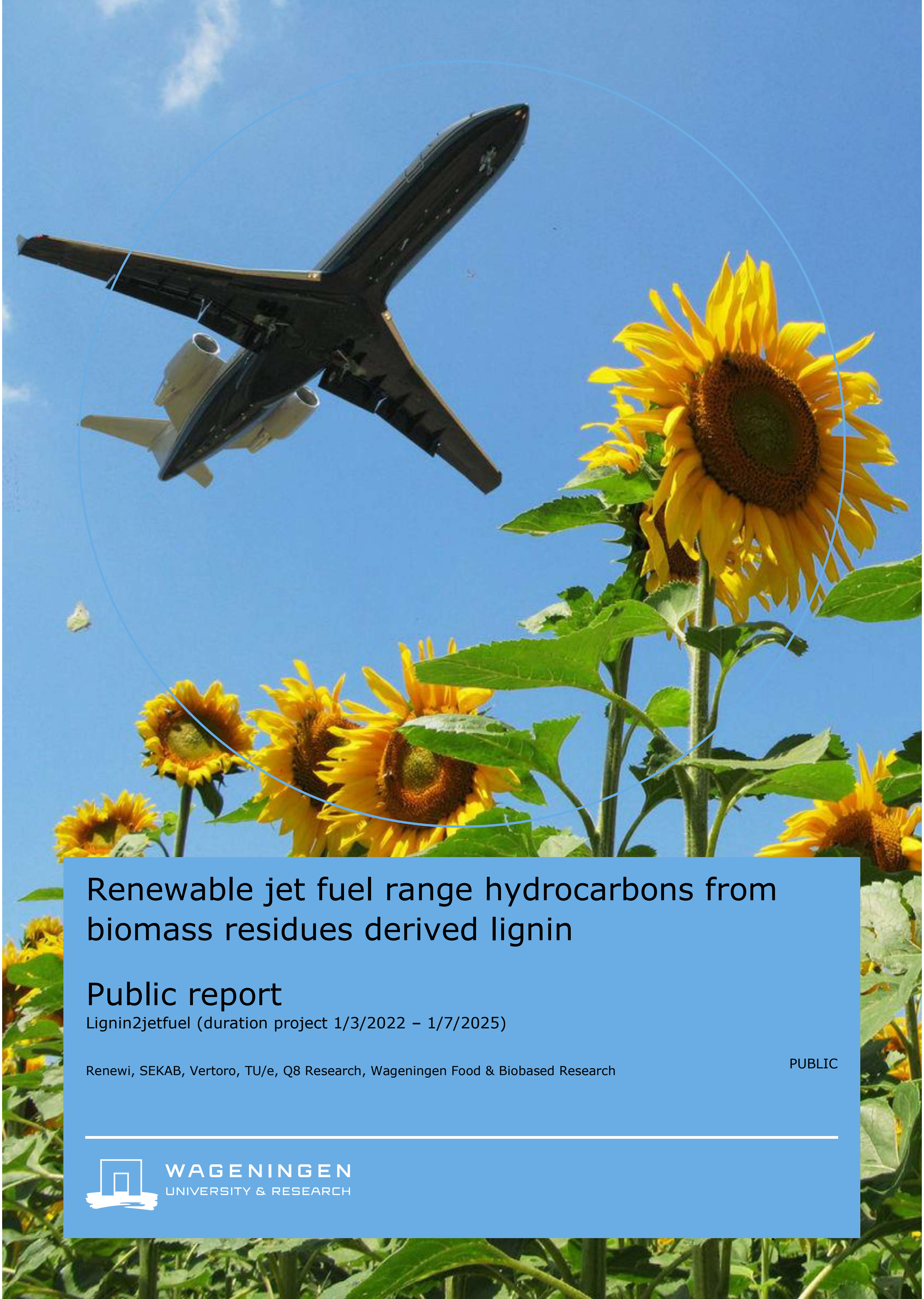

Renewable jet fuel range hydrocarbons from biomass residues derived lignin

Public report

Lignin2jetfuel (duration project 1/3/2022 – 1/7/2025)

Renewi, SEKAB, Vertoro, TU/e, Q8 Research, Wageningen Food & Biobased Research

PUBLIC

WAGENINGEN
UNIVERSITY & RESEARCH

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Authors: Renewi, SEKAB, Vertoro, TU/e, Q8 Research, Wageningen Food & Biobased Research

Institute: Wageningen Food & Biobased Research is coordinator

This study was carried out by the project partners, subsidised and commissioned by the Dutch Ministry of Agriculture, Fisheries, Food Security and Nature via funding provided by RVO.

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PO box 17, 6700 AA Wageningen, The Netherlands, T + 31 (0)317 48 00 84, E info.wfbr@wur.nl, www.wur.eu/wfbr.

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For more information about this project please contact the project coordinator:

Dr. R.J.A. Gosselink, Wageningen Food & Biobased Research
Tel. +31.317.480160 or at richard.gosselink@wur.nl

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken en Klimaat en het Ministerie van Landbouw, Natuur en Voedselkwaliteit, Regeling nationale EZK- en LNV-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

Preface

Project entitled: Renewable jet fuel range hydrocarbons from biomass residues derived lignin (Lignin2jetfuel) was running from 1 March 2022 – 1 July 2025 under projectnumber TIND221009 and supported by a grant from TSE Industry of RVO. This consortium project developed a proof of concept for the conversion of a residual side stream lignin into jetfuel components of aromatic nature. This public report describes the main objectives and achievements from this 3 year project.

Summary

Sustainable aviation fuels (SAF) or jet fuel is currently an important topic as it is expected that for the near future airplanes will continue to use liquid fuels. Conversion of biobased streams into jet fuel is so far limited to hydrotreated vegetable oils, so-called HEFA, but for the aromatic components which are important to achieve the desired jetfuel properties no biobased alternative to kerosine is available. This 3-year project called "Renewable jet fuel range hydrocarbons from biomass residues derived lignin (acronym: Lignin2jetfuel)" delivered a proof of concept for the conversion of technical lignin to aromatic jet fuel range components at TRL3-4. A lot of insights in this process as well as significant learnings were obtained.
Main conclusions are:

- A suitable purified mildly treated lignin stream, containing a high content of β-O-4 ether linkages, is necessary
- The developed catalytic depolymerisation and alkylation process resulted in an efficient and high yield process
- The subsequent HDO process gives a nearly quantitative yield in the desired jet fuel range components of carbon numbers between C8-C16
- Pd/ZrO_2 catalysts showed excellent HDO activity resulting in a high yield. A modified $10WO_3/Pd/ZrO_2$ catalyst exhibited the highest C-C bond cleavage and was further applied to a crude lignin oligomer, producing 13.2 wt% lignin monomers. These findings highlight the critical role of Brønsted acid sites in facilitating C-C bond cleavage during lignin depolymerization.
- Other jet fuel properties still needs to be evaluated
- The overall TEA and LCA needs to be further continued in combination with a sensitivity analysis to optimize the overall economics and environmental benefits, here upstream data is desired and inclusion of realistic aromatic compounds is needed in the modelling. Of the current processing chain at relatively low volume capacity showed that the minimum selling price of lignin derived aromatics is about 2-3x higher compared to sustainable aviation fuel of hydrotreated fatty acids from vegetable oils (HEFA).
- The developed technology steps to convert technical lignin via depolymerization, alkylation and hydrotreatment seems scalable for future perspective

1 Project details

Projectnumber: TIND221009
Project title: Renewable jet fuel range hydrocarbons from biomass residues derived lignin (Lignin2jetfuel)
Coordinator, project partners and role in the project:

Name	**Type of organization**	**Role in the project**
Coordinator: Wageningen Food and Biobased Research (WFBR)	Research organization	Lignin depolymerization and C-alkylation. Optimization of chemo-catalytic routes. Characterization of lignin streams. Techno-economic analysis. Project management, Coordinator, dissemination.
Technical university of Eindhoven (TU/e)	University	Development of new catalysts for the depolymerization and C-alkylation of lignin
Vertoro B.V	Small-Medium Industry	Convert non-edible biomass into a liquid lignin stream rich in phenolic oligomers
Kuwait Petroleum Research and Development BV (KPRT/Q8)	Large Industry	Hydrotreatment of alkylated lignin oil under industrial relevant conditions to produce jet fuel components
Sekab Biofuels & Chemicals (Sweden)	Large Industry	Biomass and lignin supplier together with data on availability
Renewi Nederland B.V	Large Industry	Waste based biomass aggregator, pre-processing (developer), and supplier of lignocellulosic biomass

Projectperiod: 1/03/2022 - 31/07/2025

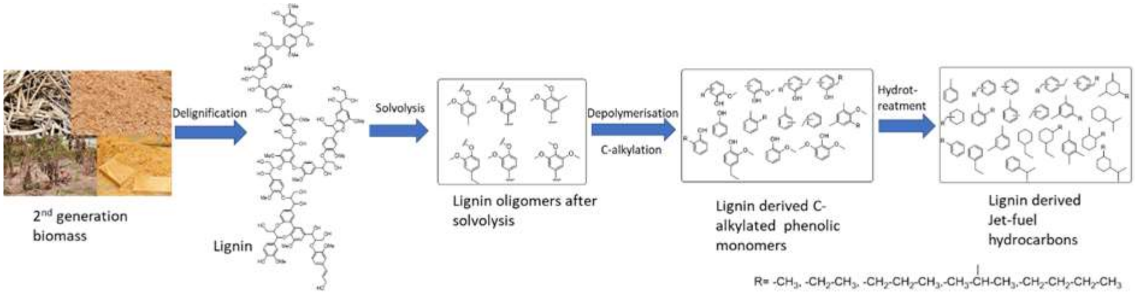
1.1 Problem description and project objective

Problem description

The International Civil Aviation Organization (ICAO) recently introduced global market-based measures to reduce the aviation CO_2 emissions from 2020 onwards. These measures aim to counterbalance any annual increase in the CO_2 emissions from international aviation through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).The European Union (EU) aviation industry that is regulated by EU Emission Trading Scheme (ETS) also aims to further reduce the CO_2 emissions in the coming decades, and under the renewable energy directive (RED), Member States are setting SAF-(sustainable aviation fuel) mandates. Under the agreement, the global aviation emission target is a 50% CO_2 reduction by 2050 compared to 2005. The aviation sector will depend on liquid fuels for many decades. To achieve the emission reduction target, therefore SAF from biomass is considered as an excellent candidate as long as a minimum of 70% greenhouse gas savings is realized. Fundamental research and process development are required to achieve the required quality SAF from various residual non-food biomass resources.

Original objective(s)

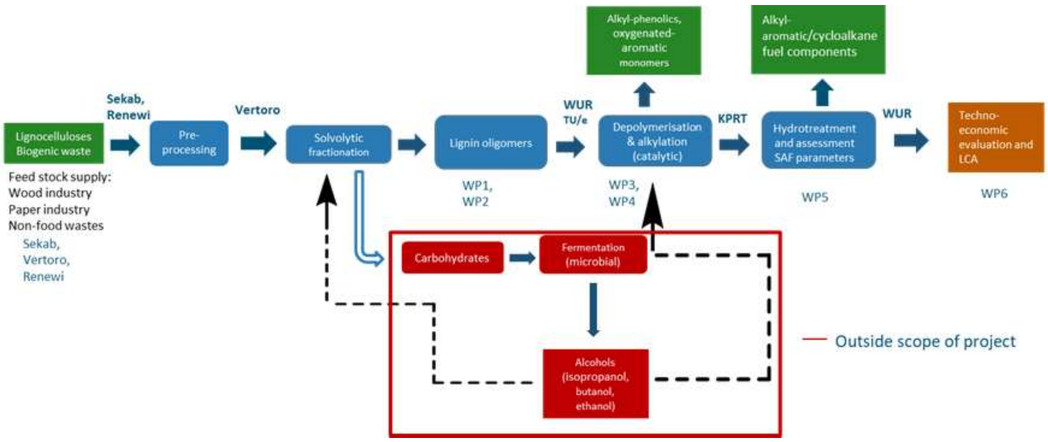
This project aims to develop a proof of concept (TRL 3-4) scalable technology to produce **jet fuel components;** oxygen free- **alkyl aromatics** and **cycloalkanes from** 2nd generation lignocellulose derived **lignin**. See scheme hereafter:



A further aim is to create new value chains and to demonstrate the attractiveness of the new to be developed sustainable technology-via techno-economic and life cycle analysis.

- To this date, efforts to produce jet fuel components from bio-renewable sources succeeded in producing n-and iso- paraffins, without any alkyl aromatics or cyclo-paraffins. Such cycloalkanes or alkyl aromatics and minor oxygen containing (phenolic) additives are required for compatibility with gaskets in the jet engines. Consequently, the bio-based paraffinic jet fuel components needed to be blended with petroleum-based alkyl aromatic/cycloalkane components at the risk of enhanced CO_2 emission. Thus, our proposal may offer a biobased and sustainable solution for the necessary aromatic/cycloalkanes and a possibility to produce a 100% bio-based jet-fuel with a more favorable reduced CO_2 footprint.

Sekab and Renewi will supply purified biomass and lignin. Vertoro will fractionate the biomass into carbohydrate and lignin oligomers. WFBR and TU/e will perform depolymerization of lignin oligomers and subsequent C-alkylation to produce monomeric alkyl-phenolic components. Depolymerization/alkylation of lignin stream will be further upscaled at WFBR/Vertoro. KPRT(Q8) will perform catalytic hydrotreatment of alkylated phenolic monomers. Product stream will be assed for suitability as jet fuel components by KPRT (Q8) and TU/e. Additionally LCA/TEA analysis will be performed at WFBR to compare the developed technology to the existing technology (see scheme hereafter).


Lignocelluloses
Biogenic waste
Feed stock supply:
Wood industry
Paper industry
Non-food wastes
Sekab,
Vertoro,
Renewi
Sekab,
Renewi
Pre-
processing
Vertoro
Solvolytic
fractionation
Lignin oligomers
WP1,
WP2
WUR
TU/e
Depolymerisation
& alkylation
(catalytic)
WP3,
WP4
Alkyl-phenolics,
oxygenated-
aromatic
monomers
KPRT
Hydrotreatment
and assessment
SAF parameters
WP5
Alkyl-
aromatic/cycloalkane
fuel components
WUR
Techno-
economic
evaluation and
LCA
WP6
Carbohydrates
Fermentation
(microbial)
Alcohols
(isopropanol,
butanol,
ethanol)
Outside scope of project

2 Project achievements and perspective for application

2.1 WP1-2 Feedstock selection, characterisation, solvolysis

In this project both relevant and regional available lignocellulosic feedstocks were organised via the project partners and tested on their suitability for conversion into aromatic jetfuel components. Next to that isolated lignin sources were used in this process to enhance the aromatic lignin oil yield.
Starting from wood (spruce saw dust) or tomato stems the resulting aromatic lignin oil after the solvolysis process has a low yield and contains a relatively high content of carbohydrates. The molar mass distribution of the obtained crude lignin oils are in the range of oligomeric aromatic structures. These oils could be further separated into carbohydrate-rich and lignin-rich streams through various processing means, with the latter being primarily considered for further valorization towards jetfuel constituents in this project. Since catalytic depolymerization utilizes butanol or hexanol solvents, the liquid-liquid separation was attempted using these solvents, ultimately avoiding the need of solvent removal after fractionation if successful and thus of huge techno-economical impact. Using butanol works fine.
Vertoro also received several lignocellulosic biomass feedstocks (woody biomass, lignin, and agricultural residues), analyzed them for their composition as well for the determination of imputies (ash, inorganics) and finally subbjected them to the its proprietery Crude Lignin Oil (CLO®) process. The resulted CLO® samples were analysed in joint collaboration with WFBR and were distributed to partners for downstream catalytic depolymerization.
Spruce and birch lignins obtained after steam explosion and enzymatic hydrolysis performed at Sekab's Biorefinery Demo Plant were less suitable for this process as they contain a relatively low content of ether linkages (<12 β-O-4 aryl ethers per 100 aromatic rings). Research showed that because of the absence of a high content of ether linkages, depolymerisation will hardly takes place.
Pressed tomato stems and waste wood contained a relatively high content of impurities, such as ashes (9 and 27 wt% respectively), and are considered as less suitable for the solvolysis process and subsequent catalytic conversion into jetfuel components via the developed technology. These ashes should be completely removed prior to the catalytic conversions steps to avoid catalyst deterioration.
Catalytic conversion of lignin via depolymerisation and alkylation into the desired alkyl carbon chain length for jetfuel application (C8-C16) works best for a mildly isolated herbaceous lignin containing a high content of β-O-4 ether linkages (about 34 β-O-4 aryl ethers per 100 aromatic rings). This lignin was purified at a high yield with solvent fractionation to remove all ashes and obtain a molar mass of medium size and reduced dispersity.

This work showed that the selection of a suitable mildly treated lignin is preferred compared to more condensed lignins with less containing ether linkages. Solvolysis of lignocellulosic biomass leads to crude lignin oils which contain a relatively high content of sugar derivatives. These latter needs to be removed to obtain the desired aromatic components for jet-fuel application. Other impurities like ashes needs to be removed as they can interfere with the solvolysis or catalytic conversion steps.

2.2 WP3-4 Depolymerisation and alkylation of lignin

For efficient alkylation of lignin with n-butanol as solvent and alkylation agent a post-modified zeolite catalyst is needed. The introduction of mesoporosity facilitates the diffusion of bulky guaiacol molecules into the pore system, where C-alkylation occurs in the presence of the zeolite's porous acid functionality as confirmed by model compound catalysis. Quantitative yields of lignin oil, predominantly composed of monomers and dimers with some oligomers, were obtained. Alkyl-substituted phenolics and di-aryl phenolics were the main components, with phenolic monomers and dimers yielding approximately 80 wt.%. The lignin oil was

depolymerized as shown by lower values for molecular weight and dispersity compared to the lignin feed, thus confirming substantial lignin depolymerization.
Characterisation of the alkylated lignin oil showed that around 60% of the lignin oil constituents falls within the desired range (C8-C16) for jet fuel components.
Analysis of the used catalyst showed that most of the surface area and porosity of the used zeolite catalyst were recovered through thermal regeneration. Analysis indicated that the palladium particles did not undergo sintering, and no leaching of palladium species from the catalyst occurs, allowing re-use of the catalyst.

In the TU/e's study, a series of Pd/ZrO_2 catalysts were developed and evaluated for the hydrodeoxygenation (HDO) and carbon-carbon (C-C) bond cleavage of lignin model compounds. A high-surface-area Pd/ZrO_2 catalyst, synthesized via flame spray pyrolysis, demonstrated excellent HDO activity in a fixed-bed reactor, converting 4-propylguaiacol and 4-propylsyringol to oxygen-free products with over 84 mol% yield, primarily propylcyclohexane (jet fuel range). To enable C-C bond cleavage, the Pd/ZrO_2 catalyst was modified with H_3PO_4 or WO_3, introducing Brønsted acidity. Among these, $10WO_3/Pd/ZrO_2$ exhibited the highest performance in a batch reactor, achieving a 47.8 mol% yield of C_6 monomers (cyclohexane and methylcyclopentane) from biphenol. The optimized catalyst was further applied to the catalytic hydrotreatment of a crude lignin oligomer, producing 13.2 wt% lignin monomers—significantly higher than the parent Pd/ZrO_2 catalyst. These findings highlight the critical role of Brønsted acid sites in facilitating C-C bond cleavage during lignin depolymerization.

In order to produce enough depolymerized and alkylated lignin oil for the final hydrotreatment step, a palladium (Pd) supported acidic mesoporous zeolite catalyst was employed for the depolymerization reaction. In each run, 50g of herbaceous lignin was depolymerized in 400mL of n-butanol, with 5g of the Pd/mesoporous zeolite catalyst. The reaction was conducted at 250°C and 15 bars for 6 hours, after which the catalyst was separated and the n-butanol solvent was removed by rotary evaporation. The process was repeated three times resulting in a sufficient quantity of lignin oil. Quantitative yields of this lignin oil were obtained.

Figure 1 Picture of the first lignin oil sample obtained by catalytic depolymerization and C-alkylation of herbaceous lignin

2.3 WP5 Hydrotreatment and product evaluation of novel advanced lignin-based fuels

The objective of this workpackage was to obtain a proof of concept for the selective formation of jet-fuel-range precursors from depolymerized and C-alkylated lignin oil via deoxygenation and condensation using a catalytic process.

Firstly, hydrotreatment reactions were performed in a 75mL Parr reactor at 250°C with hydrogen at 15 bars. Typically, a lignin monomer (2mmol) was mixed with *n*-butanol (20mL) and the zeolite catalyst. When lignin oil was used as a feed, 2g of lignin oil was dissolved in the solvent and subsequently mixed with the catalyst. The reactor was sealed and flushed with nitrogen and finally pressurized with before heated. Alternatively, lignin oil hydrotreatment was performed under solvent-free conditions. In a typical reaction, 15 mL of lignin oil and 5g of catalyst were transferred to a 75 mL Parr reactor. Product analysis was performed by GC-MS.

2-Methoxy-4-propylphenol has undergone a combined C-alkylation and hydrodeoxygenation, which is indicative of the overall feasibility of the approach. The formation of 3-butyl-2-methoxy-4-propylphenol provides evidence of alkylation, utilizing n-butanol as the reagent. Concurrently with alkylation, the detection of propyl phenol, propyl benzene, and propyl-cyclohexane suggests that hydrodeoxygenation and the reduction of the aromatic hydrocarbon also occurred. Next to that solvent conversion was limited to about 5%.

The hydrotreatment of lignin oil resulted in reactions such as hydrodeoxygenation, C-C coupling, and ring hydrogenation, leading to a high yield and the formation of valuable jet fuel range precursors (see Table 1 below).

Table 1 ***Quantification of various componenets obtained by the hydrotratment of lignin oil***

	C_8-C_{11}	**C_{12}-C_{16}**	**C_{17} and above**	**Dibutyl ether (DBE)**
Product distribution (%)	**38**	**45**	**8**	**5**

Hydrotreatment of lignin oil under solvent free conditions resulted in a high yield with the following product distribution (Table 2):

Table 2 ***Quantification of various componenets obtained by the hydrotreatment of lignin oil***

	C_8-C_{11}	**C_{12}-C_{16}**	**C_{17} and above**	**Dibutyl ether (DBE)**
Product distribution (%)	**41**	**38**	**6**	**5**

Initially, most lignin C–O–C bonds, particularly the β-O-4 linkage, were effectively cleaved through hydrogenolysis (using Pd/zeolite catalysts) or hydrolysis (with acidic zeolite). This depolymerized the bulk lignin polymer into aromatic monomers and dimers. These resulting monomers and dimers subsequently underwent dehydration, demethoxylation, and hydrogenation reactions to remove oxygen and saturate their aromatic rings. Notably, during these oxygen removal and ring hydrogenation processes (hydrotreatment), most of the lignin's C–C bonds remained stable, preserving the bicyclic carbon skeleton structures of the products. Furthermore, some monomers coupled to form dimers. Evidence for condensation reactions was obtained through reference experiments conducted with monomeric compounds. GC-MS analysis of these reactions revealed the formation of dimeric structures, alongside partial deoxygenation and trans-methylation. This demonstrates that C-C coupling, in addition to hydrodeoxygenation, occurs over the heterogeneous acid catalyst.

2.4 Main achievements for lignin conversion to jetfuel components

Our findings demonstrated the successful conversion of lignin, obtained through mild fractionation of herbaceous biomass, into jet-fuel range hydrocarbons via a two-step process involving depolymerization followed by catalytic hydrotreatment. The post-modified zeolite-Y, with its large-pore structure and abundant active acid sites, effectively depolymerized the lignin polymer into monomers and oligomers by selectively breaking C–O–C bonds. Palladium-supported zeolite exhibited significant activity and efficiency in hydrodeoxygenation reactions, providing a synergistic effect for oxygen removal from lignin-derived intermediates. Furthermore, it facilitated the coupling of lignin monomers into dimers through dimerization/alkylation reactions, leading to a diverse range of alkyl cyclohexane species suitable in jet fuel blends. C-alkylation of phenolic monomers derived from lignin can be achieved using alcohols as alkylating agents when mesoporous zeolites are present, a process beneficial for attaining the required carbon number for jet fuel applications.

Pd/ZrO_2 catalysts showed excellent HDO activity resulting in a high yield. A modified $10WO_3/Pd/ZrO_2$ catalyst exhibited the highest C-C bond cleavage and was further applied to a crude lignin oligomer, producing 13.2 wt% lignin monomers. These findings highlight the critical role of Brønsted acid sites in facilitating C-C bond cleavage during lignin depolymerization.

This work showed that a proof-of-concept has been obtained at TRL 3-4 for the efficient conversion of a suitable lignin into the targetted jet-fuel range components of carbon number between C8-C16.

Stakeholders who potentially can upscale this technology consists of a lignin producer, either from the pulp&paper or lignocellulosic biorefinery industries, catalytic convertor via a novel 2-steps technology and a jet fuel blender to obtain the desired sustainable jet fuel mix.

2.5 WP6 Techno-economic and environmental analysis

The objective of WP6 is to assess the economic feasibility and environmental performance of the established Lignin2jet process. Data from the process and partners were obtained and process simulation was performed by using SuperPro Designer v14. The mass and energy balances derived from the process simulation was then used to carry out techno-economic and environmental assessments. Techno-economic analysis is aimed to estimate the capital costs (CAPEX), operational cost (OPEX) and minimum fuel selling price (MFSP) of the novel route when implemented at industrial scale and evaluate the profitability/feasibility. The implementation at industrial scale is simulated using 1 ton/h lignin scale corresponding close to current industrial operation and 10 ton/h lignin scale considering future larger scale operation. Environmental assessment is aimed to assess at cradle-to-gate scope the environmental performance of the value chain and identify hotspots.

- Furthermore, MFSP is calculated setting net present value (NPV) calculation to zero. Sensitivity analysis was performed for the lignin price used as input.
- Environmental assessment: Life Cycle Assessment was performed based on the ISO 14040/14044:2006 and EN 16760:2015 standards for environmental analysis with a cradle-to-gate scope. LCA software SimaPro 9.6.0.1 was used for performing the impact assessment with the CML method. Ecoinvent database was used for the background data.

2.5.1 Techno-economic analysis

Three main process steps were identified as depicted in Figure 1 as: Lignin purification, Catalytic depolymerization and Hydrotreatment.

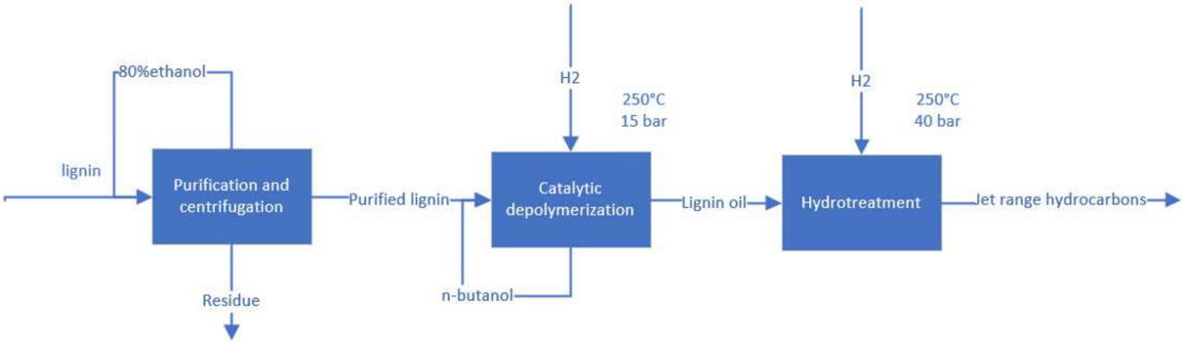


Figure 1 Simplified process flow diagram

First lignin obtained from herbaceous biomass in a pilot plant facility was purified at WFBR with ethanol. Recovery and recycling of the ethanol was performed. Then this purified lignin was catalytically depolymerized in n-butanol in the presence of hydrogen at 250°C and 15 bar. Full conversion of lignin was achieved. 90% of solvent was recovered and recycled. Finally, the lignin oil was hydrotreated in neat conditions and jet fuel range hydrocarbons were attained at 250°C and 40 bar.

Lignin purification:

First, lignin is mixed with ethanol, following centrifugation ethanol soluble fraction is separated. The remaining ethanol is recovered from the residual stream in drum dryer and sent to recycling. The residue is attained as one output. The ethanol soluble stream goes through evaporation and drum drying to separate the lignin from the ethanol water mixture. The recovered ethanol water mixture is recycled. Energy recovery is attained by using the heat from the ethanol water mixture recycle stream to heat the input stream to the evaporator.

Mass balance

Mass balance is closed with ethanol being recycled and lignin separated into two fractions of purified lignin and residue. The inputs and outputs for the 1 ton/h scale are shown in Table 1. The residue fraction is composed of remaining lignin (140 kg/h), other compounds such as glucan and xylan (89 kg/h) and ash (251 kg/h). The purified lignin is free from any impurities/ash in accordance with the demand of the reaction section.

Table 1 Mass balance for lignin purification section, 1 ton/h lignin scale

INPUTS:

	Lignin	Ethanol
Stream Name	**S-101**	**S-102**
Source	**INPUT**	**INPUT**
Destination	**P-5**	**P-5**
Stream Properties		
Activity (U/ml)	0,00	0,00
Temperature (°C)	25,00	25,00
Pressure (bar)	1,01	1,01
Density (g/L)	1.163,20	820,33
Total Enthalpy (kW-h)	14,56	131,42
Specific Enthalpy (kcal/kg)	12,53	16,75
Heat Capacity (kcal/kg-°C)	0,50	0,67
Component Flowrates (kg/h)		
Ethyl Alcohol	0,00	5.401,60
Insoluble Ligni	450,00	0,00
Soluble Lignin	500,00	0,00
Water	50,00	1.350,40
TOTAL (kg/h)	1.000,00	6.752,00
TOTAL (L/h)	859,70	8.230,82

Total: 7752 kg/h

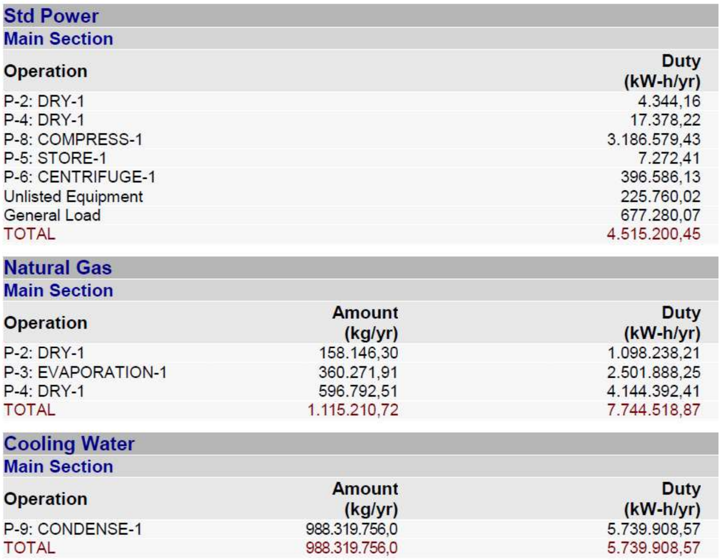
OUTPUTS:

	Residue	Purified lignin	Ethanol recycle
Stream Name	**S-105**	**S-204**	**S-303**
Source	**P-2**	**P-4**	**P-9**
Destination	**OUTPUT**	**OUTPUT**	**OUTPUT**
Stream Properties			
Activity (U/ml)	0,00	0,00	0,00
Temperature (°C)	90,00	82,00	120,00
Pressure (bar)	1,01	1,01	5,00
Density (g/L)	1.112,13	1.126,47	740,98
Total Enthalpy (kW-h)	28,17	22,71	629,73
Specific Enthalpy (kcal/kg)	46,50	40,26	80,33
Heat Capacity (kcal/kg-°C)	0,52	0,49	0,67
Component Flowrates (kg/h)			
Ethyl Alcohol	0,00	0,00	5.401,60
Insoluble Ligni	450,00	0,00	0,00
Soluble Lignin	29,66	470,34	0,00
Water	41,54	15,02	1.343,84
TOTAL (kg/h)	521,21	485,35	6.745,44
TOTAL (L/h)	468,66	430,86	9.103,43

Total: 7752 kg/h

Energy balance

Energy and resulting utility demands were attained from the process simulation and are shown in Figure 2.



Std Power

Main Section

Operation	**Duty (kW-h/yr)**
P-2: DRY-1	4.344,16
P-4: DRY-1	17.378,22
P-8: COMPRESS-1	3.186.579,43
P-5: STORE-1	7.272,41
P-6: CENTRIFUGE-1	396.586,13
Unlisted Equipment	225.760,02
General Load	677.280,07
TOTAL	4.515.200,45

Natural Gas

Main Section

Operation	**Amount (kg/yr)**	**Duty (kW-h/yr)**
P-2: DRY-1	158.146,30	1.098.238,21
P-3: EVAPORATION-1	360.271,91	2.501.888,25
P-4: DRY-1	596.792,51	4.144.392,41
TOTAL	1.115.210,72	7.744.518,87

Cooling Water

Main Section

Operation	**Amount (kg/yr)**	**Duty (kW-h/yr)**
P-9: CONDENSE-1	988.319.756,0	5.739.908,57
TOTAL	988.319.756,0	5.739.908,57

Figure 2 Utility demand of the lignin purification section, 1 ton/h scale

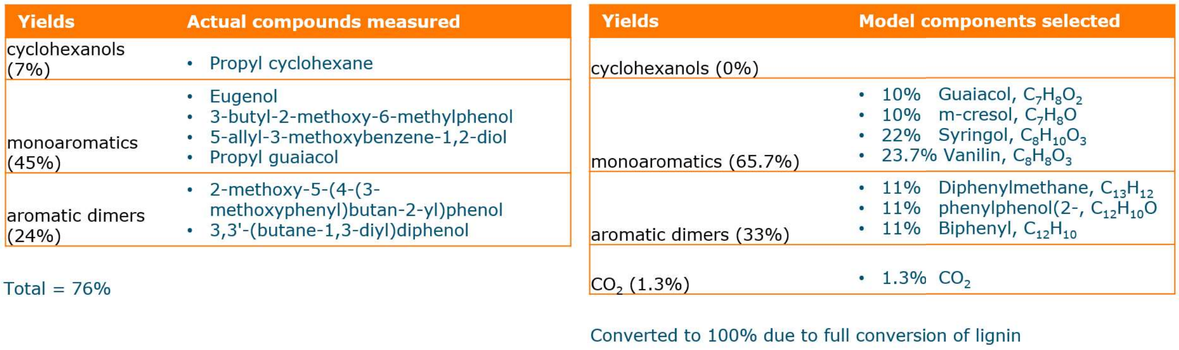
It is considered that the residue fraction which is composed of remaining lignin, other compounds (such as glucan and xylan) can be used for energy. It is considered that it is used in a CHP plant to produce electricity and heat with electricity efficiency of 35% and thermal efficiency of 50%. The lower heating value of the dry residue stream without ash (229 kg/h) is taken as 26 MJ/kg. It is seen that in this way all the electricity demand and most of the heating demand can be covered. Additionally, the remaining ash (251 kg/h) can be utilized as fertilizer or used as filler in asphalt, however this was not taken into account in current economic assessment.

Resulting utility demand after heat recovery can accordingly be calculated as:

Utility demand	Unit	
Heat (natural gas)	1128962	kWh/y
Cooling water	988319	ton/y

Purified lignin catalytic depolymerization + hydrotreatment

The reaction section was modelled to as close as possible with the actual yields and compounds attained from experiments. However, the actual components observed (see left of Figure 3 and Figure 4) are quite novel and not found in SuperPro Designer. Therefore model compounds were selected. Additionally, since 100% lignin conversion was attained, the measured yields in catalytic polymerization reaction and for the hydrotreatment reaction were converted to 100% also considering some CO_2 formation.



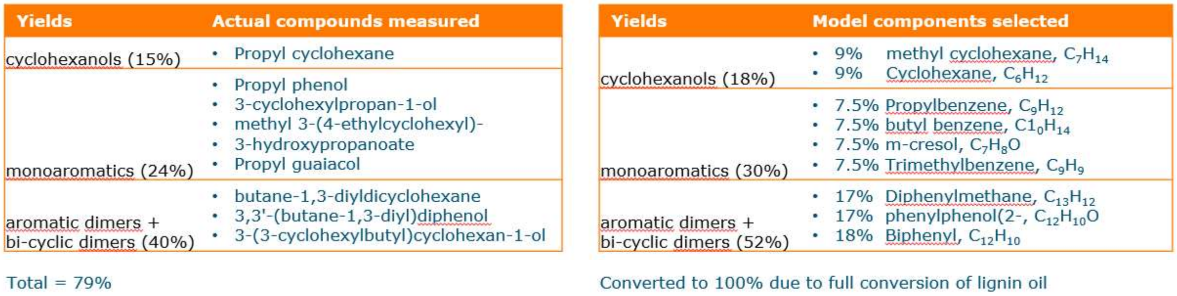
Yields	Actual compounds measured
cyclohexanols (7%)	• Propyl cyclohexane
monoaromatics (45%)	• Eugenol • 3-butyl-2-methoxy-6-methylphenol • 5-allyl-3-methoxybenzene-1,2-diol • Propyl guaiacol
aromatic dimers (24%)	• 2-methoxy-5-(4-(3-methoxyphenyl)butan-2-yl)phenol • 3,3'-(butane-1,3-diyl)diphenol

Total = 76%

Yields	Model components selected
cyclohexanols (0%)	
monoaromatics (65.7%)	• 10% Guaiacol, $C_7H_8O_2$ • 10% m-cresol, C_7H_8O • 22% Syringol, $C_8H_{10}O_3$ • 23.7% Vanilin, $C_8H_8O_3$
aromatic dimers (33%)	• 11% Diphenylmethane, $C_{13}H_{12}$ • 11% phenylphenol(2-, $C_{12}H_{10}O$ • 11% Biphenyl, $C_{12}H_{10}$
CO_2 (1.3%)	• 1.3% CO_2

Converted to 100% due to full conversion of lignin

Figure 3 ***Modelling of catalytic depolymerization reaction***



Yields	Actual compounds measured
cyclohexanols (15%)	• Propyl cyclohexane
monoaromatics (24%)	• Propyl phenol • 3-cyclohexylpropan-1-ol • methyl 3-(4-ethylcyclohexyl)-3-hydroxypropanoate • Propyl guaiacol
aromatic dimers + bi-cyclic dimers (40%)	• butane-1,3-diyldicyclohexane • 3,3'-(butane-1,3-diyl)diphenol • 3-(3-cyclohexylbutyl)cyclohexan-1-ol

Total = 79%

Yields	Model components selected
cyclohexanols (18%)	• 9% methyl cyclohexane, C_7H_{14} • 9% Cyclohexane, C_6H_{12}
monoaromatics (30%)	• 7.5% Propylbenzene, C_9H_{12} • 7.5% butyl benzene, $C1_0H_{14}$ • 7.5% m-cresol, C_7H_8O • 7.5% Trimethylbenzene, C_9H_9
aromatic dimers + bi-cyclic dimers (52%)	• 17% Diphenylmethane, $C_{13}H_{12}$ • 17% phenylphenol(2-, $C_{12}H_{10}O$ • 18% Biphenyl, $C_{12}H_{10}$

Converted to 100% due to full conversion of lignin oil

Figure 4 ***Modelling of hydrotreatment reaction***

The resulting process simulation of the reaction section is shown in Figure 5. First, purified lignin is mixed with butanol following by catalytic depolymerization reaction in the presence of hydrogen, the off-gas (CO_2) produced is separated. The resulting stream goes through evaporation to separate the lignin oil from the butanol water mixture. The recovered butanol water mixture is recycled. Then the lignin oil is mixed with hydrogen and by means of pumping and heat exchanger brought to reaction conditions. Energy recovery is attained by using the heat from the product stream to heat the input stream to the hydrotreatment reactor.

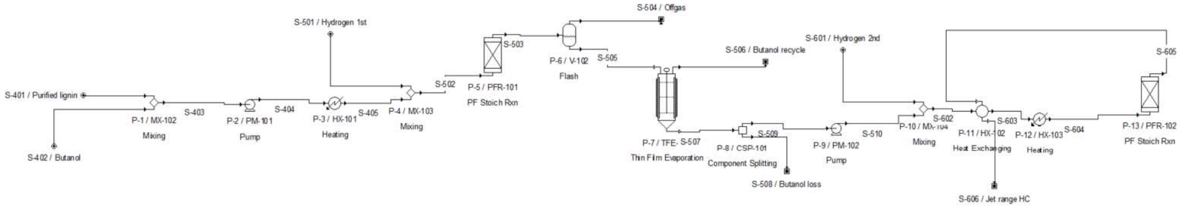


Figure 5 ***Process simulation of the reaction section***

Mass balance

The inputs and outputs to the reaction section for the 1 ton/h scale are shown in Table 2. The mass balance is closed with purified lignin input being converted into jet range hydrocarbons. Hydrogen used in the reactions was consumed. Butanol used was recycled 90%, requiring 10% make-up (314 kg/h) in a continuous operation.

Table 2 *Mass balance for reaction section, 1 ton/h lignin scale*

INPUTS:

	Purified Lignin	Butanol
Stream Name	**S-401**	**S-402**
Source	**INPUT**	**INPUT**
Destination	**P-1**	**P-1**
Stream Properties		
Activity (U/ml)	0,00	0,00
Temperature (°C)	25,00	25,00
Pressure (bar)	1,01	1,01
Density (g/L)	1.173,66	805,70
DS Flow (kg-ds/h)	485,00	0,00
Aqueous Flow (kg-aq/h)	0,00	3.142,80
DS (%)	100,00	0,00
Total Enthalpy (kW-h)	4,12	52,15
Specific Enthalpy (kcal/kg)	7,31	14,28
Heat Capacity (kcal/kg-°C)	0,29	0,57
Component Flowrates (kg/h)		
Butanol	0,00	3.142,80
Lignin	485,00	0,00
TOTAL (kg/h)	485,00	3.142,80
TOTAL (m3/h)	0,41	3,90

	H_2 1st rxn	H_2 2nd rxn
Stream Name	**S-501**	**S-601**
Source	**INPUT**	**INPUT**
Destination	**P-4**	**P-10**
Stream Properties		
Activity (U/ml)	0,00	0,00
Temperature (°C)	250,00	250,00
Pressure (bar)	15,20	40,01
Density (g/L)	0,70	1,85
DS Flow (kg-ds/h)	7,08	3,63
Aqueous Flow (kg-aq/h)	0,00	0,00
DS (%)	100,00	100,00
Total Enthalpy (kW-h)	7,10	3,63
Specific Enthalpy (kcal/kg)	862,52	862,52
Heat Capacity (kcal/kg-°C)	3,48	3,48
Component Flowrates (kg/h)		
Hydrogen	7,08	3,63
TOTAL (kg/h)	7,08	3,63
TOTAL (m3/h)	10.05	1,96

Total: 3638.51 kg/h

OUTPUTS:

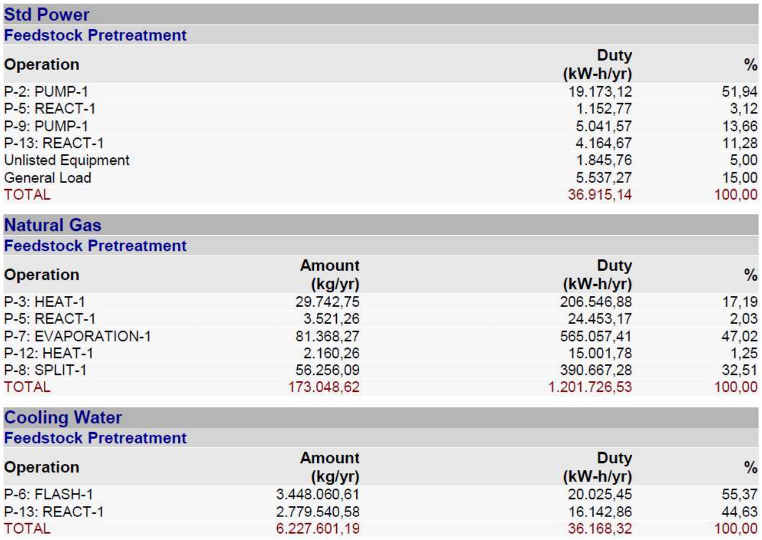
	Off-gas	Butanol Recycle 1	Butanol loss
Stream Name	**S-504**	**S-506**	**S-508**
Source	**P-6**	**P-7**	**P-8**
Destination	**OUTPUT**	**OUTPUT**	**OUTPUT**
Stream Properties			
Activity (U/ml)	0,00	0,00	0,00
Temperature (°C)	40,00	24,40	24,39
Pressure (bar)	1,01	0,01	0,01
Density (g/L)	1,71	0,02	0,01
DS Flow (kg-ds/h)	0,01	15,93	0,00
Aqueous Flow (kg-aq/h)	6,65	2.842,13	314,32
DS (%)	0,08	0,56	0,00
Total Enthalpy (kW-h)	0,11	549,72	60,54
Specific Enthalpy (kcal/kg)	14,29	165,49	165,72
Heat Capacity (kcal/kg-°C)	0,21	0,35	0,35
Component Flowrates (kg/h)			
Biphenyl	0,00	2,11	0,00
Butanol	0,25	2.828,23	314,32
CO2	6,40	0,00	0,00
Diphenylmethane	0,00	0,03	0,00
Guaiacol	0,00	6,76	0,00
Hydrogen	0,00	0,00	0,00
m-Cresol	0,00	11,76	0,00
Phenylphenol(2-	0,00	0,00	0,00
Syringol	0,00	8,99	0,00
Vanillin	0,00	0,18	0,00
TOTAL (kg/h)	6,65	2.858,06	314,32
TOTAL (m3/h)	3,89	189.959,02	20.981,22

	Jet range HC
Stream Name	**S-606**
Source	**P-11**
Destination	**OUTPUT**
Stream Properties	
Activity (U/ml)	0,00
Temperature (°C)	47,79
Pressure (bar)	39,01
Density (g/L)	930,73
DS Flow (kg-ds/h)	75,83
Aqueous Flow (kg-aq/h)	383,65
DS (%)	16,50
Total Enthalpy (kW-h)	9,33
Specific Enthalpy (kcal/kg)	17,46
Heat Capacity (kcal/kg-°C)	0,37
Component Flowrates (kg/h)	
Biphenyl	82,70
Butyl Benzene	34,46
Cyclohexane	41,35
Diphenylmethane	78,11
Guaiacol	0,00
Hydrogen	0,00
m-Cresol	34,46
Methyl Cyclohex	41,35
Phenylphenol(2-	78,11
Propylbenzene	34,46
Syringol	0,01
Trimethylbenzen	34,46
Vanillin	0,00
TOTAL (kg/h)	459,48
TOTAL (m3/h)	0,49

Total: 3638.51 kg/h

Energy balance

Energy and resulting utility demands were attained from the process simulation and are shown in Figure 6. In process simulation energy recovery was already modelled.



Std Power

Feedstock Pretreatment

Operation	Duty (kW-h/yr)	%
P-2: PUMP-1	19.173,12	51,94
P-5: REACT-1	1.152,77	3,12
P-9: PUMP-1	5.041,57	13,66
P-13: REACT-1	4.164,67	11,28
Unlisted Equipment	1.845,76	5,00
General Load	5.537,27	15,00
TOTAL	36.915,14	100,00

Natural Gas

Feedstock Pretreatment

Operation	Amount (kg/yr)	Duty (kW-h/yr)	%
P-3: HEAT-1	29.742,75	206.546,88	17,19
P-5: REACT-1	3.521,26	24.453,17	2,03
P-7: EVAPORATION-1	81.368,27	565.057,41	47,02
P-12: HEAT-1	2.160,26	15.001,78	1,25
P-8: SPLIT-1	56.256,09	390.667,28	32,51
TOTAL	173.048,62	1.201.726,53	100,00

Cooling Water

Feedstock Pretreatment

Operation	Amount (kg/yr)	Duty (kW-h/yr)	%
P-6: FLASH-1	3.448.060,61	20.025,45	55,37
P-13: REACT-1	2.779.540,58	16.142,86	44,63
TOTAL	6.227.601,19	36.168,32	100,00

Figure 6 *Utility demand of the reaction section, 1 ton/h scale*

2.5.2 Economic assessment

Economic assessment performed consists of estimation of operating costs (OPEX), capital costs (CAPEX) and calculation of minimum fuel selling price (MFSP).

CAPEX

The CAPEX is roughly estimated based on the simplified process flow diagram (Figure 1) and the mass balances at two production scales: a lignin input of 1 ton/h and 10 ton/h. For the estimation of the CAPEX, the process is devided in three sections: Lignin purification & ethanol recovery, Catalytic depolymerization & Hydrotreatment, and n-Butanol recovery. For the sections Lignin purification & ethanol recovery and n-Butanol recovery the CAPEX is estimated using (Meesters & Van Groenestijn, 2024[1]) as reference, with the total input (i.e. lignin & ethanol, and purified lignin & n-butanol, respectively) and a commonly used power of 0.6. The CAPEX of the section Catalytic depolymerization & Hydrotreatment is estimated using (Weyand et al., 2025[2]) and (Raza Khan et al., 2023[3]) as reference, with the flow of jet range hydrocarbons and again a power of 0.6. An overview of the used mass flows and estimated CAPEX for each section is shown in Table 3.

Table 3 Mass flows and estimated CAPEX

Mass flows (ton/h)		
Lignin	**1.0**	**10**
Ethanol (80%)	6.8	68
Purified lignin	0.49	4.85
n-Butanol	3.1	31
Hydrogen	0.007	0.071
Lignin oil	0.46	4.56
Hydrogen	0.004	0.036
Jet range hydrocarbons	0.46	4.59
CAPEX (M€)		
Lignin purification & ethanol recovery	10	41
Catalytic depolymerization & Hydrotreatment	20	78
n-Butanol recovery	7	26
Total	**36**	**145**

OPEX

Operating costs include direct plant costs and general expenses. Direct plant costs include variable and fixed costs. Variable costs items mainly are material costs, utility costs, maintenance costs and labour costs. For this purpose first material costs and utility costs are estimate as follows for 1 ton/h scale:

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[1] Meesters, K., & Van Groenestijn, J. (2024). Techno-economic assessment of two lignin extraction processes.

[2] Weyand, J. et al. (2025) Sustainable aviation fuel from Kraft lignin – Technical, economic and ecological process analysis, Journal of Cleaner Production, Volume 500, 144559, https://doi.org/10.1016/j.jclepro.2024.144559.

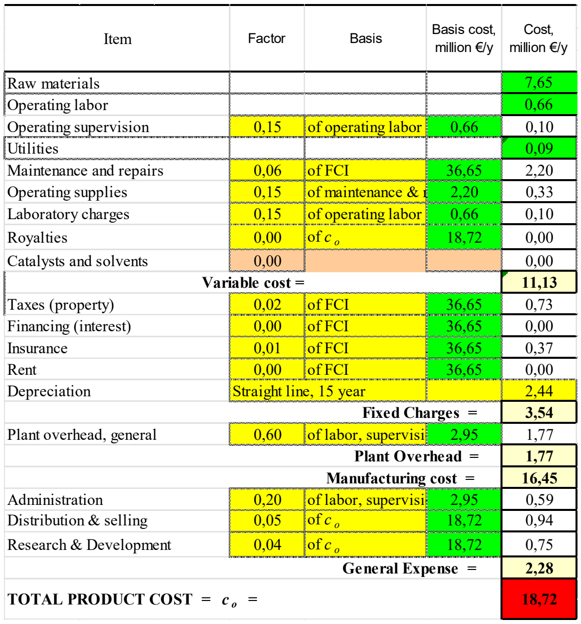
[3] Raza Khan, S. et al. (2023). Wood Hydrothermal Liquefaction-Process Modeling and Techno Economic Assessment (TEA) using SuperPro Designer. https://doi.org/10.13140/RG.2.2.29691.80164

Table 4 Material and utility costs, 1 ton/h scale

Inputs	**Flow**	**Price**	**Cost, M€/y**
Raw materials			
Lignin	8000 ton/y	600 €/ton	4,80
Hydrogen	85,7 ton/y	4 €/ton	0,34
Butanol	2512 ton/y	1 €/ton	2,51
Total			7,65
Utility			
Electricity	36.9 MWh/y	0,085 €/kWh	0,003
Heat (NG)	8390 GJ/y	10 €/GJ	0,084
Cooling water	994547 ton/y	0,005 €/m^3	0,005
Total			0,092

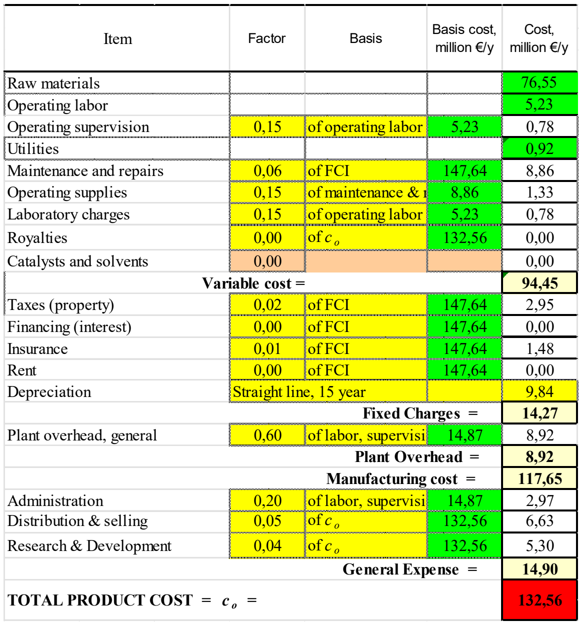
For operating labor, 3 operators per shift, with 3 shifts per day was considered using a rate of 25 €/h. The other cost terms are estimated using known parameters following Peters et al. (2003)[4] as shown in Table 5 for 1 ton/h scale and in Table 6 for 10 ton/h scale.

Table 5 Operating cost estimation, 1 ton/h scale



Item	Factor	Basis	Basis cost, million €/y	Cost, million €/y
Raw materials				7,65
Operating labor				0,66
Operating supervision	0,15	of operating labor	0,66	0,10
Utilities				0,09
Maintenance and repairs	0,06	of FCI	36,65	2,20
Operating supplies	0,15	of maintenance & r	2,20	0,33
Laboratory charges	0,15	of operating labor	0,66	0,10
Royalties	0,00	of c_o	18,72	0,00
Catalysts and solvents	0,00			0,00
Variable cost =				**11,13**
Taxes (property)	0,02	of FCI	36,65	0,73
Financing (interest)	0,00	of FCI	36,65	0,00
Insurance	0,01	of FCI	36,65	0,37
Rent	0,00	of FCI	36,65	0,00
Depreciation	Straight line, 15 year			2,44
Fixed Charges =				**3,54**
Plant overhead, general	0,60	of labor, supervisi	2,95	1,77
Plant Overhead =				**1,77**
Manufacturing cost =				**16,45**
Administration	0,20	of labor, supervisi	2,95	0,59
Distribution & selling	0,05	of c_o	18,72	0,94
Research & Development	0,04	of c_o	18,72	0,75
General Expense =				**2,28**
TOTAL PRODUCT COST = c_o =				**18,72**

Table 6 Operating cost estimation, 10 ton/h scale



Item	Factor	Basis	Basis cost, million €/y	Cost, million €/y
Raw materials				76,55
Operating labor				5,23
Operating supervision	0,15	of operating labor	5,23	0,78
Utilities				0,92
Maintenance and repairs	0,06	of FCI	147,64	8,86
Operating supplies	0,15	of maintenance & r	8,86	1,33
Laboratory charges	0,15	of operating labor	5,23	0,78
Royalties	0,00	of c_o	132,56	0,00
Catalysts and solvents	0,00			0,00
Variable cost =				**94,45**
Taxes (property)	0,02	of FCI	147,64	2,95
Financing (interest)	0,00	of FCI	147,64	0,00
Insurance	0,01	of FCI	147,64	1,48
Rent	0,00	of FCI	147,64	0,00
Depreciation	Straight line, 15 year			9,84
Fixed Charges =				**14,27**
Plant overhead, general	0,60	of labor, supervisi	14,87	8,92
Plant Overhead =				**8,92**
Manufacturing cost =				**117,65**
Administration	0,20	of labor, supervisi	14,87	2,97
Distribution & selling	0,05	of c_o	132,56	6,63
Research & Development	0,04	of c_o	132,56	5,30
General Expense =				**14,90**
TOTAL PRODUCT COST = c_o =				**132,56**

It is seen that the raw material costs, and therein lignin cost has the highest contribution to the OPEX. Therefore, it is considered to have a sensitivity analysis on the lignin price.

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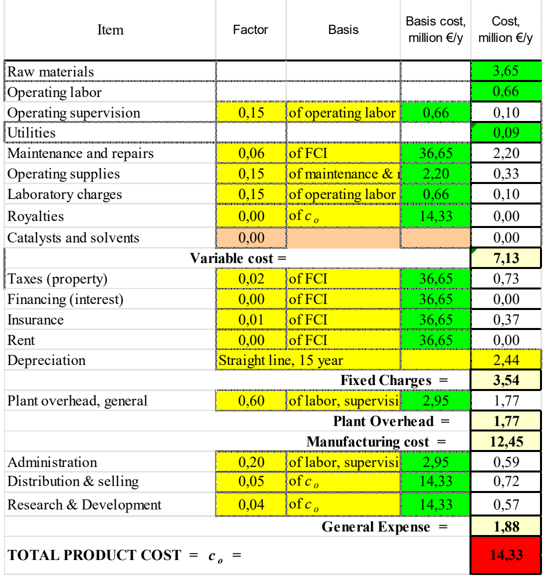
[4] Peters, M.S., Timmerhaus, K.D., West, R.E., 2003. Plant Design and Economics for Chemical Engineers, vol. 4. McGraw-Hill, New York. ISBN 0072392665.

Sensitivity analysis

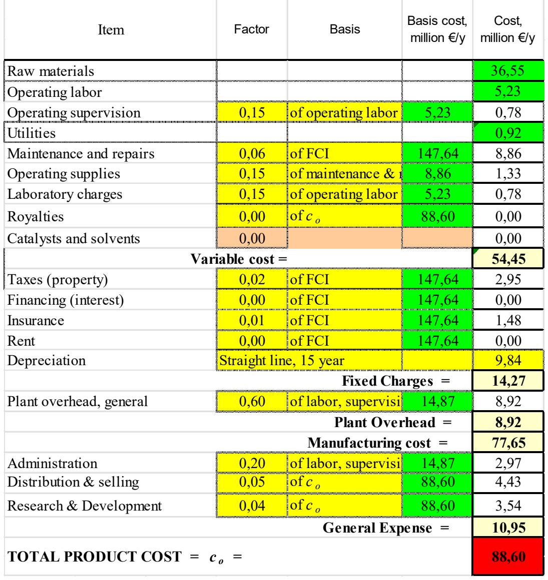
The base price considered of 600 €/ton is the market price of kraft lignin also used in literature (e.g, Weyand et al., 2025[5]). However, since the lignin attained from the herbaceous biomass biorefinery needs to undergo purification, a lower quality and therefore price can be considered. A much lower price of 100 €/ton is considered for the sensitivity analysis (see Table 7 for 1 ton/h scale and in Table 8 for 10 ton/h scale).

Table 7 Sensitivity analysis (lignin price) in cost estimation, 10 ton/h scale



Item	Factor	Basis	Basis cost, million €/y	Cost, million €/y
Raw materials				3,65
Operating labor				0,66
Operating supervision	0,15	of operating labor	0,66	0,10
Utilities				0,09
Maintenance and repairs	0,06	of FCI	36,65	2,20
Operating supplies	0,15	of maintenance & r	2,20	0,33
Laboratory charges	0,15	of operating labor	0,66	0,10
Royalties	0,00	of c_o	14,33	0,00
Catalysts and solvents	0,00			0,00
Variable cost =				**7,13**
Taxes (property)	0,02	of FCI	36,65	0,73
Financing (interest)	0,00	of FCI	36,65	0,00
Insurance	0,01	of FCI	36,65	0,37
Rent	0,00	of FCI	36,65	0,00
Depreciation	Straight line, 15 year			2,44
			Fixed Charges =	**3,54**
Plant overhead, general	0,60	of labor, supervisi	2,95	1,77
			Plant Overhead =	**1,77**
			Manufacturing cost =	**12,45**
Administration	0,20	of labor, supervisi	2,95	0,59
Distribution & selling	0,05	of c_o	14,33	0,72
Research & Development	0,04	of c_o	14,33	0,57
			General Expense =	**1,88**
TOTAL PRODUCT COST = c_o =				**14,33**

Table 8 Sensitivity analysis (lignin price) in operating operating cost estimation, 1 ton/h scale



Item	Factor	Basis	Basis cost, million €/y	Cost, million €/y
Raw materials				36,55
Operating labor				5,23
Operating supervision	0,15	of operating labor	5,23	0,78
Utilities				0,92
Maintenance and repairs	0,06	of FCI	147,64	8,86
Operating supplies	0,15	of maintenance & r	8,86	1,33
Laboratory charges	0,15	of operating labor	5,23	0,78
Royalties	0,00	of c_o	88,60	0,00
Catalysts and solvents	0,00			0,00
Variable cost =				**54,45**
Taxes (property)	0,02	of FCI	147,64	2,95
Financing (interest)	0,00	of FCI	147,64	0,00
Insurance	0,01	of FCI	147,64	1,48
Rent	0,00	of FCI	147,64	0,00
Depreciation	Straight line, 15 year			9,84
			Fixed Charges =	**14,27**
Plant overhead, general	0,60	of labor, supervisi	14,87	8,92
			Plant Overhead =	**8,92**
			Manufacturing cost =	**77,65**
Administration	0,20	of labor, supervisi	14,87	2,97
Distribution & selling	0,05	of c_o	88,60	4,43
Research & Development	0,04	of c_o	88,60	3,54
			General Expense =	**10,95**
TOTAL PRODUCT COST = c_o =				**88,60**

<u>MFSP</u>

With the OPEX and CAPEX information available, minimum fuel selling price (MFSP) can be estimated. The calculation concerns setting net present value to zero to find the break-even price for which the jet range hydrocarbons should be sold for. For this calculation, additional parameters were used (Table 9).

Table 9 Input data for MFSP calculation

Parameter	Value	Unit
Plant lifetime	20	year
Construction duration of plant	3	year
Depreciation method	Straight line	
Depreciation period	15	year
Discount rate	5	%
Inflation rate	1.34	%

The results from this analysis are shown in Table 10.

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[5] Weyand, J. (2025) Sustainable aviation fuel from Kraft lignin – Technical, economic and ecological process analysis, Journal of Cleaner Production, Volume 500, 144559, https://doi.org/10.1016/j.jclepro.2024.144559.

Table 10 Results for MFSP calculation

	1 ton/h scale	10 ton/h scale
MFSP	6291 €/ton	4360 €/ton

Sensitivity analysis
Sensitivity analysis was performed for the lignin price. The results are shown in Table 11.

Table 11 Results for MFSP calculation

	1 ton/h scale	10 ton/h scale
MFSP	4893 €/ton	2960 €/ton

MFSP of ASTM certified SAF production routes ranges from $ 1.12-3.99/l (Watson et al., 2024[6]) which corresponds to 1.4-5 $/kg and 1.2-4.3 €/kg. The results calculated for 10 ton/h scale (4.36€/kg for base case, 2.96€/kg for sensitivity falls in this range). However this is more expensive than sustainable aviation fuel of Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosine (HEFA-SPK) produced from vegetable oils. The current HEFA SPK FOB ARA is about 1200$/t.

2.5.3 Environmental assessment

Life Cycle Assessment is a standardized methodological framework for estimating and assessing the environmental impact of a product over life cycle. In this assessment, cradle-to-gate system boundary was considered including processes as depicted in Figure 7.

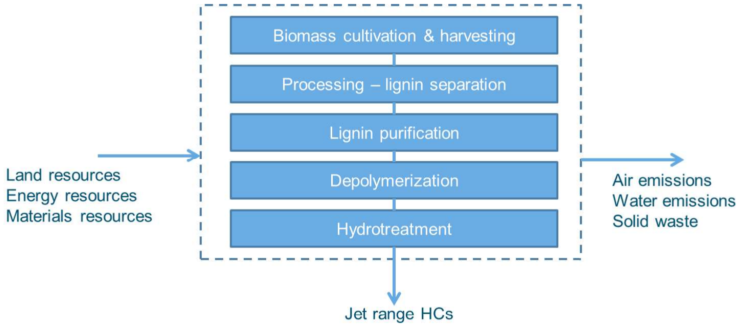

Figure 7 System boundary for environmental assessment

Lignin production (Biomass cultivation & harvesting + Processing – lignin separation)
It was not possible to get the data for the lignin production process from the supplier. Therefore, approximation of the process was made from a previous Dutch CHAPLIN study where a similar biorefining process was applied to produce lignin. The VRT-NG process from Moretti et al. (2022)[7] was considered. For the biomass feedstock, sawdust used in this process was replaced with the herbaceous biomass used by the supplier in this project. For the cultivation and harvesting of this herbaceous biomass, background data was obtained from Ecoinvent. To align with that study, for impact assessment method CML-IA was selected in this project. The environmental impact of 1 kg dry lignin is accordingly calculated as presented in Table 12.

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[6] Watson, M.J. et al. (2024) Sustainable aviation fuel technologies, costs, emissions, policies, and markets: a critical review. J. Clean. Prod. 449. https://doi.org/10.1016/j.jclepro.2024.141472.

[7] Moretti, C. et al. (2022) Using lignin from local biorefineries for asphalts: LCA case study for the Netherlands. https://doi.org/10.1016/j.jclepro.2022.131063

Table 12 Environmental impact of 1 kg dry lignin (adapted from Moretti et al., 2022)

Impact category	Unit	Lignin
Abiotic depletion	kg Sb eq	8,81E-07
Abiotic depletion (fossil fuels)	MJ	2,07E+01
Global warming (GWP100a)	kg CO2 eq	1,28E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	1,71E-07
Human toxicity	kg 1,4-DB eq	4,83E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	1,02E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	2,57E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	2,22E-03
Photochemical oxidation	kg C2H4 eq	1,22E-04
Acidification	kg SO2 eq	1,36E-03
Eutrophication	kg PO4--- eq	6,65E-04

Lignin purification
Inventory data for this process step was obtained from the process simulation as described above and are provided in Table 13.

Table 13 Inventory data for lignin purification process

Output	Inventory flow	Unit	Background data
Purified lignin	485	kg	
Residue (no allocation)	515	kg	-
Input			
Lignin	1000	kg	Table 12
Heat (natural gas)	508	MJ	Natural gas, burned in industrial furnace >100kW/RER
Cooling water	123	ton	Water, decarbonised| water production, decarbonised | Cut-off

Depolymerization and Hydrotreatment
Inventory data for this process step was obtained from the process simulation as described above and are provided in Table 14.

Table 14 Inventory data for depolymerization and hydrotreatment process

Output	Inventory flow	Unit	Background data
Jet range HC	459,48	kg	
Butanol loss (no alloc)	314,57	kg	-
Lignin oil loss (no alloc)	29,83	kg	-
Input			
Purified lignin	485,00	kg	Table 13
Hydrogen	10,71	kg	Hydrogen, gaseous, low pressure | hydrogen production, steam methane reforming | Cut-off
Butanol make up	314,57	kg	1-butanol| butanols production, hydroformylation of propylene | Cut-off
Electricity	4,6	kWh	Electricity, high voltage | market for electricity, high voltage | Cut-off
Heat (natural gas)	540,7	MJ	Natural gas, burned in industrial furnace >100kW/RER
Cooling water	778	kg	Water, decarbonised | water production, decarbonised | Cut-off
Emission			
CO_2	6,40	kg	Direct emission

Overall environmental impact

The result of the cradle-to-gate assessment for 1 kg of jet fuel range hydrocarbon production is provided in Table 15.

Table 15 Environmental impact of 1 kg of jet fuel range hydrocarbon

				Lignin purification		Catalytic depolymerization + HT				
Impact category	Unit	Total	Lignin	Purif heat	Purif CW	H2	Butanol	Rxn elect	Rxn heat	Direct
Abiotic depletion	kg Sb eq	1,66E-05	1,92E-06	2,29E-09	4,79E-08	3,44E-07	1,42E-05	1,43E-08	2,44E-09	
Abiotic depletion (fossil fuels)	MJ	1,06E+02	4,49E+01	1,19E+00	2,40E-01	4,13E+00	5,40E+01	5,36E-02	1,27E+00	
Global warming (GWP100a)	kg CO2 eq	5,56E+00	2,79E+00	7,65E-02	1,96E-02	2,55E-01	2,31E+00	3,70E-03	8,14E-02	1,39E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	4,78E-07	3,72E-07	1,09E-08	2,02E-10	9,22E-09	7,41E-08	2,71E-10	1,16E-08	
Human toxicity	kg 1,4-DB eq	6,82E+00	1,05E+00	1,64E-03	5,36E-02	2,84E-01	5,43E+00	8,63E-04	1,74E-03	
Fresh water aquatic ecotox.	kg 1,4-DB eq	1,53E+00	2,22E-01	8,07E-04	2,46E-02	4,03E-02	1,24E+00	9,19E-04	8,59E-04	
Marine aquatic ecotoxicity	kg 1,4-DB eq	3,73E+03	5,58E+02	2,12E+00	4,69E+01	1,11E+02	3,00E+03	2,23E+00	2,26E+00	
Terrestrial ecotoxicity	kg 1,4-DB eq	4,63E-02	4,83E-03	2,41E-05	3,86E-04	1,94E-03	3,91E-02	1,97E-06	2,56E-05	
Photochemical oxidation	kg C2H4 eq	1,84E-03	2,66E-04	5,17E-06	2,66E-06	1,71E-05	1,55E-03	2,78E-07	5,50E-06	
Acidification	kg SO2 eq	9,60E-03	2,96E-03	5,71E-05	4,49E-05	1,28E-04	6,34E-03	5,33E-06	6,08E-05	
Eutrophication	kg PO4--- eq	4,51E-03	1,45E-03	9,88E-06	2,68E-04	3,58E-05	2,74E-03	3,35E-06	1,05E-05	

Looking more specifically at the GWP (see Figure 8), the major contributors are lignin and butanol used as input. Fossil fuel comparator provided in RED III is 94 gCO_2-eq/MJ. Using jet fuel LHV = 43.15 MJ/kg, this corresponds to 4.06 kg CO_2 -eq/kg fuel. The 5.56 kg CO_2 -eq/kg fuel calculated in this study is higher than this amount which calls for especially a reduction in lignin production impacts and/or higher recovery and recycle of the butanol used.

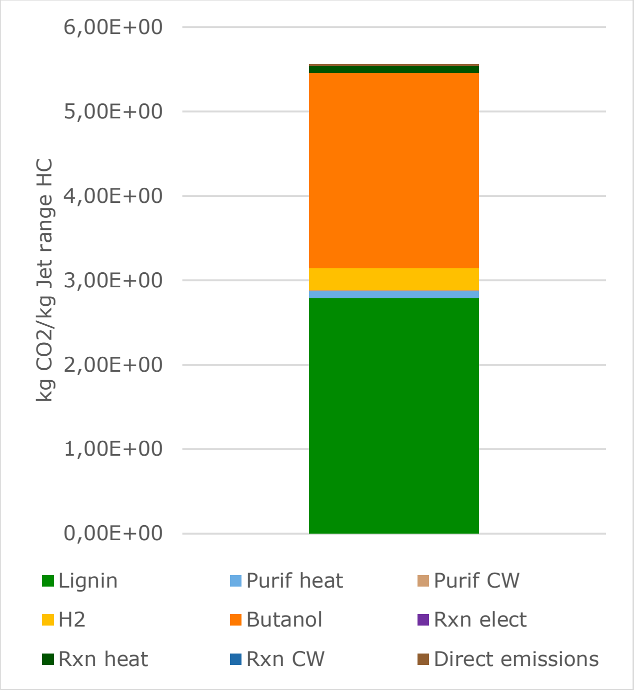

***Figure 8** GWP of 1 kg of jet fuel range hydrocarbon*

2.5.4 Techno-economic and environmental conclusions

- Process was modeled in two parts: lignin purification + reactions (with model compounds). The process simulation yielded mass and energy balance used in economic and environmental assessments. Utility needs were determined after heat integration.
- Economic assessment was performed for two scales: 1 ton/h and 10 ton/h lignin.
- Minimum fuel selling price was calculated as 6291 and 4360 €/ton, respectively. With sensitivity analysis, considering lower lignin price, the values are reduced to 4893 and 2960 €/ton, respectively.
- This was found not economically competitive with SAF available in market with selling price of 1200 $/ton. But the values calculated for 10 ton/h lignin falls in the range of ASTM certified SAF production routes.
- Cradle to gate LCA was performed. GWP was found higher than fossil fuel comparator. The main contributors to the GWP are lignin production and butanol used in the process.

Recommendations:

- Supplying lignin with a higher (or desired) purity will simplify or remove the purification step. Also this will result in higher yield per input (base case 0,46 kg/kg)
- Increasing the recovery rate of butanol will reduce the amount of make-up needed reducing environmental impact and costs. Yet, it should be considered that this can result in higher equipment and utility demands.

Further research:

- It was not possible to get primary data from supplier to model the upstream sustainability impact of lignin production. Since it has a significant contribution to environmental impacts, it will be desirable to more specifically analyse this process to make a more accurate calculation of the impacts and find places of improvement.
- Model compounds were needed to be selected to simulate the reactions since actual components do not exist in the database. Further research can look at introducing the novel compunds actually obtained from the reactions into the software to make a more realistic modeling of the reactions

2.6 Main conclusions

This project delivered a proof of concept for the conversion of technical lignin to aromatic jet fuel range components at TRL3-4. A lot of insights in this process as well as significant learnings were obtained.

Main conclusions are:

- A suitable purified mildly treated lignin stream, containing a high content of β-O-4 ether linkages, is necessary as feedstock for the conversion into aromatic jet fuel components
- The developed catalytic depolymerisation and alkylation process resulted in an efficient and high yield process
- The subsequent HDO process gives a nearly quantitative yield in the desired jet fuel range components of carbon numbers between C8-C16
- Pd/ZrO_2 catalysts showed excellent HDO activity and after introducing Brønsted acid sites these modified catalysts facilitates C-C bond cleavage during lignin depolymerization
- Other jet fuel properties still needs to be evaluated
- The overall TEA and LCA needs to be further continued in combination with a sensitivity analysis to optimize the overall economics and environmental benefits, here upstream data is desired and inclusion of realistic aromatic compounds is needed in the modelling. Of the current processing chain at relatively low volume capacity showed that the minimum selling price of lignin derived aromatics is about 2-3x higher compared to sustainable aviation fuel of hydrotreated fatty acids from vegetable oils (HEFA).
- Cradle to gate LCA was performed. GWP for the lignin2jetfuel process was found higher than for the fossil fuel comparator. The research showed that the main contributors to the GWP are lignin production and butanol used in the process, which needs to be optimized to lower the environmental impact.

3 Contribution of project to the goals of the call

The International Civil Aviation Organization (ICAO) recently introduced global market-based measures to reduce the aviation CO_2 emissions from 2020 onwards. These measures aim to counterbalance any annual increase in the CO_2 emissions from international aviation through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).The European Union (EU) aviation industry that is regulated by EU Emission Trading Scheme (ETS) also aims to further reduce the CO_2 emissions in the coming decades, and under the renewable energy directive (RED), Member States are setting SAF-(sustainable aviation fuel) mandates. Under the agreement, the global aviation emission target is a 50% CO_2 reduction by 2050 compared to 2005. The aviation sector will depend on liquid fuels for many decades. To achieve the emission reduction target, therefore SAF from biomass is considered as an excellent candidate as long as a minimum of 70% greenhouse gas savings is realized. Fundamental research and process development are required to achieve the required quality SAF from various residual non-food biomass resources.

This is exactly at the heart of this project, as non-food lignocellulosic biomass was evaluated to convert it via the lignin fraction into aromatic hydrocarbons suitable for jet fuel application. In particular the use of lignin, which is the most abundant aromatic resource on earth, for processing into the aromatic hydrocarbons is not well studied in the last decade. This Lignin2jetfuel project delivered valuable insights to achieve this goal:

- Selection of suitable lignins
- Development of technology steps to convert lignin via depolymerization, alkylation and hydrotreatment into the desired jet fuel range aromatic hydrocarbons of carbon number C8-C16
- Development of scalable technology to feed the aviation sector with SAF based on lignin
- Correlate lignin characteristics to functionality and ability to be converted to SAF components
- Preliminary techno-economic assessment showed that currently the economics of the developed route is 2-3x higher compared to HEFA, but hotspot analysis indicated the highest contributors which can be further optimized
- First global warming potential of the lignin derived jet fuel components is somewhat higher than this amount for the fossil counterpart, which calls for especially a reduction in lignin production impacts and/or higher recovery and recycle of the alkylation agent used. Only then, a more sustainable jet fuel can be developed.

Overall, this project will leverage important novel insights in a sustainable lignin to jetfuel process which shows high potential for further development and final future implementation. This could contribute to the further development of SAF and contribute to lowering of the GHG emissions within the airline sector which is an important sector in the Netherlands and worldwide.

4 Knowledge dissemination

During the project several ways of knowledge dissemination has been performed and these are listed hereafter:

Project description on Topsector Energy: *https://projecten.topsectorenergie.nl/projecten/renewable-jet-fuel-range-hydrocarbons-from-biomass-residues-derived-lignin-lignin2jetfuel-36399*

Newsitems about start of the project:
03/2022 Renewable jet fuel range hydrocarbons from biomass residues derived lignin

https://www.wur.nl/en/research-results/research-institutes/food-biobased-research/show-fbr/clean-aviation-fuel-from-waste-wood-and-tomato-stems

Project Lignin2Jetfuel https://q8research.com/international-research-projects/project-lignin2jetfuel/

11/07/2022 https://www.agro-chemistry.com/news/flying-on-waste-wood-and-tomato-stems/

21/09/2022; update 10/08/2023

https://recyclingnederland.nl/artikelen/schone-vliegtuigbrandstof-uit-resthout-en-tomatenstengels/

Renewi:
Renewi contributed to the dessimination activities by co-writing press releases.
The project is mentioned in various presentations, amongst others at the “Wastebuild conference” on 11-05-2023, for the Dutch “Planbureau voor de Leefomgeving” on 25-06-2023, and for the Dutch Ministery of Infrastructure and Waterways on 09-02-2024.

Sekab:
Overall project objectives and theoretical background was presented by Sekab (Mathilda Johansson) on the 25th of October 2023 at the 5th Future of Biofuels European Conference arranged by Fortes Media.

Vertoro:
14-3-2025 Thermochemische omzettingen biogebaseerde materialen en brandstoffen by Vertoro at
Green Chemistry Campus workshop

TU/e: *Manuscript in preparation*: Lignin to jet fuel: Hydrodeoxygenation and carbon-carbon bond cleavage of lignin model compounds over Pd/ZrO2 based catalysts by Huaizhou Yang, Davey F. de Waard, Alexandra Radu, Wencong Zhang, Yu Gao, Emiel J. M. Hensen.

5 Spin off inside and outside sector/ Follow-up research

This project delivered a proof of concept for the conversion of technial lignin to jet fuel components at TRL3-4. A lot of insights in this process as well as significant learnings were obtained. All partners are very enthusiastic about the outcome of the project and are thinking about follow up steps. Next steps will be in a potential research project to further elaborate on the achievements obtained in this project.

Key learnings are:

- A suitable purified mildly treated lignin stream, containing a high content of β-O-4 ether linkages, is necessary
- The developed catalytic depolymerisation and alkylation process resulted in an efficient and high yield process
- The subsequent HDO process gives a nearly quantitative yield in the desired jet fuel components
- Pd/ZrO_2 catalysts showed excellent HDO activity and after introducing Brønsted acid sites these modified catalysts facilitates C-C bond cleavage during lignin depolymerization
- Other jet fuel properties still needs to be evaluated
- The overall TEA and LCA needs to further continued in combination with a sensitivity analysis to optimize the overall economics and environmental benefits, here upstream data is desired and inclusion of realistic aromatic compounds is needed in the modelling

Based on the overall results of the project a follow-up is supported by the partners. Most likely a suitable funding option needs to be selected to continue this work to further develop this route to higher TRL. This step is necessary to further explore the potential of this technology before a spin off and future investments can be considered.

Results from the catalytic depolymerisation, alkylation and hydrotreatment of technical lignin will further contribute to the knowledge base of all partners involved.

To explore
the potential
of nature to
improve the
quality of life

Wageningen Food & Biobased Research
Bornse Weilanden 9
6708 WG Wageningen
The Netherlands
E info.wfbr@wur.nl
wur.eu/wfbr

Report 2749

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