PYROS – ROADMAP FOR REALIZATION OF A VALUE CHAIN FROM FOREST TO BIOFUELS VIA BIO-OIL

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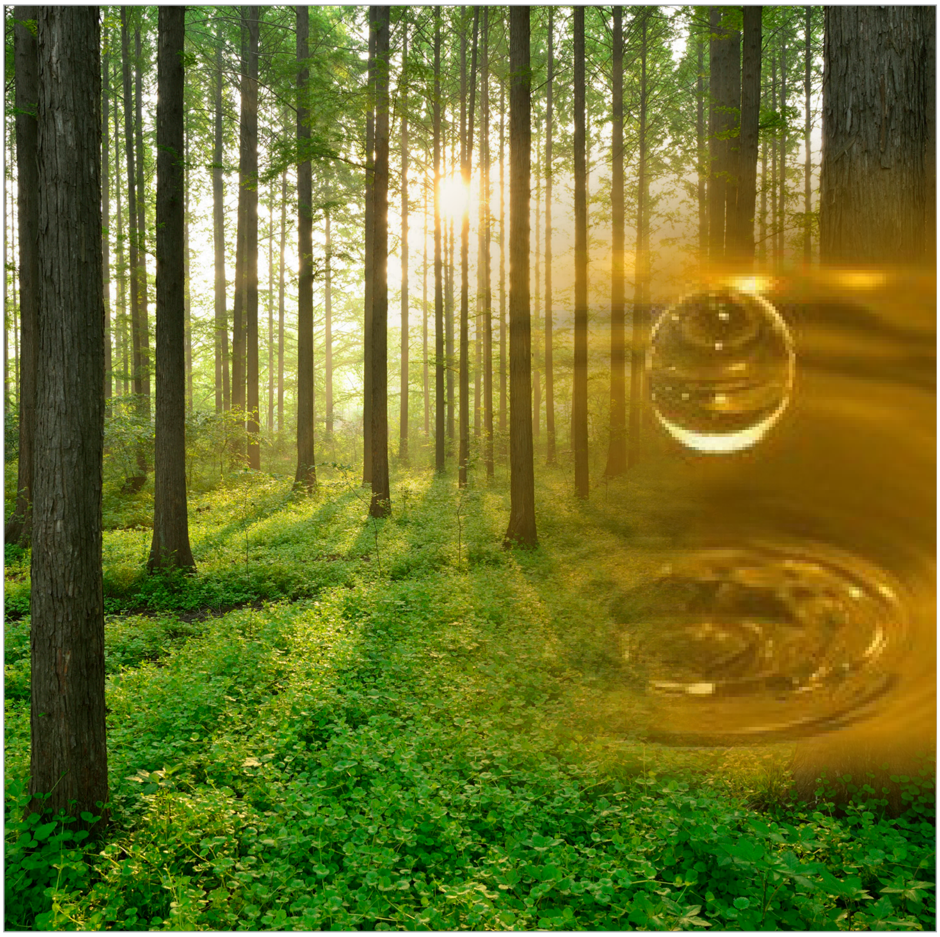
BIODRIVMEDEL FÖR SVERIGE 2030



Energiforsk

PyRos

Roadmap for realization of a value chain from forest to biofuels via bio-oil

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Foreword

The project has been conducted within the Energiforsk programme Biofuels for Sweden 2030 (Biodrivmedel för Sverige 2030), with the goal to contribute to the development of biofuels for the transportation sector and a fossil free transportation fleet by 2030.

The programme has been financed by EON Gas Sverige AB, Gasnätet Stockholm, Göteborg Energi, Neste and the Region Skåne.

Within this project, new value chains from forest raw materials to bio-based transportation fuels via the production of a biocrude, have been evaluated. Anna von Schenck and Niklas Berglin, NiNa Innovation AB, have led the project. The project has been performed in collaboration with Rottneros Biorefinery. This work was also financed by Rottneros AB, 2GEN AB and Addngo AB.

The reference group for the project had the following members: Tomas Ekbom (Svebio), Sören Eriksson (Preem), Nippe Hylander (ÅF), Marcus Elmer (Business Värmland) and Anton Fagerström (Energiforsk). The reference group is gratefully acknowledged for invaluable contribution in finalizing the report.

Stockholm December 2018

Bertil Wahlund

Energiforsk AB

Sammanfattning

Nya värdekedjor från skogsråvara till biobaserade transportbränslen har utvärderats. Studien analyserar förutsättningarna under vilka det kan vara tekniskt och ekonomiskt möjligt att producera en bioolja som kan användas för framställning av transportbränslen och försöker beskriva en färdplan för att förverkliga sådana värdekedjor i Sverige inom tidsramen 2020- 2030. Som råmaterial har fokus varit på olika fraktioner av skogsråvaror, såsom sågspån, bark och skogsrester (GROT). Tekniker som har utvärderats grundar sig främst på snabb pyrolys (FP) och hydrotermisk förvätskning (HTL).

Den övergripande slutsatsen är att det är både tekniskt och ekonomiskt möjligt att producera betydande volymer av transportbränslen i Sverige via bioolja under tidsramen 2020-2030.

Den tekniska utvärderingen visar att processerna för omvandling av trä till bioolja som är närmast kommersiella applikationer är processerna för snabbpyrolys (TRL 8-9), men också att hydrotermisk förvätskning (HTL) och integrerade hydropyrolysprocesser (för närvarande TRL 6-7) kommer att kunna ha påverkan inom den studerade tidsramen. Tekniken för konvertering av bioolja till transportbränslen är fortfarande under utveckling, men kan anses vara påTRL 6-7 för upp till 10% inblandning av pyrolysoljor från snabbpyrolysprocesser i en FCC (fluidized catalytic cracker) vid befintliga oljeraffinaderier . Hydrotreatment och hydrodeoxygenation (HDO) av snabb pyrolys och HTL oljor ligger på TRL 5.

HDO är en nyckelteknik för att uppnå fullständig substitution av fossila bränslen med biobränslen, men samprocessning i en FCC är en bra närstående lösning som har lågt investeringsbehov i befintlig infrastruktur på raffindarerierna och som inte kräver någon extern källa till väte. Detta verkar vara den föredragna vägen på kort sikt baserat på input från teknikleverantörerna.

För de första anläggningarna, i en skala om cirka 25 000 ton per år, kommer kostnaden för att producera biooljor att vara i storleksordningen 600 SEK/MWh, vilket gör det endast marginellt lönsamt utan någon form av investeringsstöd. I takt med att tekniker och marknader mognar kan kostnaden komma ner till 400 SEK/MWh i större anläggningar (100 000 ton per år) och bör kunna ge attraktiv avkastning för industriella investerare. Det finns även en uppsida i ekonomin som ett resultat av det reduktionspliktssystem för minskning av koldioxidutsläpp från transportsektorn som trädde i kraft i Sverige 1 juli 2018.

I ett scenario där det finns kontinuerlig investering och expansion i biooljeproduktionsanläggningar under 2020-2030 är det inte orealistiskt att förvänta sig att produktion av bioolja skulle kunna vara uppe i en årsproduktion på 1 Mton per år fram till 2030. Omvandling av bioolja i oljeraffinaderier kan leda till substitution av fossila transportbränslen i storleksordningen 3 TWh per år. Den totala investeringen för biooljeproduktionsanläggningar skulle då ligga i storleksordningen 10 miljarder kronor.

Råvara skulle exempelvis vara sågspån på kort sikt, med en ökande andel skogsrester på längre sikt. Mångd råvara som används för detta ändamål 2030 skulle då kunna motsvara ca 2 TWh sågspån samt 5 TWh skogsrester per år.

Summary

New value chains from forest raw materials to bio-based transportation fuels were evaluated. The study analyzes the conditions under which it can be technically and economically attractive to produce a bio-oil that can be used for the production of transportation fuels, and attempts to describe a roadmap for the realization of such value chains in Sweden in the 2020-2030 time frame. As feedstock the focus has been on different fractions of forest raw materials, such as sawdust, bark and forestry residues. Technologies that have been assessed are primarily based on Fast Pyrolysis (FP) and Hydrothermal Liquefaction (HTL).

The overall conclusion is that it would be both technically and economically feasible to produce significant volumes of transportation fuels in Sweden via bio-oil in the 2020-2030 time frame.

The technical assessment shows that the front-end processes (converting wood to bio-oil) which are closest to commercial application are the fast pyrolysis processes (TRL 8-9), but also that the hydrothermal liquefaction (HTL) and integrated hydropyrolysis processes (currently TRL 6-7) will be able to have an impact in the studied time frame. The technologies for conversion of bio-oil to transportation fuels are still under development, but can be considered to be at TRL 6-7 for up to 10% co-processing of fast pyrolysis oils in fluidized catalytic crackers (FCC) at existing oil refineries. Hydrotreatment and hydrodeoxygenation (HDO) of fast pyrolysis and HTL oils is at TRL 5.

HDO is a key technology to reach full substitution of fossil fuels with biofuels, but the FCC co-processing route is a good near-term solution that has very low investment requirements in refinery infrastructure and does not require an external source of hydrogen. This seems to be the preferred route in the near term based on input from the technology suppliers.

For early plants, at a scale of about 25 000 tonnes per year, the cost of producing bio-oils will be on the order of 600 SEK/MWh, making it only marginally profitable without some form of investment subsidy. As technology and markets mature, the cost can come down to 400 SEK/MWh in larger facilities (100 000 tonnes per year), and should give attractive returns for industrial investors. There is an upside in the economics as a result of the Carbon emissions reduction obligation system that came into effect in Sweden as of 1 July, 2018.

In a scenario where there is continuous investment and expansion in bio-oil production plants in the 2020-2030 time frame, it is not unrealistic to expect that the production of bio-oil could reach 1 000 000 tonnes per year by the end of the decade. Conversion of the bio-oil in oil refineries could lead to substitution of fossil transportation fuels on the order of 3 TWh/y. Total investments would be on the order of 10 billion SEK in the bio-oil production plants.

Feedstock would be, e.g. sawdust in the near term, with an increasing share of forestry residues in the longer term. The required feedstock in 2030 could then correspond to about 2 TWh/y of sawdust and 5 TWh/y of forestry residues.

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1 Introduction

In this project a new value chain from forest raw materials to bio-based transportation fuels has been evaluated. The study analyzes the conditions under which it can be technically and economically attractive to produce a bio-oil that can be used for the production of transportation fuels. As feedstock the focus has been on different fractions of forest raw materials, such as sawdust, bark and forestry residues. Technologies that have been assessed are primarily based on Fast Pyrolysis (FP) and Hydrothermal Liquefaction (HTL).

Large volumes of biomass are not easy to handle for industries that do not have the experience or logistics around this. Converting the biomass into a liquid, a bio-oil or biocrude, which can then be further processed in an oil refinery is therefore an interesting opportunity to make the biomass available to today's transportation fuels producers.

An understanding of how a value chain could look like is given but also how far in the development different suppliers of pyrolysis and HTL technologies have come.

An important part of the project has been to contact technology suppliers as well as additional value chain actors in order to get an understanding of the production costs that arise and how a business model can look like to achieve a competitive product price. In the contacts with the technology suppliers it has also been important to understand if they today are ready to offer a commercial plant under an EPC contract and if so with what plant performance (feedstock, capacity, efficiency, availability etc).

Finally, we have tried to define a possible scenario and attempted to describe a roadmap for the realization of such value chains in Sweden in the 2020-2030 time frame, showing how production of bio-oil via pyrolysis and HTL could develop under commercial conditions.

2 Background

2.1 WHAT IS BIO-OIL?

There is already a relatively large market for liquid biofuels that are used to substitute fossil fuels in industrial boilers and furnaces and for heat and power production. The term "bio-oil" is commonly used to refer to these products, although they can be very different in chemical composition, physical properties, and in which feedstock they originate from. The common denominator is that they are produced from some kind of biomass, that they are pumpable and can be handled in a similar way as mineral oils, and that the driving force for using them is that they come from renewables and assist in reducing fossil carbon dioxide emissions.

In the Swedish market there are at least three groups of bio-oils that are used:

- tall oil and tall oil pitch
- mixed fatty acids
- vegetable and animal oils and fats

These bio-oils all have heating values that are on the same order as mineral oils, but they are normally acidic and require modified storage and firing systems. They consist mainly of fatty acids and fats and are by-products from various types of process industries (e.g. pulp mills, biodiesel plants, food processing).

In this report we have chosen to use the word "bio-oil" to represent also liquid fuels produced by fast pyrolysis of hydrothermal liquefaction of solid biomass. As will be described later, these bio-oils differ in properties from the bio-oils above that contain mostly fats or fatty acids.

We have also used the word "biocrude" when the bio-oil is used as feedstock to a conventional oil refinery.

2.2 NEW POLICIES

Sweden aims at reducing the CO_2 emissions from the road transport sector by 70% to 2030 compared to the year 2010. A carbon emissions reduction obligation system has been introduced in Sweden from July 1, 2018. This new system aims to give the industry a long-term more predictable market demand for the renewable transportation fuels.

Under the new legislation, suppliers to the Swedish road transportation fuel market are required to reduce CO_2 emissions from gasoline and diesel that they sell by blending biofuels into the products. The reduction obligation increases year by year. As an example, for diesel the level of reduction starts at 19.3% in 2018, and increases to 20% in 2019 and 21% in 2020. Companies that do not fulfil their obligation will be required to pay a penalty corresponding to 4 SEK/kg CO_2-equivalent for diesel.

The Swedish transportation fuel market will also be affected by the revised EU Renewable Energy Directive ("RED II"), which will require suppliers to substitute a minimum of 14% of fossil fuels with biofuels (calculated on an energy basis). A maximum of 7% of the total 14% can be from food and feed crops. The remainder must come from “advanced biofuels”, categorized by certain feedstocks listed in the directive, for example:

- Waste and residues from forestry and forest industries: bark, branches, precommercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin, and tall oil;
- Other non-food cellulosic material, including for instance perennial grasses, but also non-starchy cover crops before and after main crops as well as ley crops. This category also includes industrial residues after the extraction of vegetable oils, sugars, starches and proteins.
- Other ligno-cellulosic materials, including for instance woody short rotation crops, pulp logs and other forest-based biomass, but excluding veneer logs and saw logs.

Today, about 19 TWh of the total 87 TWh fuels used in the Swedish road transport sector are based on renewable fuels. However, some 80-90% of the biofuels consumed in Sweden are imported (as fuel or as feedstock) and the main part comes from vegetable oils (SPBI, 2018).

Forest-based biomass can therefore be expected to account for a relatively large proportion of the additional potential. In a study by Börjesson, 2016 the potential for increased outtake of solid biomass from the Swedish forest has been estimated to 24-33 TWh today and 36-50 TWh for year 2050 (Börjesson, 2016).

The Swedish saw mill industry has had a strained position with rather small profit margins. Today, the market conditions are favorable with relatively low exchange rate, low electricity price and increased demand. However, the market can change fast. For the saw mill industry it is desirable to find use of the by-products coming out of the saw mills, such as sawdust, for a higher value product than today to increase the profitability. Sawdust is therefore seen as an interesting raw material to be used for bio-crude production.

2.3 EARLIER PROJECTS AND OTHER RELATED ACTIVITIES

2.3.1 Projects connected to the Rottneros site

Rottneros AB has two pulp mills, of which one is a mechanical pulp mill situated in Rottneros in the county of Värmland in the western part of Sweden. The mill has acapacity of 170 000 tonnes/year, making the mill one of Europe's largest producers of mechanical market pulp. The location of this mill is good from a raw material point of view since there are several saw mills in the surroundings and also forestry residues available nearby. At the site there is also free space where a new production facility could be built.

Rottneros and 2GEN are stakeholders in Rottneros Biorefinery, a joint venture between Rottneros, Tyréns and 2GEN. The company has been formed in order to find opportunities to produce new products from raw materials that today are mainly burned (sawdust, bark) or left in the woods (forestry residues). Rottneros

Biorefinery has previously looked at the production of methanol via gasification, which led to an application in 2012 within the EU program NER300 entitled "Lignocellulose for biofuel or biofuels and/or for energy through direct gasification". They looked at the production of 150-230 000 tonnes methanol/year from about 200 MW biomass. The investment cost was estimated to around 3 billion SEK.

In that study, Rottneros Biorefinery investigated the production of transportation fuels where the raw material is available, at the same location as the mill. In this project, we look at the possibility of producing an intermediate product in the form of a biocrude where the raw material is available, but which can then be further processed to a final product, e.g. diesel and gasoline, in an existing oil refinery.

2.3.2 Biofuels via syngas from gasification

In Sweden there has been several gasification projects on a pilot/demo scale. Up until around year 2000 the main focus was on electricity production due to the high power to heat ratio in combining gas and steam turbines but with the increased focus on climate change the attractiveness for production of transportation fuels increased. There has been quite a few Swedish industrial projects on gasification, e.g. EON (Bio2gas), Göteborg Energi (GoBiGas), Domsjö Fabriker and Värmlandsmetanol.

There is also a development plant in Piteå, northern Sweden for demonstration of the Chemrec black liquor gasification technology where the spent cooking liquor (black liquor) from a pulp mill has been gasified. The syngas has been used for methanol and DME production. However, none of these projects have taken the step to commercialization.

2.3.3 Pyrolysis

When it comes to pyrolysis, Billerud (today BillerudKorsnäs) started in 2012 an industrial project called Pyrogrot at their mill in Skärblacka. They applied for funding within the NER300 programme and were awarded a grant. However, in 2013 the project was abandoned due to the lack of the right market conditions.

Pyrolysis plants have however been built at other places in Europe, Fortum Joensuu plant commissioned 2013 using a pyrolysis technology from Valmet and Empyro pyrolysis plant by BTG-BTL located in the Netherlands. Technology to transform the pyrolysis oil to acceptable transportation fuel is under development and verification but there is no commercial use of pyrolysis oil in oil refineries today.

Bioshare is a Swedish start-up company looking at developing both a pyrolysis and a gasification technology that could be integrated with an existing CHP plant. There is however no experimental work done on these technologies yet.

Hydrothermal liquefaction is an alternative to pyrolysis. The biomass is here used wet, as a slurry using water as solvent at supercritical conditions.

2.3.4 Lignin

Base-catalyzed depolymerization, characterized by the use of a solid catalyst and alkaline process conditions has originally been developed in Denmark and then further in other countries. This process has been adapted for kraft lignin as feedstock at Chalmers University in Gothenburg, Sweden.

The Swedish start-up company SunCarbon is also developing its own HTL technology using membrane filtrated lignin from black liquor as a feedstock. The remaining cooking chemicals from the pulp mill are here used as catalysts.

RenFuel is another Swedish start-up company that is developing catalytic depolymerization of kraft lignin. RenFuel operate a pilot plant and are planning scale-up of the technology to an industrial plant at the Rottneros chemical pulp mill in Vallvik.

2.3.5 Recent industrial activity

On an industrial level in the Nordic countries the following pre-studies and collaboration projects have been announced during 2017-2018

- Setra has been granted SEK 117 million in investment support from Klimatklivet (Naturvårdsverket) to build a pyrolysis plant at Kastet's saw mill outside Gävle, Sweden. The production capacity is planned to be 25 000 tonnes biocrude/year based on sawdust. A new company, Pyrocell, has been set up together with Preem.
- The Norwegian company Bergene Holm has initiated a pre-study together with Preem in its subsidiary Biozin to look at the possibility of using a hydro-catalyzed pyrolysis process (the IH^2 process) for the production of biofuels from saw mill residues.
- RenFuel and Preem have formed a joint venture, Lignolproduktion, to develop production of bio-oils from kraft lignin. The first site that is studied is the Rottneros pulp mill in Vallvik, Sweden.
- SilvaGreen Fuel (joint venture between Statkraft and Södra) has announced that they will build a demo plant in Tofte (where Södra previously had a pulp mill) for production of bio-oil based on Steeper Energy's HTL process.
- Preem has initiated a collaboration project with Fortum and Valmet to look at the possibility of upgrading pyrolysis oil so that it can be used for the production of transportation fuels.
- Preem and St1 are both undertaking investments to increase HVO production capacity in their respective refineries in Gothenburg.

Some examples of ongoing R&D activities in Sweden in this area are:

- Within the Energy Agency's Biofuels Programme, there is an ongoing project led by RISE ETC " Anpassning av pyrolysolja för att möjliggöra samuppgradering i konventionella raffinaderier”
- Within BioInnovation, a project with RISE Processum as coordinator and NiNa Innovation as project leader has been going on for about a year "HTL - Hydrothermal liquefaction of residual streams from forestry and agriculture".

- A recently completed project by RISE AB "Tekniska och ekonomiska förutsättningar för oljeersättning i industrin med pyrolysolja"
- Within f3 (The Swedish Knowledge Centre for Renewable Transportation Fuels), RISE Bioeconomy with partners published a report in 2017 evaluating the production of an intermediate product (biocrude) for further upgrading in an oil refinery to produce transportation fuels.

PyRos complements these projects by taking a step closer to industrial application by mapping commercial technology providers for pyrolysis and HTL, as well as studying the value chain and business model that need to come in place with partially new market conditions in order for Swedish biofuel production to start. This would also contribute to more employment and contribute to regional development.

2.4 OBJECTIVES

The overall objective of the project is to define a realistic roadmap based on the information from the contacted suppliers and other value chain actors, which through demonstration, can take the entire value chain from raw material to final product (biofuels) to a commercial scale, enabling Swedish production of biofuels available on a large scale at a reasonable cost.

3 Bio-based transportation fuels production and its feedstocks

Due to different policies and political decisions the use of renewable energy in Sweden has increased during the last decades. Bioenergy today stands for 1/3 of the total energy use in Sweden. Globally the bioenergy is to a large extent based on waste products and by-products from forestry, agriculture and biomass-based industries such as saw mills, pulp mills and food industries. Bio-based wastes from households are also contributing (with about 10 TWh).

The total bioenergy used in Sweden 2016 was about 139 TWh (Energimyndigheten, 2018).

The use of bio-based transportation fuels in Sweden has increased, in 2011 it was about 5.5 TWh and in 2017 it had increased to 19 TWh or 20% of the total use of transportation fuels (SPBI, 2018). The bio-based transportation fuels are mainly found as biodiesel such as HVO (Hydrogenated Vegetable Oils) and FAME (Fatty Acid Methyl Esters). Ethanol (as E5 and E85 in gasoline and ED95 for heavy duty engines) and biogas are also used.

The main part of the bio-based transportation fuels used in Sweden is imported, mainly produced from crops and oil seeds feedstock. Notable exceptions are the HVO produced from tall oil, ethanol produced from wheat, and biogas produced from food waste and sewage. FAME originates mostly in countries around the Baltic Sea, ethanol in Eastern Europe, while HVO is sourced from all over the world.

Palm oil or waste products from the palm oil industry can be used as raw material in the production of HVO. In 2016, all use of palm oil in HVO was replaced by the waste product PFAD (Palm Fatty Acid Distillates). In 2016, 23% of the HVO used in Sweden was produced from PFAD. There was recently a decision by the Swedish government that PFAD will no longer be classified as a waste stream and it will therefore have less value as raw material than previously. This new decision will be implemented 1 July, 2019.

The use of biofuels in Sweden in the transport sector is shown in Figure 1.

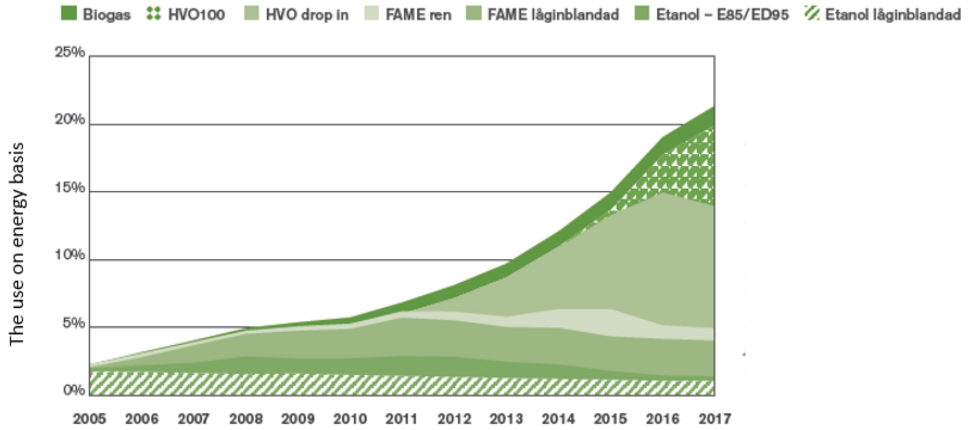

Figure 1. Biofuels used in the transportation sector in Sweden 2005-2016 (SPBI, 2018)

The price of transportation fuels in Sweden for the year 1980-2017 is shown in Figure 2 below (calculated to 2017 consumer price level). The price for vehicle gas is not included in the figure but is on an average 10-15% lower than the price of gasoline (on an energy basis).

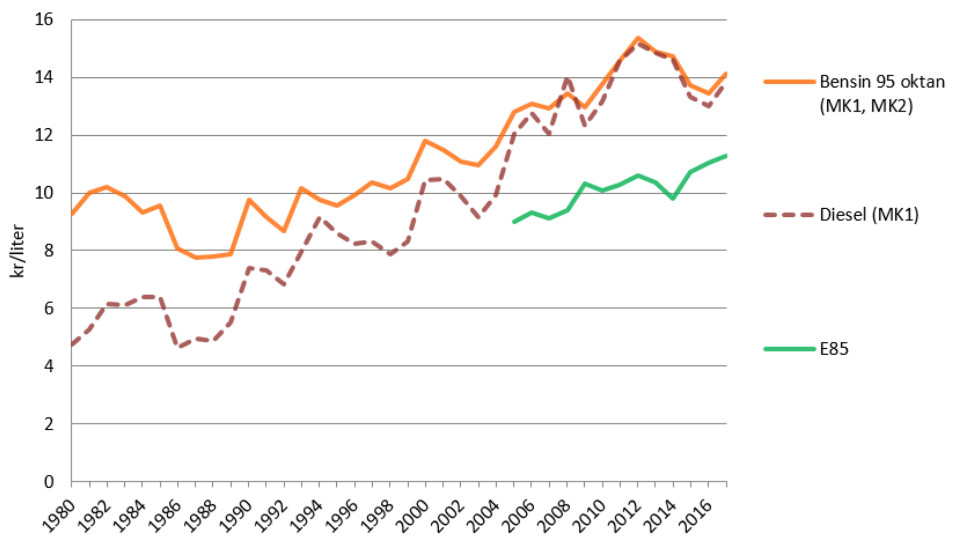

Figure 2. Price of transportation fuels in Sweden 1980-2017 calculated to 2017 price level (Energiläget, 2018)

If looking at wood a rather large part is also used for energy purpose since it comes out as residue streams from production of sawn timber and pulp, e.g. sawdust, lignin (part of the tree that ends up in the spent cooking liquor in pulp mills), bark and forestry residues. There are also trees that have been damaged in different ways and therefore are not suitable to be used for the production of materials and therefore go directly to the energy sector.

Today there is one side stream from the pulp mills that is used for transportation fuels, namely tall oil. There is one company, SunPine in Piteå, in the northern part of Sweden that upgrades tall oil to an intermediate product that is shipped to the Preem oil refinery in Gothenburg and there upgraded and used as blend-in to produce renewable diesel and gasoline. The pulp and paper company SCA and the oil refinery St1 have also announced that they will start using tall oil as raw material for production of renewable transportation fuels in a partnership. In a press release (May, 2018) they announced that they will jointly invest about 500 MSEK in a production plant with the capacity of 100 000 ton/year. The facility is planned to be up and running in 2021.

Agriculture contributes to the bioenergy by energy forests and energy crops, also residual products such as straw and bagasse are being used. Important feedstocks globally for production of transportation fuels are sugarcane, sugar beets, corn, wheat and rape seed.

In Sweden, Agroetanol has a facility in Norrköping producing arond 230 000 tonnes of ethanol per year for transportation fuel using wheat as feedstock but also waste streams from food industry such as old bread and cakes.

Forestry residues (branches and tops) are often thought of as an interesting raw material to use in thermochemical processes. Its use does not compete with the parts of the trees that are being used for sawn timber and pulpwood, but is today rather used for energy purposes, i.e. electricity and heat in CHP plants.

Forestry residues are however not an ideal raw material to use in a pyrolysis and HTL processes. Most of the suppliers state that their process can use forestry residues as feedstock but it will give a lower yield of bio-oil which therefore even though the price might be lower is not necessarily the most economically advantageous feedstock to use. There will also be a higher ash content in the bio-oil from forestry residues. However, some of the suppliers have solved this problem by using an extra step after the pyrolysis/HTL process to purify the bio-oil.

The historical prices for different woody fuel fractions are shown in Figure 3.

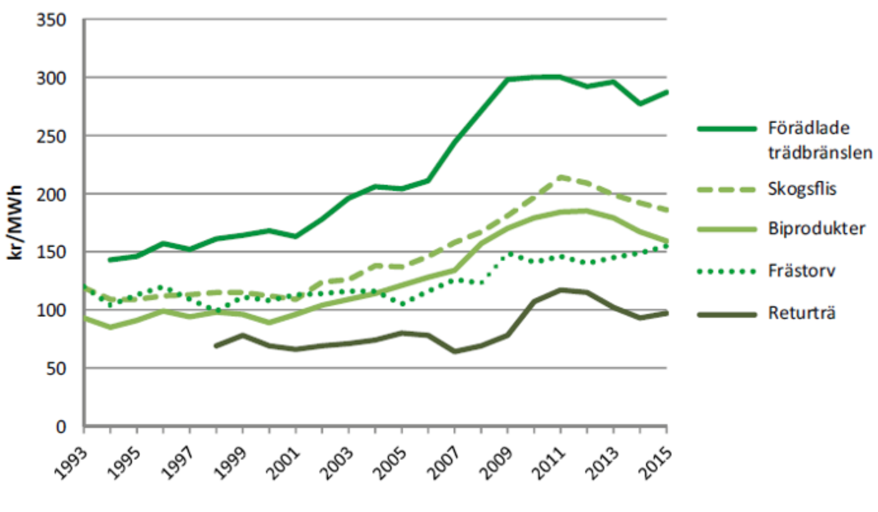

Figure 3. The price for different woody fuel fractions 1993-2015 (Energimyndigheten, 2018)

4 Technologies for thermochemical processes

Direct thermochemical biomass liquefaction processes such as pyrolysis and hydrothermal liquefaction (HTL) are future possible pathways for production of advanced biofuels.

A screening study of different technologies and suppliers of thermochemical processes resulted in 7 companies that were contacted for further discussions. The suppliers to contact were selected in agreement with the reference group and based mainly on Technology Readiness Level (TRL) of the technology and the possibility to access realistic process data. A short summary of the 7 companies and their level of technology development are given in Table 1.

The companies represent three different kind of technologies; Fast pyrolysis, Hydro pyrolysis and Hydrothermal liquefaction.

Table 1. Selected technology suppliers of pyrolysis and HTL in the screening study

Company	Country	Process	Scale	Type	Not
Envergent (UOP)	USA, Canada	RTP	Demo/ commercial	Fast pyrolysis	Commercial plant in Quebec, Canada planned start-up Q4 2018. Pyrolysis oil will be used as heating oil. Production about 50 000 t /year
BTG	Holland	BTG-BTL	Demo/ commercial	Fast pyrolysis	Demo/Commercial plant in the Netherlands in operation since 2015. Pyrolysis oil is used as heating oil. Production about 25 000 t /year.
Valmet (Fortum)	Finland	Valmet	Demo/ commerical	Fast pyrolysis	Commercial plant in Finland in operation since 2013. Pyrolysis oil is used in Fortum's power plant in Espoo. Production about 50 000 t/ year. Initiated collaboration with Preem in 2018 to look at possible integration in oil refinery.
CRI (Shell)	USA, India	IH^2	Pilot/Demo	Hydropyrolysis	Demo in India since 2017 with capacity of 5 t/d feedstock in. Ongoing pre-study with Preem and Bergene Holm in Norway (Biozin).
Steeper Energy	Denmark, Canada	Hydro-faction	Pilot	HTL (supercritical)	Building a Demo plant in Norway together with Silva Green Fuel (JV between Statkraft and Södra) Planned start-up Q1 2019, production capacity 4000 l bio-oil/d.
Licella	Australia, Canada	Cat-HTR	Pilot	HTL (near supercritical)	JV with Canfor pulp in Canada since 2014, looking at integration with a pulp mill.
Renmatix	Rome (NY) and Atlanta, USA	Plantrose® Process	Pilot	Supercritical hydrolysis	Decompose biomass into C6, C5 and lignin for use as biochemicals in food and cosmetic applications

RenMatix does not produce a bio-oil in their Plantrose Process but sugars and lignin for use in cosmetics and food products. The process is therefore not further described since their products are not in the scope of this study.

4.1 FAST PYROLYSIS

Fast pyrolysis is a process where the biomass is heated in absence of oxygen in order to produce vapors that can be condensed to obtain a liquid: the pyrolysis oil. Fast pyrolysis is a rapid thermal process that occurs at low pressure and temperatures around 300-500°C. The reaction takes place in just a few seconds. Three product streams are being produced; pyrolysis oil, biochar and non-condensable gases. The yields of the different products are dependent on the process conditions, such as reactor technology, temperature, pressure, residence time, feedstock etc. The yield from biomass to bio-oil is in the range of 45-70 mass% depending on the quality of the feedstock.

In general a pyrolysis plant consists of raw material handling system, a dryer, a grinder (depending on raw material), pyrolysis reactor, boiler, gas purification system, condenser and a storage tank.

The process starts with the drying of biomass to about 90% dry substance and then the biomass is ground to about 2-5 mm before mixing with hot sand in the pyrolysis reactor.

Today there are 3 commercial suppliers of fast pyrolysis technology; BTG-BTL, Envergent and Valmet. A presentation of these three process concepts is given below.

4.1.1 BTG-BTL

BTG-BTL is a subsidiary to the Dutch company BTG (Biomass Technology Group). BTG-BTL has a patented pyrolysis technology based on the use of a RCR (Rotating Cone Reactor).

Dried biomass particles are fed into the pyrolysis reactor at the top together with an excess flow of sand, which acts as a circulating heat carrier material. The biomass and sand are mixed within the pyrolysis reactor and converted into pyrolysis oil vapors, gas and char. The produced vapors and gases pass through several cyclones before entering the condenser, in which the vapors are quenched by re-circulated oil. The sand and char are transported to a fluidized bed combustor, where air is added to combust the char. The non-condensable pyrolysis gases enter the combustor from the condenser and are also combusted. The now reheated sand is then transported back to the reactor via a sand cooler to ensure a constant reactor sand feeding temperature. Excess heat from the sand cooler and from the hot combustor flue gasses is captured as high pressure steam (btg-btl, 2018)

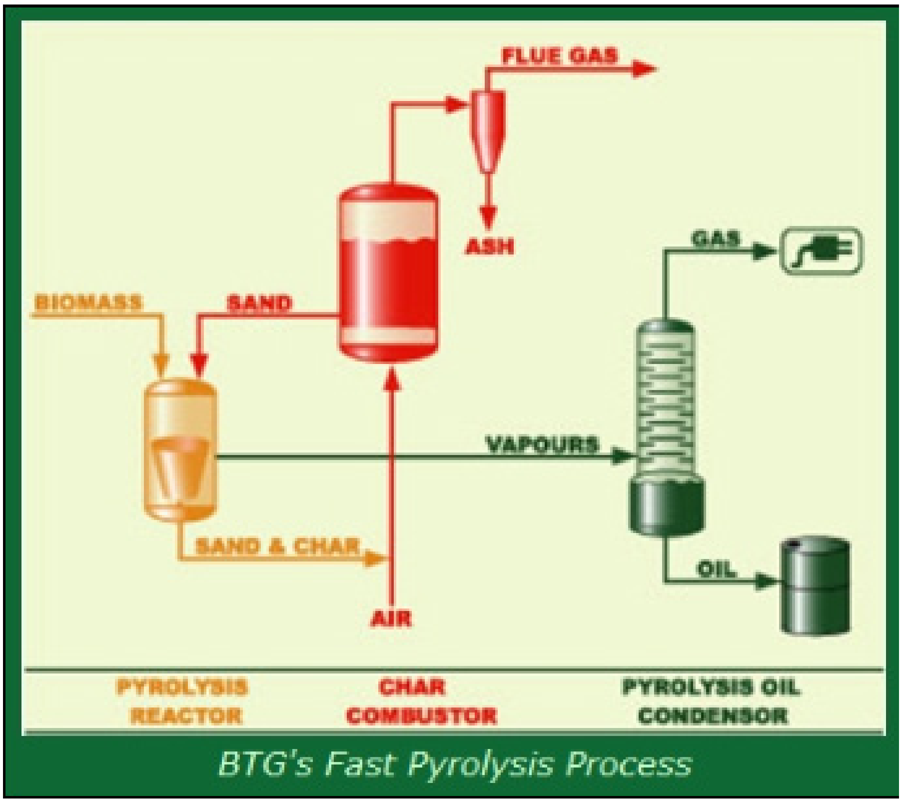

Figure 4. A process layout of the btg-btl process concept (btg-btl, 2018)

The technology has been demonstrated in a facility in Hengelo, the Netherlands since 2015. The capacity of this plant is about 25 000 tonnes pyrolysis oil/year and the feedstock is dust and small particles left from pellets storage. The pyrolysis oil is used as fuel oil in a dairy production facility. The pyrolysis oil is delivered in tank trucks. The high pressure steam coming out from the pyrolysis process is used as process steam at a production facility close to the pyrolysis plant. This is further described in 5.1.2.

BTG-BTL has a cooperation with Technip when it comes to deliver the process equipment. They are also working together with Technip in developing the possibility of feeding in the pyrolysis oil into an oil refinery. Technip is the second largest (after Honeywell UOP) technology supplier to the oil refinery industry.

They can today deliver the process equipment in modules of 25 000 tonnes/ year pyrolysis oil production. If higher capacity is wanted the recommendation today is to buy several modules.

4.1.2 Envergent

Envergent Technologies is a joint venture between Honeywell UOP and Ensyn. The technology is based on a circulating transported fluidized bed reactor, similar to the one used in the UOP Fluid Catalytic Cracking (FCC) technology. Hot sand vaporizes the biomass, which is then rapidly quenched.

RTP™ technology also produces char and a non-condensable gas, both of which can be used to provide process energy in the reheater to maintain the RTP process and/or in the dryer to dry the biomass. (Envergenttech, 2018)

Figure 5. A process layout of the Envergent process concept (Envergenttech, 2018)

Ensyn has had commercial plants in use for over 25 years, producing bio-oil used for food ingredients, but also fuel oil as a side stream that has been used for industrial heating.

A commercial plant is right now being built in Quebec, Canada, the so called Côte-Nord Project with planned start-up Q4, 2018.

The project partners are Ensyn, Arbec Forest Products and Groupe Rémabec. Arbec Forest Products Inc. is a leading, privately-held forest products company operating in Eastern Canada and Groupe Rémabec is a major forest products company operating in Quebec, with a focus on timber harvesting and wood processing. The plant will process about 65 000 dry tonnes /year of cellulosic woody biomass from local sources. The bio-crude will be sold to customers in the U.S. Northeast and in Eastern Canada for heating applications and as a renewable feedstock for oil refineries in the production of transportation fuels.

The facility has been engineered by Honeywell UOP through a contract signed with Envergent Technologies.

Envergent has good knowledge of the unit operations in an oil refinery via UOP, which is the largest technology supplier to the oil refinery industry. They have development projects ongoing on how to integrate the bio-oil in an existing oil refinery depending on the process equipment available. They state that 3-5% bio-crude as blend-in is doable in a FCC (Fluidized catalytic cracker).

4.1.3 Valmet

Valmet has a technology based on a circulation fluidized bed boiler reactor. Heat to the pyrolysis reactor is supplied by circulating hot sand from the fluidized bed boiler. Char and non-condensable gas produced in the pyrolysis reactor are combusted in the boiler. Low-temperature heat from condensing is used to dry the biomass prior to the pyrolysis reactor. This means that the technology is based on an integration with a fluidized bed boiler.

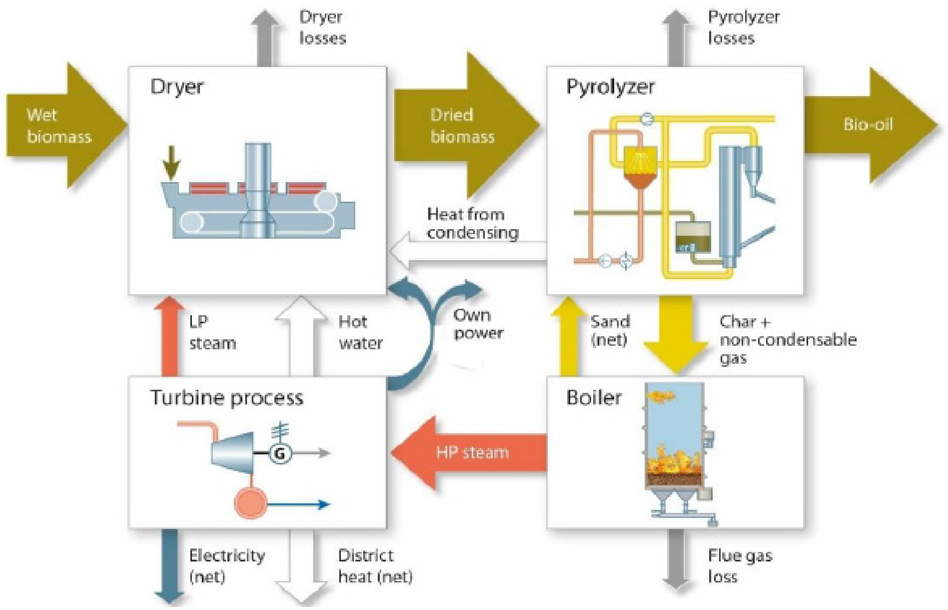

Figure 6. A process layout of the Valmet process concept (Valmet, 2018)

Valmet has since 2013 a commercial pyrolysis plant in Joensuu, Finland. The facility was handed over to Fortum in June 2015. The bio-oil production is integrated with a CHP boiler and the plant has an annual production capacity of 50 000 tonnes of bio-oil using saw dust, wood chips and forestry residues as feedstock.

The bio-oil produced at the plant in Joensuu is used at Fortum´s CHP plant in Espoo, just outside Helsinki. This is further described in 5.1.1.

Valmet, Fortum and Preem have an ongoing common project looking at the possibilities of using the bio-oil in an oil refinery.

4.2 HYDROPYROLYSIS

The IH² process is a catalytic thermochemical process invented by Gas Technology Institute, Chicago (GTI) and jointly developed with support from US DOE (US Department of Energy) and CRI (a catalyst company owned by Shell) to which CRI has acquired exclusive license rights.

The IH^2 process starts with biomass drying to about 10–30 mass% moisture. A hydrodeoxygenation of the volatilized biomass to produce a raw hydrocarbon product over proprietary CRI catalysts in the presence of low to medium-pressure hydrogen is then taken place. This serves both to remove oxygen and remove highly reactive and corrosive components to provide a stable hydrocarbon product. This step is followed by a fixed-bed hydrotreater, which uses other proprietary CRI catalysts to upgrade the first-stage product and transform it into a finished hydrocarbon fuel or blend stock. There is also a Hydrogen Manufacturing Unit (HMU), which converts light gases generated in the first stage to renewable hydrogen, in sufficient quantity to supply the process.

The products out from the IH^2 process are liquid hydrocarbons such as gasoline, diesel and kerosene with very low oxygen content.

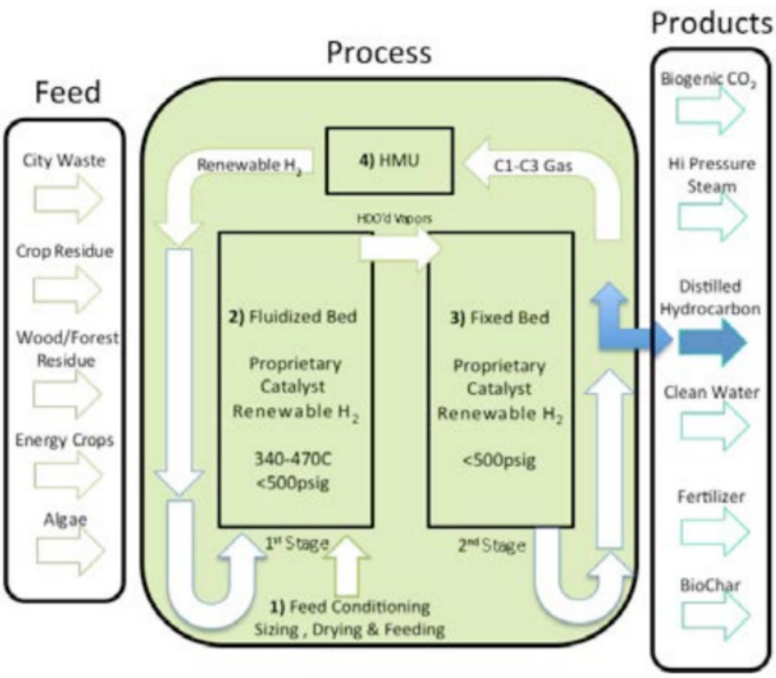

Figure 7. A process layout of the IH^2 process concept for production of hydrocarbons (CRI, 2018)

A pilot plant was installed at GTI in 2012 with the capacity of 50 kg/day of feedstock. Since 2017 there is a demonstration plant in Bangalore, India with the capacity of 5 tonnes/day of feedstock.

Biozin Holding AS is a subsidiary to Bergene Holm AS, a Norwegian saw mill and wood products industry. Biozin today has an ongoing pre-study with Preem to evaluate the possibility of producing biofuels via the IH^2 technology mainly using sawdust but also other available wood fractions as feedstock. The first site that is being evaluated is Jordøya in Åmli, Norway.

4.3 HYDROTHERMAL LIQUEFACTION (HTL)

In hydrothermal liquefaction (HTL) a slurry of biomass and water reacts at high temperatures 300-400°C and at about 250-300 bar, meaning that the water present in the biomass is in a supercritical state or near supercritical state.

The outgoing streams are a gas phase, often two liquid phases and a solid phase. The HTL oil product is a water in oil emulsion containing 10-15 mass% water. So, the big difference between pyrolysis and hydrothermal liquefaction is the presence of water in the reactor and the high pressure, resulting in lower oxygen content in the bio-oil.

There are two suppliers of this kind of technology that we identified have come closest to commercialization, namely Steeper Energy and Licella. A presentation of these two is given below.

4.3.1 Steeper Energy

Steeper Energy is a Danish-Canadian company with offices in Copenhagen, Denmark and Calgary, Canada. Steeper Energy´s technology uses supercritical water as a reaction medium for the conversion of biomass directly into a high-energy density renewable crude oil, referred to as Hydrofaction™ Oil. The yield is about 45 mass% and around 85% on energy basis according to Steeper Energy (Steeper Energy, 2018)

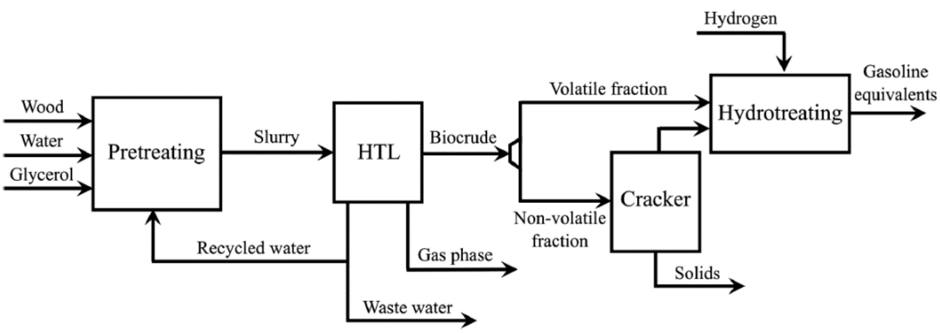

Figure 8. A process layout of the Steeper Energy process concept (Pedersen et al, 2017)

The process has been demonstrated at a pilot plant at Aalborg University, Denmark since 2013 with a capacity of about 30 kg/h of slurry throughput. A demonstration plant is now being built together with Silva Green Fuel (Joint venture between Södra and Statkraft) in Tofte, Norway where Södra used to have a pulp mill. The capacity will be 4 000 l bio-oil/d with forestry residues as raw material. The start-up is planned in Q1, 2019.

4.3.2 Licella

Licella is an Australian company that over the last 10 years has developed a process called Cat-HTR™. The process is using water at near or supercritical conditions, the Cat-HTR™ converts a wide variety of low-cost, waste feedstocks and residues into high-value products.

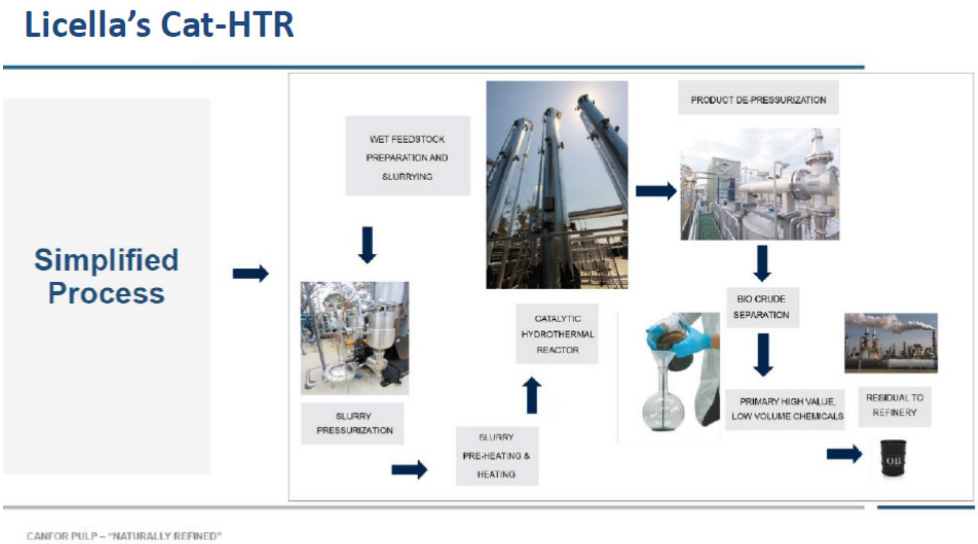

Figure 9. A process layout of the Licella process concept (Licella, 2018)

Licella has a pilot since 2009 in Australia that has been scaled up 2 times until 2013.

Since 2014, Licella has a joint venture with the Canadian pulp mill Canfor pulp looking at the possibility to produce a bio-crude from forestry side streams close to the pulp mill.

Licella is also looking at the possibility on using wastes as the feedstock. In August 2018 it was announces that Licella, Neste in Finland and the UK-based chemical recycling company ReNew ELPhave partnered to explore the potential of using mixed waste plastic as a raw material for fuels, chemicals, and new plastics using the Licella Cat-HTR technology.

5 Processing and handling of bio-oils

In order to make a transportation fuel from the bio-oils that can be produced with the thermochemical processes, there is a need for further processing downstream of the pyrolysis or liquefaction plant. This chapter describes some of the possible routes, and the experience that has already been gained in testing. The current use of some pyrolysis oils to replace fuel oil for heating is included, since this is a natural first market for the bio-oils.

5.1 EXPERIENCE FROM DISTRIBUTING AND FIRING PYROLYSIS OIL

Pyrolysis oil has been used and is being used to replace mineral oil in steam and hot water boilers, and there is thus relatively extensive experience of how to design storage and logistics systems to handle the pyrolysis oil.

The main difference compared to conventional fuel oils is that the pyrolysis oil is acidic and has a lower heating value. Storage and distribution systems must thus be manufactured in stainless steel, which calls for separate handling and distribution all the way to the burner in a boiler.

5.1.1 Fortum Vermo plant

Fortum has operated a 46 MW district heating peak-load boiler on pyrolysis oil in Espoo, Finland, since 2014. The pyrolysis oil is brought by tank truck from the Joensuu plant to Espoo. Operating experience has shown that the boiler can be operated on pyrolysis oil only, i.e. without any support fuel.

Before switching fuels, the plant was revamped with new pumps and pipes, and a modified burner was installed in the top-fired boiler. A new stainless steel tank for storage was constructed - inside the tank previously used to store heavy fuel oil. The boiler is equipped with an electrostatic precipitator to reduce particle emissions, required also when firing heavy fuel oil.

Pumping, transport and storage has worked well in the four years of operation. The pyrolysis oil needs to be agitated and the storage tank is also equipped with a pumparound system. There is redundancy in the pumping system to allow inspection and cleaning of fuel filters as required.

Figure 10. The Fortum Vermo Plant that has been converted to firing with pyrolysis oil. A stainless steel tank was built inside the former heavy fuel oil tank to accommodate the pyrolysis oil.

5.1.2 FrieslandCampina Domo

The pyrolysis oil produced in the Empyro plant in Hengelo has been used since 2015 for steam production in a dairy owned and operated by FrieslandCampina Domo in Borculo, Netherlands. The pyrolysis oil is co-fired with natural gas or biogas to produce 40 t/h of steam. There is a 12-year off-take agreement for up to 100% of the bio-oil produced in the Empyro plant.

The transport distance is about 30 km and there are three truck loads per day.

Figure 11. Pyrolysis oil from the Empyro plant in Hengelo is transported by tank truck to FrieslandCampina in Borculo.

5.1.3 Karlshamn power station

In 2015, E.ON performed a large scale test firing pyrolysis oil in one of the three boilers at the Karlshamn power station in Sweden. The bio-oil was supplied by Fortum from the Joensuu plant. The tests were performed at part load up to 130 MWth, generating 25 MW of electricity (Bjäreborn & Fransson, 2016).

An extensive emissions-monitoring program showed that the boiler could operate with lower CO and NOX emissions than when firing heavy fuel oil, and that the electrostatic precipitator could operate better than when firing fuel oil to reduce particle emissions, although the dust content was higher before the precipitator.

The test was carried out during three days and there were no significant operational problems encountered. The flue gas flow was slightly larger than when firing heavy fuel oil and the mass flow of fuel larger than when firing fuel oil due to the lower heating value of the bio-oil.

In the assessment it was pointed out that all materials that may come in contact with the pyrolysis oil need to be corrosion-resistant because of the low pH of the oil (about 2.8).

5.1.4 Specifications and standards

Since fast pyrolysis oil is already used as a fuel product in several markets, there have been collaborative efforts between producers and users to define standards. There are currently two standards in use:

- ASTM D7544 Standard Specification for Pyrolysis Liquid Biofuel, which defines the specifications heating value, water content, viscosity, density, flash point, pour point, sulfur content and ash content.
- EN 16900 Fast pyrolysis bio-oils for industrial boilers - requirements and test methods (Swedish standard SS-EN 16900:2017). In addition to the specification in the ASTM standard, the Na, K, Ca, Mg, N contents are specified.

Fast pyrolysis oils can have a water content of 20-35 %, which contributes to the relatively low heating value (typically 13-18 MJ/kg) and high density (about 1200 kg/m3) compared to mineral oils. The organic content of the fast pyrolysis oils consists of a multitude of components, including light fractions such as acids, aldehydes, ketones and sugars, but also lignin structures of both high and low molecular weight, in addition to extractives such as fatty acids. All in all, this makes fast pyrolysis oils sensitive to aging and phase separation.

Standards do not encompass HTL-type oils yet, but typically the HTL products have higher heating value and lower water and oxygen content than the fast pyrolysis oils.

5.2 ROUTES TO INTRODUCE PYROLYSIS AND HTL OILS IN AN OIL REFINERY

The bio-oil production technologies described in this report give substantially different products and will therefore require more or less upgrading in a refinery, if that is the route which is chosen to make a transportation fuel that can be blended into the gasoline or diesel pool. From the perspective of the oil refinery these oils can be handled as various types of “bio-crudes” that may be co-processed with conventional crude oil.

Routes that are discussed for introduction of bio-crudes in conventional oil refineries include:

- Hydrotreatment/Hydrodeoxygenation
- Hydrocracking
- Fluid Catalytic Cracking

The direct hydrotreatment and hydrodeoxygenation is also a possible path for conversion of the bio-crudes. The integrated hydropyrolysis process described in the previous chapter (IH²) is an example of a process that incorporates these steps inside the concept. Conversion of fast pyrolysis bio-crudes has been directed more at finding ways of co-processing.

5.2.1 Hydrogenation of fast pyrolysis oils and HTL oils

The relatively recent industrial and commercial breakthrough of producing HVO (Hydrogenated Vegetable Oil)-diesel products from fats and fatty acids has been achieved through modifications of the type of hydrotreaters used for desulfurization in most oil refineries. By reengineering these, e.g. to accommodate the heat released from more exothermic reactions, it has been possible to design processes that remove the oxygen contained in triglyceride feedstocks and at the same time saturate unsaturated hydrocarbon chains to make diesel components.

Using the same type of hydrotreatment or hydrodeoxygenation (HDO) on pyrolysis or HTL oils is more challenging since they (especially pyrolysis oils), contain much more oxygen than the feedstocks used for HVO production. The amount of hydrogen required is then considerably higher.

This route has been investigated e.g. by Routray et al (2017), using a two stage-concept with mild hydrotreatment at relatively low temperature as a first step to treat low-molecular weight components, followed by a more severe treatment at higher temperature to treat higher molecular weight components. A common challenge is the coking that takes place on the catalyst leading to deactivation and plugging of catalyst beds.

Sauvanaud et al (2017) examined the co-processing of lignocellulosic bio-crude with petroleum gas oils in lab scale at 350° C and 70 bar. The HTL oil used was obtained from Licella using pine wood chips as the raw material. Mixtures of up to 20 % bio-crude and 80 % Straight Run Gas Oil (SRGO) were evaluated. Almost complete deoxygenation was possible using a distilled fraction of the bio-crude that contained approximately 12 % oxygen. The researchers did not use the entire HTL oil fraction, however, only the lighter fraction after distillation.

PNNL and VTT assessed the economics of fast pyrolysis and HTL routes followed by hydrodeoxygenation (Tews et al, 2014). They advocate a mild hydrotreatment (at about 140° C) as a first stage and a more severe hydrodeoxygenation and hydrocracking stage (at about 420 °C) as a second stage. The first stage uses a ruthenium catalyst and the second stage a molybdenum catalyst. PNNL and VTT use the term "deep stabilization" to describe the first stage. The overall mass and energy yields for the two routes are given below.

Table 1. Efficiencies for the Fast Pyrolysis and HTL routes when hydrotreatment/hydrodeoxygenation was used for the conversion from bio-oil to hydrocarbons (Tews et al, 2014).

	FP & Upgrading	HTL & Upgrading
Total energy efficiency to product, LHV	50	57
Product mass yield, % dry feed	24	27

5.2.2 Fluid catalytic cracking of fast pyrolysis oils

A possible route to finished hydrocarbons from the bio-oils produced in the fast pyrolysis processes is through co-processing with mineral oils in a fluid catalytic cracker (FCC). The FCC unit operation is a part of most oil refineries and is used for cracking of one of the heavier fractions of the distilled crude oil, usually called vacuum gas oil (VGO). It consists mainly of components with a boiling point higher than 340°C.

The main desired product from the fluid catalytic cracker is naphtha that can be used as gasoline components. Other products are light gases, mainly C3 and C4, and a light cycle oil (LCO). By co-processing pyrolysis oil with VGO, a considerable part of the pyrolysis oil will be converted to gasoline components.

Pinho *et al.* (2017) studied extensively the co-processing of pyrolysis oil with VGO in a 200 kg/h demonstration plant operated by Petrobras. They concluded that at 5% and 10% co-processing (by mass) with VGO the product mix of the FCC would be largely unaffected, producing the same amounts of gasoline and diesel components as when VGO was processed alone. Gas yields shifted so that there were more unsaturated and less saturated C3/C4 gases. Oxygen in the pyrolysis oil was converted to CO, CO_2 and water.

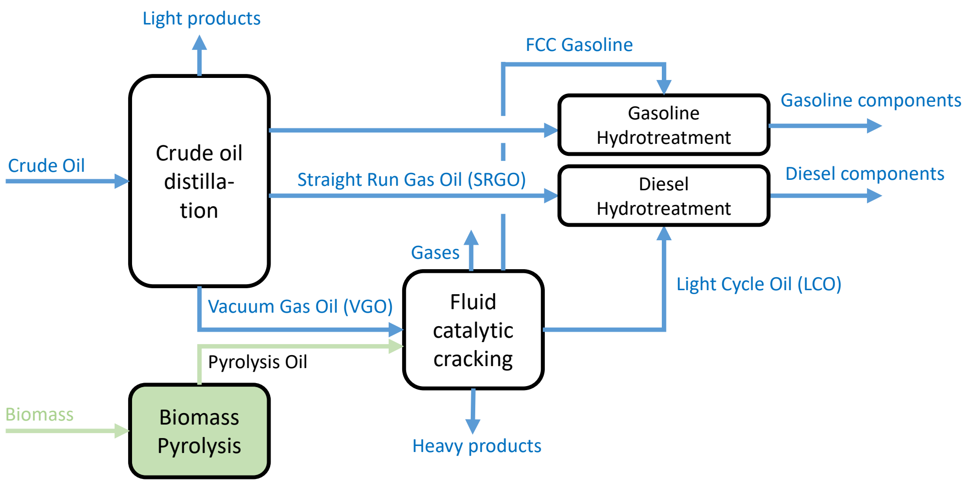

Figure 12. Simplified flow diagram describing the FCC co-processing route for pyrolysis oils in an oil refinery.

6 Techno-economic assessment

6.1 EARLIER STUDIES

In a study performed by Anheden et al (2017) fast pyrolysis was compared with the emerging new technologies as hydropyrolysis and hydrothermal liquefaction (HTL). As already mentioned, both hydropyrolysis and HTL give a bio crudes with lower oxygen content which are favored in the upgrading step where hydrogen will be used to get a bio-crude that can be used in an oil refinery. The amount of hydrogen used will give rise both to operation cost and CO_2 emissions, depending on how it has been produced. The amount of hydrogen needed is therefore an important parameter to keep track of.

Anheden et al showed that the production cost for transportation fuel components from fast pyrolysis is about 100 EUR/MWh (or 0.9 EUR/l), where the largest contribution to the cost is the raw material, in this case forestry residues (~35%) and intermediate conversion and upgrading (~30%).

In the same way, the production cost for hydropyrolysis and HTL was about 65 EUR/MWh (or 0.6 EUR/l). This means that the production cost could compete with the price on the European spot market in 2016, which was in the range of 82-100 EUR/MWh. The cost is also lower than the 122-127 EUR/MWh reported production cost for Swedish suppliers of biofuels according to data submitted in 2016 to the Swedish Energy Agency by biofuel producers (Anheden et al, 2017).

These results were based on forestry residues as feedstock and a production capacity of 100 000 tonnes gasoline and diesel components/yr. The data used was for fast pyrolysis "Pyr-FR" based on BTG-BTL technology, hydropyrolysis "Hydro-Pyr-FR" based on the IH^2 technology (GTI) and for hydrothermal liquefaction "HTL-FR" based on data from PNNL (Pacific North West National Laboratories). For the upgrading of the bio-crude that comes out of the pyrolysis and HTL processes hydrotreating and hydrocracking are assumed to be applied.

Table 2. Overview of total investment of the different value chains for production of 100 000 t/y gasoline and diesel components (Anheden et al, 2017)

		Pyr-FR	HydroPyr-FR	HydroPyr-FR	HTL-FR
Intermediate production	MEUR	200*	87	230	110
Intermediate conversion & upgrading	MEUR	150	0	0	98
Total investment	**MEUR**	**350**	**87**	**230**	**210**

***Three parallel plants for conversion to bio-oil.**

Looking also at the operation cost with the same assumptions as mentioned above the production cost [EUR/MWh] is showed in Figure 13 below

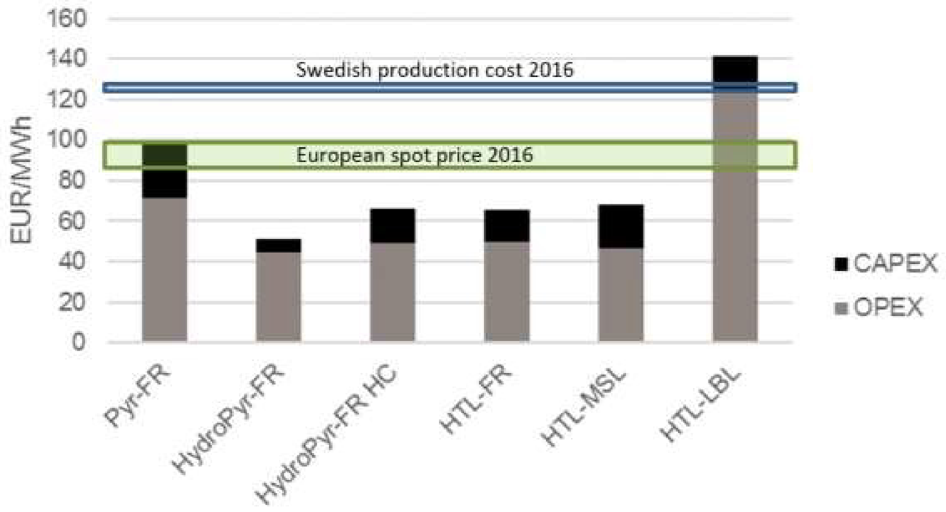

Figure 13. Total value chain production cost, including contribution of OPEX and CAPEX in EUR/MWh transportation fuel. The blue area indicates the reported biofuel production cost for ethanol and HVO for Swedish suppliers (2016), while the green area represents the yearly average spot price (ARA, FOB) on the European market in 2016 (Anheden et al, 2017)

It should be pointed out that the economic data (operation and investment cost) used for hydropyrolysis and HTL processes are not proved at the same technology readiness level as is the case for fast pyrolysis. For the hydropyrolysis 2 different levels were shown, our guess is that the higher level is the most realistic one. (HTL-MSL and HTL-LBL are using lignin as feedstock and therefore not further discussed in this study).

Benjaminson et al (2013) has made a comparison between stand-alone pyrolysis plants and pyrolysis plants integrated with CHP plants or pulp mills. A production cost for the pyrolysis oil in the range 380-580 SEK/MWh was reported. The technologies included were BTG-BTL, Envergent and Metso (nowadays Valmet). It was only the BTG-BTL process that was evaluated as a stand-alone plant while all three of them were evaluated integrated with CHP plant ("KVV") or a pulp mill ("massabruk").

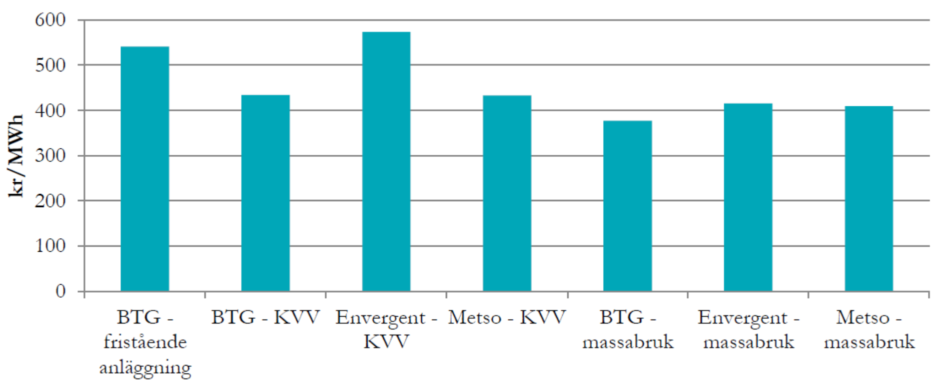

Figure 14. Production cost for pyrolysis stand-alone plant or integrated with CHP or pulp mill. (Benjaminsson, 2013)

6.2 CASE STUDY –ROTTNEROS

As a case study for a pyrolysis facility the site in Värmland where Rottneros has one of their pulp mills has been looked further into.

The location is shown on the map below. The location is good for transports on roads. There is also a rail road with access to the mill.

Figure 15. The location of Rottneros mill in the county of Värmland in Sweden.

The mill produces mechanical pulp at a capacity of about 170 000 tonnes/year. The location of this mill is good from a raw material point of view since there are several saw mills in the surroundings and also forestry residues available nearby. At the site there is also free space where a new production facility could be built.

<u>Assumptions</u>

- The plant is based on one of the technologies for fast pyrolysis, e.g. BTG-BTL or Envergent
- Saw dust is used as raw material at a cost of 150-200 SEK/MWh and available in a radius of 20-100 km
- The production capacity is 25 000 tonnes bio-oil/year. This size is based on the raw material that has been estimated to be available at a reasonable distance and also a size that the process suppliers are ready to deliver with process guarantees.
- Business case based on replacement of fuel oil in short to medium term, assumed price about 650-750 SEK/MWh (Replacement of fossil oil for transportation fuel production will probably give a higher value)
- The investment including site preparation is estimated to about 300-400 MSEK
- The production facility is assumed to have a 15 years life time.

6.2.1 Economy of scale

A 25 000 tonne per year plant would have a production cost on the order of 600 SEK/MWh. Due to the economy of scale, the production cost would be expected to decrease significantly and it should be able to reach a production cost of about 400 SEK/MWh with a 100 000 tonne per year plant. In the short term, with the still low commercial maturity of the technology and market, such a plant would however incur a significant technical and market risk. Figure 16 illustrates the economy of scale based on relatively simple assumptions, e.g. that the feedstock cost will increase from about 150 SEK/MWh to about 200 SEK/MWh as the scale increases. A larger plant may have higher specific feedstock costs due to the longer distances of transporting the raw material, but will also have more purchasing power, which could work in the other direction.

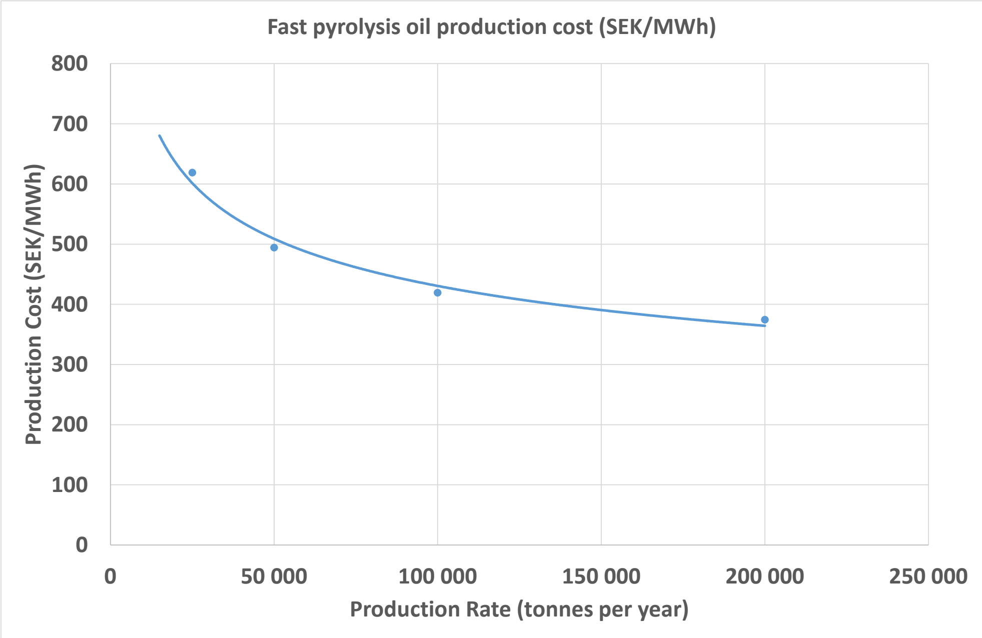

Figure 16. Estimated production cost for the pyrolysis oil expressed on energy basis (SEK/MWh in the product). 150-200 SEK/MWh for the feedstock. Annuity factor 0.1 and capex scaled with an exponent of 0.6.

6.2.2 Profitability

The potential economy of scale will make it attractive for an investor to add on capacity later as the technology and markets mature. While a 25 000 tonnes per year plant would probably require public co-funding, a 50 000 or 100 000 tonnes per year plant should bring returns that are attractive for industrial investors and would open possibilities for conventional capital funding.

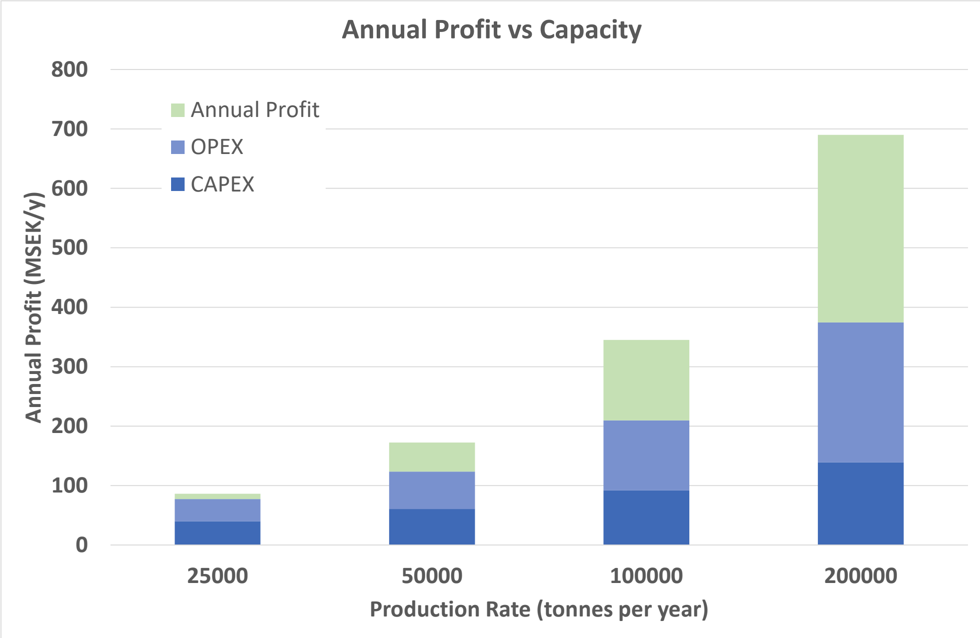

Figure 17. The potential profit for plants of different sizes, given the assumptions of raw material and product cost listed above (150 – 200 SEK/MWh for the feedstock, 650 SEK/MWh for the bio-oil). Annuity factor 0.1 and capex scaled with an exponent of 0.6.

7 Swedish potential for bio-oil production

7.1.1 Scenario description

For the base scenario we have assumed that the investments will only take place in fast pyrolysis plants in the 2020-2030 time frame, and that these facilities would produce a biocrude of a quality that would allow co-processing in a FCC unit of a conventional oil refinery.

We have assumed that a first plant can start up in 2021 and a second one in 2022, each producing 25 000 tonnes per year of bio-crude.

We have then assumed that expansion of the existing facilities, or investment in new facilities, could take place in steps 2024-2025, resulting in added capacity of 50, 100 and 200 000 tonnes per year, respectively.

In the second half of the decade further expansion could take place, and more sites added, resulting in a total production of bio-crude of 100 000 tonnes per year.

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	
Site 1	25			50			100				175
Site 2		25			100			100			225
Site 3					100				100		200
Site 4						100				200	300
Site 5							100				100
											1000

Figure 18. Illustration of a scenario for bio-crude production via fast pyrolysis, where investments take place in steps at a number of sites in the period 2020-2030. The numbers represent the assumed capacity for bio-crude production taken into operation in a specific year.

7.1.2 Production potential in the 2020-2030 time frame

Assuming that the first two plants will need to operate for 1-2 years before further investments are made, the production potential will be limited to about 50 000 tonnes of bio-crude per year until 2023. With more confidence in the technology and an established market, it is expected that more investors and industrial players would become involved, taking the total production of bio-crude to 1 million tonnes per year.

7.1.3 Potential to replace fossil fuels

Assuming that the mass yield from bio-crude to gasoline and diesel components would be about 30%, the production capacity in 2030 could correspond to about 300 000 tonnes of biofuel blended into transportation fuels, equivalent to approximately 3 TWh/year.

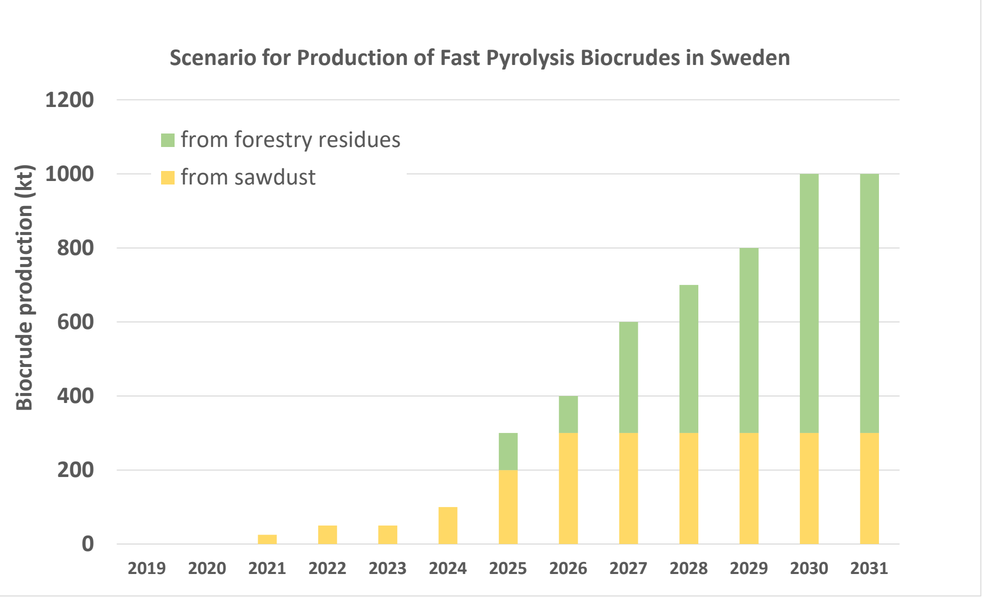

Figure 19. A scenario estimating the amount of fast pyrolysis bio-crudes that could be produced in the 2020-2030 time frame.

7.1.4 Feedstock required

With the assumptions above the total consumption of saw dust would be about 400 000 dry tonnes per year and the consumption of forestry residues about 1 000 000 dry tonnes per year, corresponding to about 2 TWh/year and 5 TWh/year respectively.

7.1.5 Required investments

The total investment in the base scenario would be on the order of 10 billion SEK in the pyrolysis plants, assuming that the plants are built according to the staged scenario in Figure 18. Although this is a substantial total investment, it is by no means extraordinary in comparison with investments in e.g. wind power and combined heat and power over 10-year periods of time.

Investments in the oil refineries will be relatively limited in the short term, if the FCC co-processing route is chosen as the first path to introduce biocrudes. With HDO processing the investments in the oil refinery could be estimated to be on the order of 5 billion SEK based on the information in Chapter 6, Table 2.

7.1.6 Potential for co-processing in Swedish refineries

The FCC route for co-processing may be the most attractive solution in the near term, since it is technically less challenging than hydrotreating and hydrodeoxygenation and does not require an external source of hydrogen.

The FCC capacity in Sweden today is about 1.8 million tonnes per year, with Vacuum Gas Oil (VGO) being the primary feedstock. With 10% co-processing of pyrolysis oil, the total amount of pyrolysis oil that could be processed per year is about 180 000 tonnes, and at 20% co-processing about 360 000 tonnes per year.

Pyrolysis oil produced in Sweden could of course be processed in other European refineries and the product sold back to Sweden, if the goal is to reduce the CO_2 emissions from the Swedish transport sector *per se*. The total FCC capacity in the Nordic countries is 8.2 million tonnes per year, and in Northwestern Europe (Belgium, Netherlands, France, Germany, UK) it is about 68.2 milllion tonnes per year (MathPro, 2015). A 10% co-processing rate would thus allow up to eight million tonnes of biocrude per year to be processed.

7.1.7 Other scenarios

In an advanced scenario there will be investments also in industrial plants that produce a partly refined and more concentrated bio-crude, e.g. through hydrothermal liquefaction, integrated hydropyrolysis, or catalytically assisted fast pyrolysis. If these technologies become fully commercial in the first half of the decade, it is conceivable that some of the fast pyrolysis plants in the scenario would be replaced by these technologies. This would increase the amount of biofuel that could be produced by at least 15% compared to the scenario above, maybe leading to a realistic potential of up to 4 TWh/year. More importantly, these technologies could lead to a more rapid substitution of fossil fuels through higher blending rates.

8 Roadmap to develop the value chain

8.1 THE VALUE CHAIN

A business model for the entire value chain is of course crucial whether there will be investments in pyrolysis- or HTL plants or not. The value chain contains a number of actors dependent on each other which is of course a challenge. They can in some parts of the value chain be relatively unaware of each other's prerequisites if they are more than about two steps apart from each other in the chain.

It is important to identify what costs that actors in the value chain will be able to affect, these are for example raw materials costs, operating costs, investment costs and transportation/ distribution costs.

For example, trying to optimize the raw material by looking both at the price (low-cost) and the yield to bio-oil (often rather clean raw material is needed for high yields). It is also important to keep the transportation cost for the raw material down, it should therefore be retrieved relatively close to the plant.

Integration possibilities with an already existing site can also keep the costs down, for example if there already is a good logistic system in place. To some extent the same personnel such as process operators might be used in both the facilities. Some administration functions might also be in common for the existing facility and the new one. This will however be site specific and also dependent on the set up for the new facility, if it will be owned by a separate company etc. On the revenue side, it is primarily the value of the main product and the co-products that can be influenced. It can be about increasing the value beyond the actual product through maybe upgrade it a bit further at the facility, or identifying new markets to process co-products or by-products. In some of the process concepts described above steam is a by-product and in that case it is of high importance for the total economy to look at possible users of this heat located nearby the bio-oil plant, especially at the larger facilities.

External factors that can be influenced may be linked to social development, for example, increased benefits through more jobs and the environmental benefit of reduced emissions of climate-affecting gases. Economic incentives and other policies decided politically belong to this category.

These are all aspects that should be taken into account when finding the right actors that could be part of this new value chain.

An example of what the value chain could look like is shown in Figure 22 below.

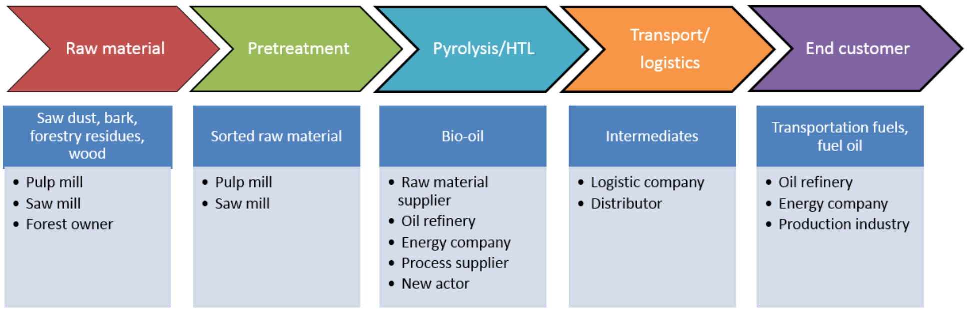

Figure 22. The suggested value chain with different actors in each stage

8.2 ROADMAP 2020-2030

In order to meet the type of scenario that is described in Chapter 7, a number of parallel activities need to take place in the 2020-2030 time frame. The development is summarized in a roadmap in Figure 23, where we have listed activities related to market development, technology development and the development of actual investment projects.

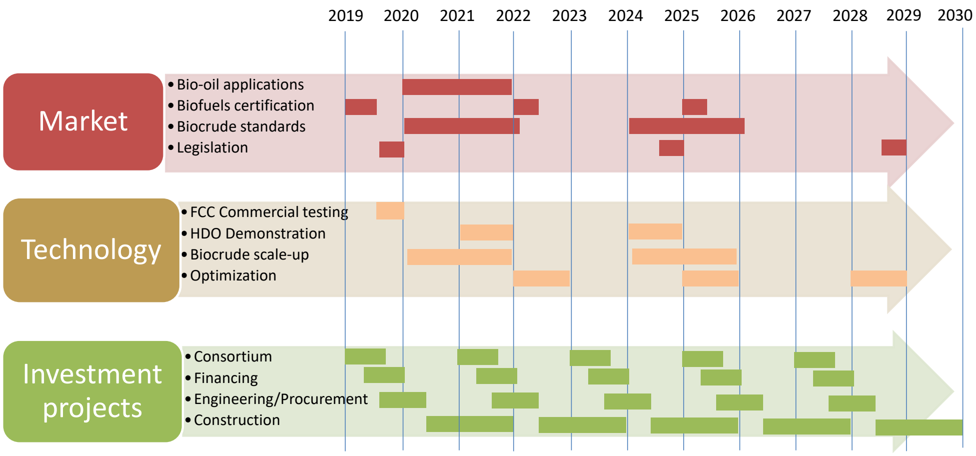

Figure 23. Roadmap for commercial development in Sweden of transport biofuels production via biocrudes.

8.2.1 Market development

Activities related to market development that can be pointed out:

- Current use of fast pyrolysis oil outside Sweden is mainly for heating applications. Moving forward with tests and establishing a market for this type of bio-oils in Sweden is probably a good measure to make industrial actors more comfortable in having an offtake possibility in a market segment with many small and medium-sized actors. Production of biofuels for transportation will rely on a market with fewer but larger actors.
- A requirement for the co-processing of bio-oils or biocrudes in oil refineries is that the product can be sold to the market that is regulated in the way that reduced carbon dioxide emissions have a high value. The products then need to be certified in relation to the requirements in the updated Renewable Energy

Directive ("RED II"), and the Swedish legislation for sustainability of biofuels. The certification process takes time and needs to be repeated for different feedstocks and production processes. Since the value of the product is strongly related to the certification, the process needs to be dealt with at an early stage.

- As the market for bio-oils and biocrudes develops, there will be more actors, suppliers, distributors and users. Efficient trading in this market will benefit from standardization of the products. Fast pyrolysis oils are already covered by some standards as discussed in Chapter 5, but HTL oils are not yet standardized; neither are fast pyrolysis or other biocrudes. Since biocrude specifications are expected to be much more stringent for metals content, for example, there will be benefits in developing standards also for these.
- Legislation in the biofuels area is still very much evolving, and it will be necessary for actors in the bio-oil and biocrude market to be active in communicating with policy makers and following political discussion that takes place, e.g. in connection with the proposed revisions of the Renewable Energy Directive.
- With the new incentives there will be renewed interest also in other biomass-to-transportation fuel value chains, based for example on gasification, lignin extraction, cellulosic ethanol and biogas production. Possibilities to compete or collaborate to utilize synergies with these will be important to consider.

8.2.2 Technology development

Although some parts of the technology to be used in the bio-oil and biocrude value chain are already commercial or close to commercial, in particular the fast pyrolysis processes, there are other parts that need further development:

- The FCC route for co-processing has been demonstrated at small industrial scale and relatively short periods of operation. Although the refinery technology suppliers express that they are confident that co-processing at rates of up to 5-10% will work also at commercial scale, this remains to be proven. In the longer term it would be desirable to increase the co-processing rate, which will require more testing and possibly further development of the technology.
- The HDO technology for co-processing or final processing of biocrudes needs to be developed beyond bench scale. It is possible that this development could be relatively rapid using the experience gained from the hydrogenation processes used for HVO production, but also these will have to be demonstrated at industrial scale. In contrast to the FCC route it is likely that the HDO route will require larger investments in the oil refinery, and it will also increase the demand for hydrogen available at the refinery. Introduction of the HDO technology will therefore require long-term planning and should thus be included in the roadmap.
- The biocrude production processes that are currently reaching demonstration scale, such as HTL and hydropyrolysis, need to be scaled to commercial installations and proven in long-term operation. These processes will be important as blending requirements increase over time, since they hold promise of making it possible to achieve higher substitution rates.
- For all production processes, there will be opportunity for optimization as more experience is gained from commercial operation. Such optimization may

also include adaptation to feedstocks of lower and more heterogeneous quality than what is foreseen for the first plants. It will also be advantageous to identify synergies with other value chains and technologies.

8.2.3 Investment projects

Technology and market development in itself will not lead to any establishment of production. Industrial actors and investors will have to become sufficiently interested in starting investment projects that lead to production in specific sites. Below are listed some of the main activities that need to take place:

- Create a consortium that can a start financing a pre-study and developing a business model that can create stable conditions for making an investment decision.
- A way to handle cost-benefit and risk-opportunity sharing between involved actors must come in place.
- Identify suitable sites where the bio-oil or biocrude production can benefit from existing infrastructure and raw material handling capabilities. Such sites could be connected to, e.g., saw mills, pulp mills and combined heat and power plants.
- Determine where on the site the new plant is to be located (take into account for example routes for transport of raw material in/product out, energy and material integration with the mill, land works etc.
- Identify the possibility of investment support (e.g. government support, regional support, loans or loan guarantees)
- Assess markets and willingness to pay for bio-oil produced from Swedish forest raw materials (fuel companies, energy companies, traders etc.)
- Secure/understand possible access to raw material supply (may be part of the business model)
- Secure/understand the possibility for off-take agreements (may be part of the business model)
- Carry out preparatory work to apply for environmental permits for the new production facility
- In-depth discussions with 2-3 technology suppliers.

A roadmap with milestones for building a pyrolysis plant at the site of the Rottneros mill is shown in Figure 24. It has been estimated to take about 3 years from pre-study to start-up of the plant.

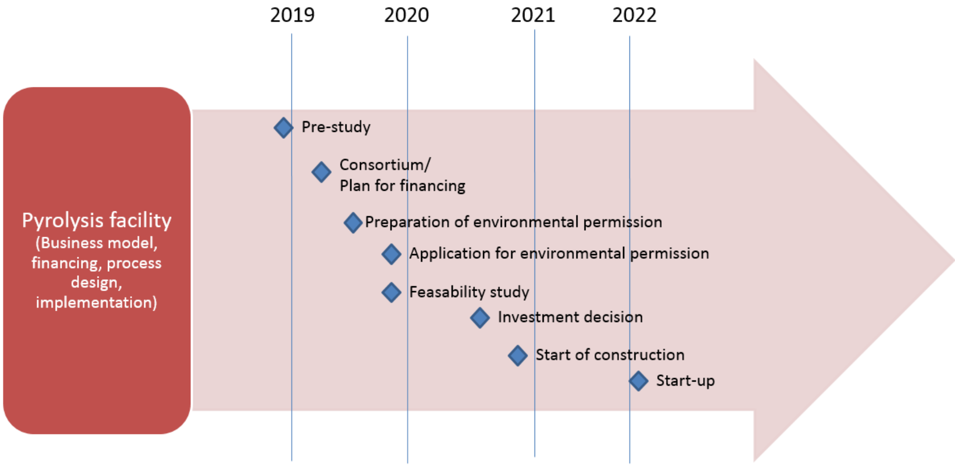

Figure 24. Roadmap for building a pyrolysis plant including the most important milestones connected so such a project.

9 Conclusions

The overall conclusion is that it would be both technically and economically feasible to produce significant volumes of transportation fuels in Sweden via bio-oil in the 2020-2030 time frame.

The technical assessment shows that the front-end processes (converting wood to bio-oil) which are closest to commercial application are the fast pyrolysis processes (TRL 8-9), but also that the hydrothermal liquefaction (HTL) and integrated hydropyrolysis processes (currently TRL 6-7) will be able to have an impact in the studied time frame. The technologies for conversion of bio-oil to transportation fuels are still under development, but can be considered to be at TRL 6-7 for up to 10% co-processing of fast pyrolysis oils in fluidized catalytic crackers (FCC) at existing oil refineries. Hydro-treatment and hydrodeoxygenation (HDO) of fast pyrolysis and HTL oils is at TRL 5.

HDO is a key technology to reach full substitution of fossil fuels with biofuels, but the FCC co-processing route is a good near-term solution that has very low investment requirements in refinery infrastructure and does not require an external source of hydrogen. This seems to be the preferred route in the near term based on input from the technology suppliers.

For early plants, at a scale of about 25 000 tonnes per year, the cost of producing bio-oils will be on the order of 600 SEK/MWh, making it only marginally profitable without some form of investment subsidy. As technology and markets mature, the cost can come down to 400 SEK/MWh in larger facilities (100 000 tonnes/year), and should give attractive returns for industrial investors. These calculations are based on the use of the pyrolysis oil as a replacement for fuel oil. There is most probably an upside in the economics as a result of the emissions reduction obligation system that came into effect in Sweden during 2018 if it instead can be used as biocrude in an oil refinery for transportation fuel production.

In a scenario where there is continuous investment and expansion in bio-oil production plants in the 2020-2030 time frame, it is not unrealistic to expect that the production of bio-oil could reach 1 000 000 tonnes per year by the end of the decade. Conversion of the bio-oil in oil refineries could lead to substitution of fossil transportation fuels on the order of 3 TWh/year. Total investments would be on the order of 10 billion SEK in the bio-oil production plants.

Feedstock would be, e.g., sawdust in the near term, with an increasing share of forestry residues in the longer term. The required feedstock in 2030 could then correspond to about 2 TWh/year of sawdust and 5 TWh/year of forestry residues.

As already mentioned, the market conditions in Sweden for production of bio-based transportation fuels have changed due to the emissions reduction obligation system that came into effect during 2018. This will of course also put other technologies in a new position, such as biomass gasification, black liquor gasification, biogas production, cellulosic ethanol, lignin oil, etc. Possible near-term advantages with pyrolysis technology is that the investments are rather low in comparison with other technologies, it can be built in a fairly small scale and it can handle a variety of feedstock. The biocrude can go in to the existing oil refinery and be further processed to transportation fuels so that no new infrastructure has to come in place for handling of new products. For investors in such a facility it might also reduce the risk if an intermediate product that can go in to the existing supply chain can be produced and not having to take place as a new actor in the transportation fuel market.

In the scenario that we have described where about 1 000 000 tonnes bio-oil can be produced in 2030 the available amount of sawdust is being used but only a rather small amount (10-15%) of forestry residues that potentially could be taken out from the Swedish forests.

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PYROS – ROADMAP FOR REALIZATION OF A VALUE CHAIN FROM FOREST TO BIOFUELS VIA BIO-OIL

The overall conclusion is that it would be both technically and economically feasible to produce significant volumes of transportation fuels in Sweden via bio-oil in the 2020-2030 time frame.

In a scenario where there is continuous investment and expansion in bio-oil production plants in the 2020-2030 time frame, it is not unrealistic to expect that the production of bio-oil could reach 1 000 000 tons per year by the end of the decade. Conversion of the bio-oil in oil refineries could lead to substitution of fossil transportation fuels on the order of 3 TWh/y. Total investments would be on the order of 10 billion SEK in the bio-oil production plants.

The technical assessment shows that the front-end processes of converting wood to bio-oil that is closest to commercial application is the fast pyrolysis processes. But the hydrothermal liquefaction (HTL) and integrated hydro-pyrolysis processes (currently TRL 6-7) will also be able to have an impact in the studied time frame.

The technologies for conversion of bio-oil to transportation fuels are still under development but can be considered to be at TRL 6-7 for up to 10 percent co-processing of fast pyrolysis oils in fluidized catalytic crackers at existing oil refineries. Hydrotreatment and hydrodeoxygenation of fast pyrolysis and HTL oils is at TRL 5.

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