With a lab-scale test setup, a number of liters of the product has been produced, enabling a 100 km field test with a four-wheeled specialty vehicle in a 75%/25% blend with diesel.

Next step is the development of a demonstration plant. Technology developer BTG has the ambition to develop a demo plant by the end of 2023 with a production capacity of several (oil) barrels a day, and has set up a new company, called BTG-NeXt, for this purpose. Initially the plant is expected to produce – on a campaign-basis - transport fuel which can be further distilled to e.g. gasoline, aviation fuel and diesel.

4.2.4 Potential EU Market size advanced biofuels from pyrolysis oil

To determine the potential EU market size of advanced biofuels from pyrolysis oil, use is made of the most recent EU Reference Scenario 2020 (European Commission 2021a). In this reference scenario information on current and projected energy use in the EU is determined. This scenario is the baseline scenario which the EU uses to determine the effects of certain policy initiatives such as the Green Deal. This means that the reference scenario in itself contains no new (after 2020) policy.

Based on this reference scenario the amount of final energy consumption in the transport sector – which includes road, rail, marine and aviation - in the EU is given, as well as the current (RED II) mandate for advanced biofuels, which starts at 0.2% of the final energy consumption in the transport sector and increases to 3.5% in 2030 (Figure 12).

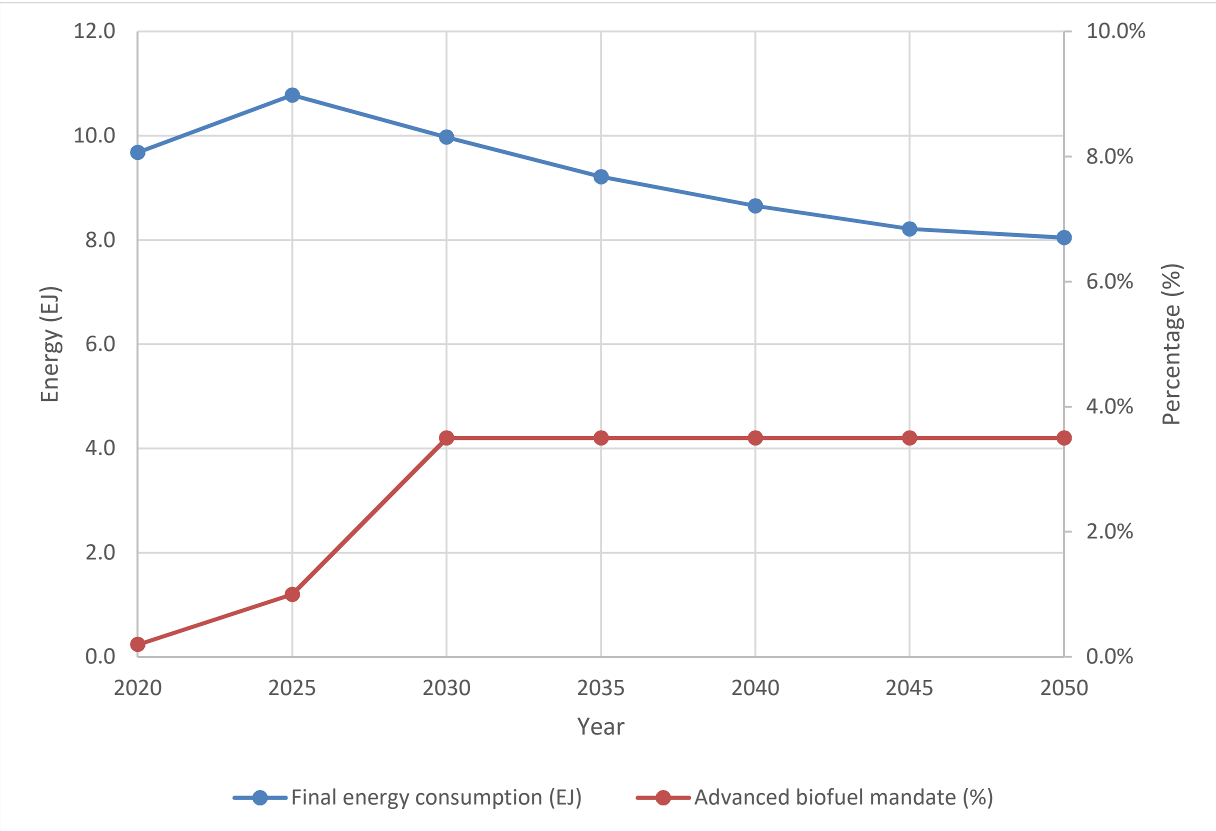


Figure 12: Total amount of final energy consumption (left axis) in the transport sector and the advanced biofuel mandate (right axis)

Based on these data, it is possible to forecast the potential market size for pyrolysis oil-based transportation fuels in a low scenario and a high scenario assuming resp. 25% and 33% of advanced biofuels derived from pyrolysis oil (Table 2).

Table 2: Market size for pyrolysis oil use for advanced transportation fuels using the EU reference scenario 2020

Year	2020	2025	2030	2040	2050
Pyrolysis oil use (PJ) - low estimate	2.5	13.9	45.0	39.1	36.3
Pyrolysis oil use (PJ) - high estimate	3.3	18.4	59.4	51.6	47.9

In this projection the current mandate for advanced transportation fuel (3.5%) is taken. Because advanced biofuels may be 'double-counted', the actual amount of advanced transportation fuels mandated is 1.75% of the final energy consumption in the transport sector in the EU. The reference scenario foresees a gradual increase in efficiency in the transport sector, so that – despite a substantial projected increase in total transport kilometers – the total energy use in transport is declining.

The 59.4 PJ/year of pyrolysis oil energy projected to be used in 2030 in the high scenario is equivalent to production of 3.7 million tonne of pyrolysis oil per year or 155 plants of the size of Empyro (24,000 tonne pyrolysis oil production per year). In case the advanced fuel mandate would be set at 2.2% with no double counting – which is still an increase of 0.45 percent-point, the corresponding figures are 74.7 PJ, 4.7 million tonne of pyrolysis oil production and 195 'Empyro-sized' plants. This figure of 2.2% is reportedly (European Commission 2021b) considered to be the new advanced fuel mandate.

It should be noted that – apart from the 2.2% advanced fuel mandate – no further policy initiatives were considered in these projections. When projections on additional policy are being included, as was done by (Uslu 2019), the total amount of biofuels – including also food-crop based biofuels – would increase to 2.0 EJ in 2030 and 3.0 EJ in 2050, which is several factors more than the volumes of pyrolysis oil use projected above. This shows that there is further upward potential regarding the use of pyrolysis oil-based transport fuels because of the larger expected market size.

5 Production of bio-based chemicals and materials from pyrolysis oil

Pyrolysis oil from biomass is a complex emulsion containing many different chemical components. Reason for this is the feedstock composition and the pyrolysis process itself. During fast pyrolysis, the cellulose, hemicellulose, and lignin components of the biomass are 'cracked', and a liquid – the pyrolysis oil - containing water and a host of chemical substances is retrieved (Heeres 2019a).

To convert this pyrolysis oil to higher valued products, one way is chemical upgrading, as was shown in the previous chapter. Another option is separating off fractions of the pyrolysis oil with distinct functionalities – fractionation.

5.1 Fractionation of pyrolysis oil

Distillation cannot be applied to fractionate pyrolysis oil, i.a. because pyrolysis oil is reactive and elevated temperatures lead to secondary reactions that can destroy components.

Two more suitable options are:

- *Fractional condensation* entails the in-process separation on the basis of condensation point. Different pyrolysis oil fractions are produced in in a condensation train, a set-up of multiple condensers operating at different temperatures. Research into fractional condensation is taking place at e.g. Avello, VTT, UMSICHT, and TNO-ECN (Van de Beld 2021).
- *Liquid-liquid extraction* concerns the post-production separation on the basis of functionality. Different pyrolysis oil fractions are produced using organic and aqueous solvents. This process is developed by BTG and a pilot plant has been built in the EU H2020 project Bio4Products[10].

Key advantages of these processes are that essential functionalities are retained in the pyrolytic oil fractions and that no unwanted by-products or wastes are generated.

The full – most elaborate – BTG liquid-liquid extraction of pyrolysis oil is shown in Figure 13. First, using an organic extractant, 'extractives' are separated from the FPBO. These are mostly rosins and fatty acids. Then the pyrolysis oil is separated into a sugar fraction and a lignin fraction, whereby light phenolics can be retrieved from the lignin fraction.

[10] https://bio4products.eu/

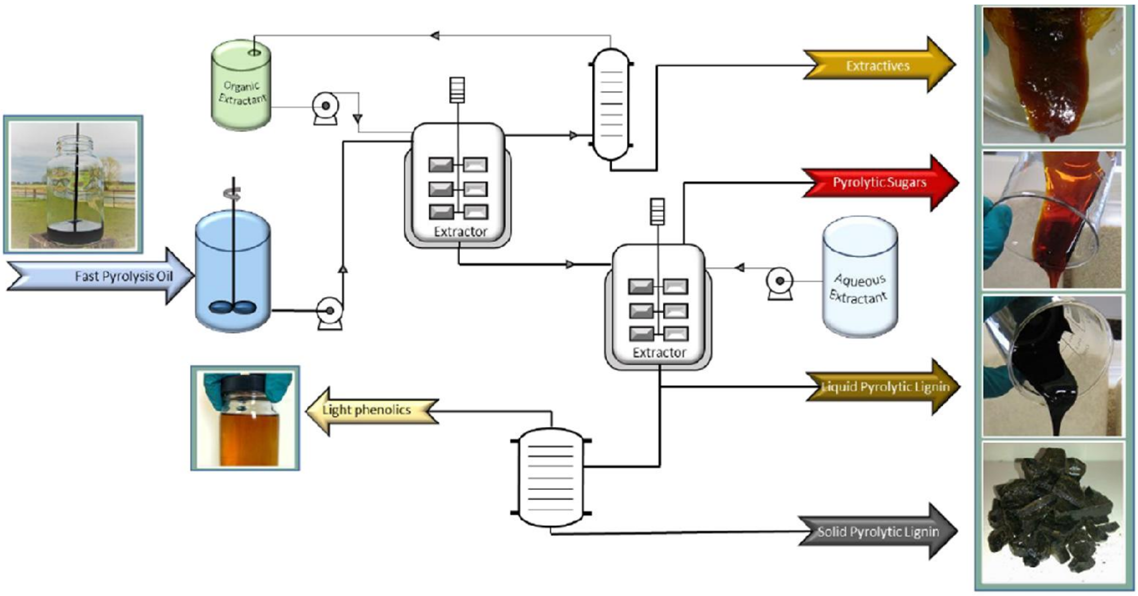


Figure 13: Fractionation of pyrolysis oil using liquid-liquid extraction (Van de Beld 2021)

Technology status

The pyrolysis oil fractionation technology has been demonstrated at TRL 6-7.

A demonstration plant was developed in the framework of the Bio4Products project, with a capacity of 3 tonne of pyrolysis oil per day (see Figure 14).

This demo plant was commissioned in 2018, in the framework of the EU Bio4Products EU H2020 project.

Product properties and yields are similar to previous pilot plant experiments (3 wt% extractives, sugar fraction up to 40 wt% and lignin fraction up to 30 wt%) (Heeres 2019b).

Figure 14: BTG's 3 tonne/day pyrolysis oil fractionation demo plant

5.2 Production of bio-based chemicals and materials

All three pyrolysis oil fractions (sugars, lignin, and extractives) can be in principle utilised for a large number of products. This would mean that fast pyrolysis could be one of the key technologies for a biorefinery – a complex where biomass is refined to a spectrum of products.

Dedicated, product-specific R&D is needed to ensure the functionality of the FPBO-based products, whilst securing more sustainable production processes compared to those for fossil alternatives. Examples of applications of pyrolysis oil fractions that are being developed are shown below.

Bio-based foam resins

Pyrolytic lignin can be used as partial replacement of phenol in insulating foams, mainly used in the construction sector. The pyrolytic lignin is used as a basis for a phenol-formaldehyde (PF) resin, that is used to produce these foams.

These bio-based foams show improved properties compared to fossil-based foams, especially on the – highly important – fire retardance. Also, the compressive strength is improved, while the thermal conductivity is still good.

Figure 15: Insulating foams produced from pyrolytic lignin

The environmental impact of these bio-based foams is lower than comparable fossil-based foams[11].

Moulding compound

Granulated plastic moulding compound is the base material for many moulded plastic products, such a pan handles or parts for the automotive industry.

New moulding compounds have been developed that contain a large percentage of bio-based pyrolytic lignin, while maintaining excellent mechanical properties. By limiting the use of fossil resources this innovation could help to reduce the environmental impact linked to a whole range of business-to-business and consumer products[12].

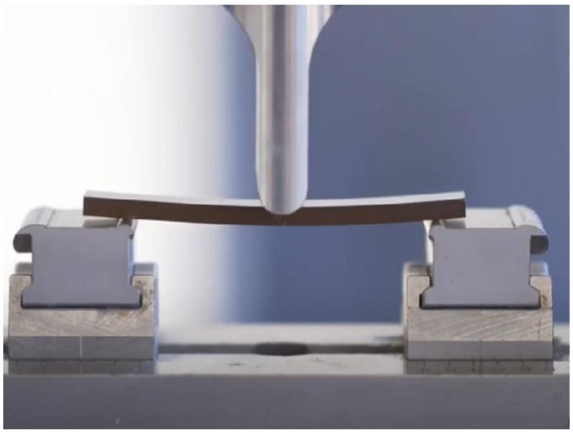


Figure 16: Mechanical testing of product made from bio-based moulding compound

Sustainable chemicals from renewable raw materials

Polyfurfuryl alcohol is a versatile chemical component, currently produced from furfural, which is manufactured mainly outside of the EU, usually using the Quaker Oats batch process. This

[11] https://bio4products.eu/process/#1583858430526-93f93e7e-8015
[12] https://bio4products.eu/process/#1583858492040-a2b050a8-97ff

process has low yields (less than 50%), high energy requirements and generates large amounts of effluent (Win 2005).

Polyfurfuryl alcohol is used in bio composites for automotive and furniture applications, fire resistant components for mass transport applications, wood modification, industrial adhesives for foundry, refractory and anti-corrosion applications, and as sand-moulding resins. The pyrolytic sugars from the pyrolysis process can be used in combination with Polyfurfuryl alcohol to increase the sustainability of these products[13].

Figure 17: Sand molding resins containing pyrolytic sugars

Sustainably modified wood

Softwoods are generally not as suited for outdoor applications as hardwoods. By applying impregnation, softwoods can be modified in such a way that they are just as suitable.

The Dutch company Foreco has launched the brand Faunawood, that uses European pinewood impregnated with a special bio-based resin, produced in part from pyrolytic sugars. The result is a durable, strong wood pole, perfect for a wide range of applications. The impregnation ensures the product is not damaged by wood rotting fungi and termites. Studies have shown that Faunawood contributes 82% less greenhouse gas emissions compared to fossil-based creosotes, and due to its lower toxicity is also 7.4 times less damaging to human health. Old wood poles can be reused to produce the modification resin – making Faunawood a truly circular product[14].

Figure 18: Sustainable modified wooden poles

[13] https://bio4products.eu/process/#1583858558963-3ae85c72-f6da
[14] https://www.foreco.nl/en/products/faunawood

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