



***Advanced Biomass Catalytic Conversion to
Middle Distillates in Molten Salts***

Deliverable 2.11

**Public report on the marketability of the ABC-SALT
middle distillates biofuels**

Project information

Grant Agreement n°	764089
Dates	1 st April 2018 – 30 th September 2022

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Document Status

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Work package No. Title:	Techno-economic evaluation - socio-economic - environmental aspects
Work package leader (partner):	DLR
Date released by WP leader:	29/09/2022
Date released by Coordinator:	30/09/2022

Dissemination level

PU Public

X

Revisions

Version:	Date:	Changed by:	Comments:
V1	12/08/2022	Sandra Adelung (DLR)	First version
V2	09/09/2022	Sandra Adelung (DLR)	Second version
VF	30/09/2022	L. Naiglin / BENKEI	Finall version

Project identification

Grant Management No:	764089
Project acronym	ABC-Salt
Project tilte:	Advanced Biomass Catalytic Conversion to Middle Distillates in Molten Salts
Type of Action:	RIA
Topic:	LCE-06-2017 New knowledge and technologies
Start date of project:	1st April 2018
Duration:	48 months
Project Coordinator:	Rijksuniversiteit Groningen (RUG)

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1 Executive Summary

1.1 Description of the deliverable content and purpose

Acknowledging the low TRL, this deliverable targets to analyze the ABC-Salt process with respect to its marketability. The process is investigated from a technical, economic, ecological and social perspectives:

- The jet fuel market and current price development and production routes to produce sustainable aviation fuels are outlined.
- Objectives of the process, the feedstock availability (and an according prospective product availability) and the target specifications of the final product are highlighted.
- ABC-Salt products are benchmarked against the targeted jet fuel specifications.
- Process efficiencies, net production cost, global warming potential and the acceptability and acceptance are investigated. The results may aid to steer further researches beyond this project.

1.2 Brief description of the state of the art and innovation breakthroughs

Feedstock availability and product properties: Product samples of representative runs are analysed and compared against target specifications (ASTM D7566). The results of this comparison indicate a good agreement of the ABC-Salt product properties with these target specifications. Lignin is investigated as the feedstock derived from the pulp industry. The analysis indicates availability of 0.5-0.90 Mt/y in Sweden, 1.7-2.8 Mt/y in Europe and 9.2-15.4 Mt/y on a global scale. With a conversion efficiency of 61 % it would only be possible to supply less than 3 % of the total global jet fuel demand in 2019. However, around half the jet fuel consumed in Sweden in 2019 could have been provided from the amount of lignin available in Sweden.

Product yields: Targeting already very ambitious key performance indicators at the beginning of the project, the final outcomes are even beyond these initial expectations. Overall yields are above 45%, with associated carbon yields nearing or higher than 80%, are demonstrated for lignin feedstocks with slightly higher hydrogen consumptions than anticipated, also realizing that further optimisation can be done.

Techno-economic analysis: In a previous deliverable a preliminary techno-economic analysis of a stand-alone ABC-Salt plant was conducted resulting in net production cost of 6.66 €/kg_{Product}. During the project, the process design and process unit models are updated with new experimental data and the ABC-Salt process is thermally and materially integrated into a kraft pulp mill process. The technical analysis indicates that the carbon and the energy efficiency regarding hydrogen and biomass conversion are both drastically increased (η_C : 35.5% vs. 78.2% and η_{H_2+BtL} : 29.3% vs. 67%). The new net production cost is 1.81 €/kg_{Product} at an estimated lignin price of 362 €/t.

Ecological analysis: The first life cycle assessment based on the process simulation of a previous deliverable resulted in a rather high global warming potential of 61.2 gCO₂-eq./MJ_{product} which is equivalent to a 35% reduction compared with fossil fuel. After improving the process design and addressing the integration of the kraft pulp mill, the global warming potential of the product was reduced to 16.8 gCO₂-eq./MJ_{product} (82% reduction).

Social analysis: Methodological advances were necessary in order to deploy systematic and standardised tools for assessing the biofuels acceptability (favourable attitude towards



biofuels) and acceptance (to support, to use, to pay for buying biofuels). The creation of standardised tools to measure people's beliefs towards biofuels is useful in order to standardise the measurement of potential predictors for biofuels marketability. The main result is represented by a list of 5 barriers and 16 drivers for biofuels acceptability and acceptance as depicted in section 3.6.

2 Background

2.1 Jet Fuel Market and Price

The global biofuel market in 2020 was over 120 billion USD [1] and the global demand reached 145.3 billion litres also in 2020 [2]. The annual demand of biofuels is forecasted to increase, e.g. to 186 billion litres in 2026 [2]. The different fuel markets (gasoline, diesel and jet fuel) differ in size, consumers and demand locations. Regarding jet fuel, the IATA expects the global jet fuel consumption for 2022 to be 84 billion gallons (= 318 billion litres) [3]. Prospectively, the passenger demand is expected to further increase. Although predictions are difficult, global demand may increase to 230 billion gallons (= 909 billion litres) in 2050 [4]. The jet fuel market has a comparably small number of costumers (airlines, fuel suppliers) [4]. A good indicator for the pricing is the ultra-low-sulphur diesel price [4]. The average for 2022 jet fuel price (year to date: 12.07.2022) is around 143 USD per barrel (= 0.9 USD/litre) [5]. Figure 1 shows the longer-term jet fuel and crude oil price development in the past years [5]. In order to reach the self-set goals, the IATA's vision is that sustainable aviation fuels (SAFs) will contribute to 65 % of the emission reductions in 2050 [6]. Hence, SAF are an important pillar in the strategies to reducing net-carbon emissions. In 2020 the global biojet consumption was 113 million litres and is forecasted to reach almost 5.5 billion litres in 2026 [7].

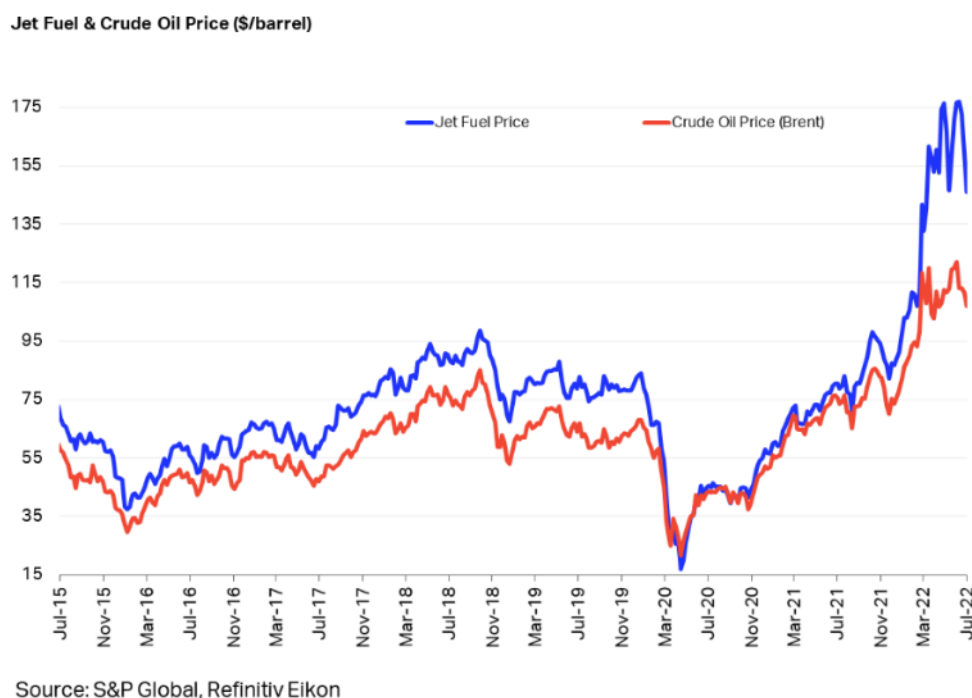


FIGURE 1: JET FUEL AND CRUDE OIL PRICE DEVELOPMENT OVER THE PAST YEARS [5]

2.2 Jet Fuel Certification and Production Routes

In order to substitute conventional jet fuel, SAFs need to have the same quality and properties as conventional jet fuels. Therefore, new jet fuels must be approved in the ASTM D4054 process, which consists of four tiers. The approval process typically takes 3-5 years and has been reported to cost up to 15 million USD [4]. In the first tier, the fuel properties of the blended fuel are analysed and benchmarked against conventional jet fuel specifications. Some important property specifications are listed in ASTM D1655, which regulates the

specifications for conventional jet fuel [8]. The specifications in ASTM D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons), which regulates the specifications for alternative jet fuels to be used as drop-in fuels, is closely related to the specs for conventional jet fuel in D1655. SAF production routes that are approved of through the process described in ASTM D4054 are listed in ASTM D7566's Annexes (currently seven routes certified). In 2020, a fast track approval was added to D4054 to allow for 10 % of drop-in, if very tight specifications are met (composition, boiling curve, ...) [4]. It is worth mentioning that pre-screening methods are available in the literature to estimate if a fuel is deemed suitable to enter the ASTM D4054 process. The approach for this Tier α and Tier β screening is described in [9].

So far, the following production routes have been certified and consequently are included as annexes in ASTM 7566-20b (March 2020):

- Annex A1: Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) (2009)
- Annex A2: Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) (2011)
- Annex A3: Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP) (2014)
- Annex A4: Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A) (2015)
- Annex A5: Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK) (2016)
- Annex A6: Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ) (2020)
- Annex A7: Hydrocarbon-Hydroprocessed Esters and Fatty Acids (HC-HEFA SPK).

3 ABC-Salt Marketability

3.1 ABC-Salt Process– Motivation and Objectives

Novel routes are required to produce sustainable liquid biofuels from various cheap lignocellulosic waste streams (including forestry residues, straw and lignins from the paper and pulp industries).

Promising routes should target high overall yields to liquid, and addressing fuels in the middle distillate (MD) range (all based on the biomass dry input). This is ambitious, especially in comparison to existing technologies using wood as a feedstock, such as the IH2 process developed by GTI in Chicago (25 to 32 % yields; 2/3 gasoline and 1/3 in the MD range), the catalytic fast pyrolysis process as scaled up by KiOR (10 % yield, most in the gasoline range) and the combination of fast pyrolysis and catalytic liquid-phase hydro-deoxygenation (24 to 30 % yields; 1/2 in MD range) that is currently under development by various consortia (such as the partner BTG in the Netherlands, and PNNL in the USA).

ABC-Salt involves liquefaction and subsequent catalytic hydro-pyrolysis of the biomass in a molten salt environment, followed by the catalytic hydro-deoxygenation of the vapour phase using suitable catalysts to obtain a hydrocarbon product with at least 2/3 of being suitable for use as a middle distillate biofuel. MD are important fuels in the transportation sector, both for road (diesel) and air transport (jet fuel). The ABC-SALT project aimed at bringing the technology to convert biomass residues into middle distillate from TRL 2 to TRL 4. An integrated lab scale process is indeed developed in the project, as a prototype for such a future fuel production systems.

The project included technical aspects (such as various waste biomass selection, biomass liquefaction and hydro-pyrolysis in molten salts and subsequent hydro-deoxygenation and their integration) and assessments of the techno-economic viability of the technology (substrates availability and supply chain, future end-users and economic sustainability of the process). Studies in the social domain includes an investigation of the possible barriers for social acceptance of transport induced by sustainable biofuels in general and the MD's derived from the ABC-salt process in particular.

In ABC-Salt lignocellulosic waste streams are converted through an advanced thermochemical conversion process involving biomass liquefaction, hydro-pyrolysis and hydro-deoxygenation. Four core objectives are targeted, as summarised listed below.

Objective 1: Enable the development of an economically viable, environmentally friendly and socially acceptable process for the conversion of lignocellulosic waste streams to middle distillates

Deploying the ABC-SALT process, the target estimated manufacturing costs of the MD's are below 0.8 €/L. This corresponds to a minimum profitable biofuel price low enough to compete with fossil fuels, oil costing 75-90 \$/barrel (and equivalent to 3 \$/gallon gasoline equivalent). Though ambitious, this is justified if:

- High yields can be obtained, >35% in weight from biomass;
- Biomass costs are well below 70 €/t: in contrast with fossil fuels the price of biomass is unlikely to vary depending on policy issues, but much more on local availability and demand;

- Limited investment costs per unit installed capacity can be realised, tentatively estimated below 200,000 €/t (bbloil equivalent/d). (For comparison green grass root refineries are around 10,000 €/t (bbloil equivalent/d)).

The anticipated biomass feedstocks used in ABC-SALT for MD biofuels must be cheap waste streams (ideally lower than 70 €/t) widely available. Alternatively, it can use streams that can be transformed into much higher yields. The feedstocks sought after included a number of lignocellulosic biomass waste streams from the forestry and agricultural sector. Especially the ability to process lignin rich substrates appeared a key feature of the proposed technology. and especially the integration of a pulp/paper mill with the ABC-SALT process led to interesting synergies also to be investigated within the project.

The alternative fuels produced in this way have a much lower carbon footprint. To evaluate the environmental impact of production of MD fuel from forestry, agricultural and pulp and paper waste streams, the environmental impact is investigated by using input parameters such as conversion efficiency, use of chemicals and fossil raw material for upgrading of the fuel and utilisation of by-products.

Objective 2: Select the most appropriate lignocellulosic waste streams and assess the ability of molten salts to liquefy such streams below 200 °C and atmospheric pressure with 90 wt% yield based on biomass input (90 wt% based on carbon input)

The input for the ABC-SALT process are sustainable lignocellulosic waste streams. Over 900 Mt waste is produced per year in the EU, amongst which 220 Mt is sustainably available. These 220 Mt represents 16% of the total European transport requirements if processed with current technologies. Furthermore, supply chains for such biomass feeds have been developed and are in place (e.g. forestry residues, and agricultural residues like straw) but mainly with the objective of heat and power generation. Special attention is given on the processing of lignin rich waste streams, with an emphasis on lignin rich waste streams from the pulp and paper industry. Such lignins are now used for power and heat production, both having low economic value while more waste and residual material is available due to improved energy efficiencies. They are very difficult to process with existing competitive catalytic-thermochemical processes, but are neat examples that can be used in ABC-SALT as a feed to produce MD.

The proposed concept allows the use of a variety of feedstocks, which brings flexibility to the process technology and makes it more robust. This is of particular relevance when considering that the lignocellulosic waste stream is expected to change in the future. For instance, the currently agreed EU targets for the share of second generation biofuels in the overall biofuel mix creates a demand for use of new sources of waste raw materials from existing agricultural activities and forestry. On the longer term with an increase in the worldwide demands of second generation liquid biofuels, a large share of the feedstock is expected to come from underutilised agricultural land and pastures and from agricultural and forestry activities.

Objective 3: Conversion of the liquefied biomass to MD's using hydro-pyrolysis followed by hydro-deoxygenation with a yield of 35 wt% based on biomass input (55% based on carbon input)

High hydrocarbon yields in the MD range from the liquefied biomass are demonstrated and make the process techno-economically viable while reducing the carbon

footprint. As such, char formation and the formation of CO₂ or CH₄ is indeed minimised. In the ABC-SALT process, following the primary liquefaction in the molten salt, the liquefied biomass is hydro-pyrolised and turned into intermediate products that are then hydro-deoxygenated and refined into hydrocarbons with a large proportion of MD's using H₂ in combination with a suitable catalyst (e.g. bimetallic supported Ni catalysts). In these combined steps, yield of hydrocarbon fuels > 45 wt.% on biomass input with more than 30 wt% (based on the lignin input) of the hydrocarbons in the MD range are demonstrated.

Objective 4: Demonstrate the conversion of the lignocellulosic waste streams into a MD biofuel in an integrated process with over 35% yield based on dry biomass input (55 wt% based on carbon input) for at least 100 hours at a minimum scale of 100 g/h input

The individual process steps developed in ABC-SALT are optimised in lab scale equipment. Liquefaction of biomass in molten salts has been proven on small lab scale (TRL 3-4) and in continuous operation. This lab scale validated (TRL 4) integrated process provided the proof of concept for the conversion of lignocellulosic wastes into MD biofuels and will be studied in detail. The integrated process is the starting point for further scale up activities beyond the current proposal to TRL 5 to 7, enabling participation of key stakeholders (end users, engineering companies and investors).

As the project started at low TRL 2, preliminary process designs were continuously monitored, evaluated and updated according to the outcomes of the experimental investigations. The state-of-the-art ABC-Salt process design is depicted in section 3.4; which also highlights the derived efficiencies and net production of the investigated ABC-SALT process.

3.2 Feedstock Availability

3.2.1 Lignin: the raw material

Lignin is the second most abundant natural polymer on the planet with market potential in various fields such as chemicals, materials, and bioenergy production. The biomass reserves on the earth are estimated to be approximately $1.85\text{--}2.4 \times 10^{12}$ tons of which roughly 20 % is lignin. The global attention to transition from petroleum-based materials, chemicals and fuel into their bio-based and sustainable counterparts has encouraged many research groups and companies to deeply explore and heavily invest in lignin valorization over the past decade. Lignin is commercially produced as by-products of pulp industries and more recently biorefineries (biofuel production).

The main challenges related to valorization of lignin are the heterogenous structure of lignin and the uncertainty related to consistent supply of a certain quality and type of lignin. The structure of lignin varies based on the botanical source, extraction process, and refining parameters. These factors affect the numbers and distribution of various functional groups and monomeric units, molecular weight, and purity of lignin which will influence the lignin valorization process. In addition, different applications of lignin might require a certain type or quality of lignin. To make desired products from lignin and have a consistent processability in lignin valorization, it is necessary to identify the properties of the lignin needed in each application.

Development and commercialization of lignin valorization technologies requires stable supply of lignin and consistency in the quality of the selected lignin. Currently, most of the lignin

produced in kraft pulp mills is burned as low-value fuel to generate energy and a very small fraction of it is used for producing value added materials, chemicals, and fuels.

3.2.2 The kraft pulping process

The kraft (or sulphate) pulping process is currently the most common method used to produce pulp. The basics of kraft pulping technology were developed nearly 130 years ago, but the process continues to be the subject of intensive research and development pushed by increasing production capacities, growing environmental awareness and new innovative application fields for future forest products. A large part of these research efforts is directed towards different issues of energy optimization, e.g., design of robust and efficient evaporation plants, reducing fresh steam consumption, minimizing the risks of scaling, etc.

The kraft process' most prominent stages are seen in Figure 2 and can be summarized as below. In the kraft process an aqueous solution of sodium hydroxide (NaOH) and sodium sulphide (Na_2S), the so-called 'white liquor', is applied to wood chips at pressurized conditions, 150-170°C and high pH for the wood lignin dissolution/hydrolysis (and other minor wood components) and at the same time fibers are liberated from the wood [10]. This process stage, called cooking, conducted in a pulp digester, produces a mixture of fibers, dissolved wood solids and spent cooking chemicals. The liberated cellulose fibers are removed and subsequently washed. The washed fibers are most often delignified further in an oxygen delignification stage, then washed and bleached in several stages with washing in between. The remaining liquid from the digester, consisting of dissolved organic solids from the wood, spent inorganic chemicals and the washing liquid, is known as "weak black liquor".

The weak black liquor is evaporated to a high dry solids content, typically from 14-18 to 70-85 wt% in 5-8 serial evaporators and concentrators. It is during this evaporation that the recovery of by-products, such as, turpentine and tall oil is conducted, and it is also where lignin is extracted. The perhaps most characteristic feature of the kraft process is the unique method of regenerating the process chemicals (NaOH and Na_2S) in the white liquor with a high yield. The high dry content black liquor is from the evaporation is combusted in the recovery boiler for recovery of the spent cooking chemicals. The combustion at the same time allows utilization of the latent heat of the black liquor for production of green, biomass-based steam and power. The chemical smelt from the recovery boiler is essentially a mixture of Na_2S and Na_2CO_3 which is subsequently dissolved in water and then termed green liquor. Lastly, the white liquor is restored in a causticization step from the green liquor by the conversion of Na_2CO_3 to NaOH by the use of $\text{Ca}(\text{OH})_2$ which then converts to CaCO_3 . The CaCO_3 , is calcinated in a lime kiln at high temperature to restore CaO, which is subsequently slaked with water to obtain $\text{Ca}(\text{OH})_2$ again.

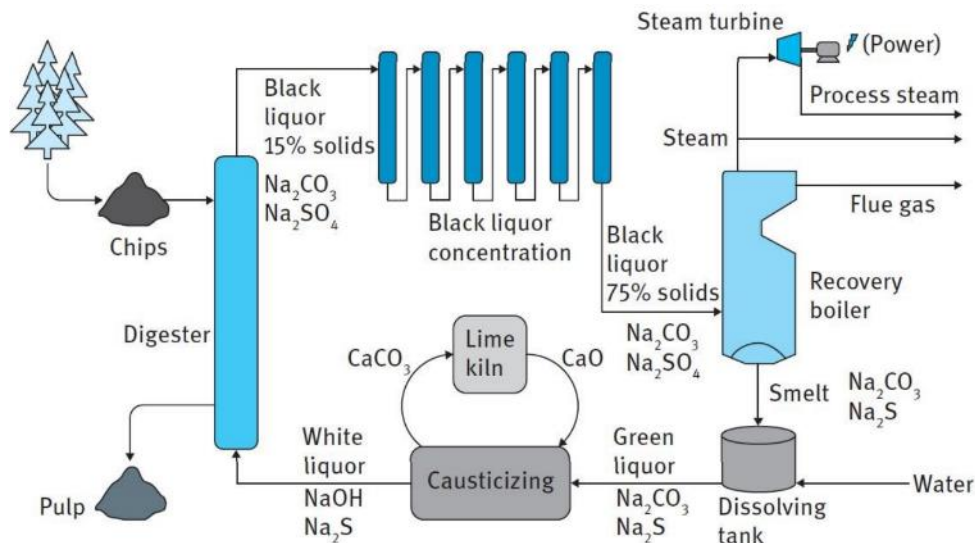


FIGURE 2: SCHEMATIC DIAGRAM DISPLAYING THE MAIN STAGES IN A KRAFT PULP MILL [11]

3.2.3 Kraft lignin separation

The multi-component mix, black liquor, made up of various organic and inorganic compounds is considered one of the key process streams in the kraft pulp production process. Its most common components include diverse organic compounds including carbohydrates, alcohols, organic acids etc. along with inorganic salts like Na₂S, NaOH, NaCl, Na₂SO₄, Na₂CO₃, Na₂S₂O₃ as well as wood-derived elements (Ca, K, P, Si, Al, Ba, Mg, Mn etc.). Most importantly, it contains lignin. Extraction of lignin from the black liquor is an alternative for kraft pulp mills to both debottleneck the recovery boiler when production increases are desired and to create a by-product that can be further developed into various value-added applications such as chemicals, activated carbon, carbon fibers, thermoplastics, biofuels etc.

There are a few developed lignin extraction techniques for alkaline pulping liquors, each with very similar process stages. Some of the most common techniques are listed below:

- LignoBoost [12] with one large scale plant in USA, Plymouth, and one in Finland, Sunila, with a combined capacity of 75 000 ton per year.
- LignoForce [13] with one large scale plant in Canada, Hinton, with a capacity of 10 500 ton per year.
- A-Recovery+ technology [14], marketed by Andritz, does not seem to yet exist in industrial scale.

The general process principle for the LignoBoost concept (see Figure 3) is briefly explained below. In the first step, black liquor (at 30-40 % dry solids) is precipitated to a pH of ~10 with CO₂ and then filtered. The resulting filter cake is resuspended with H₂SO₄ to a pH of ~2-3 and then displacement washed and pressed to ~65 % dry solids content. A ring drier further decreases the moisture content to >10%. The two filtrates from the presses are led back to the pulp mill.

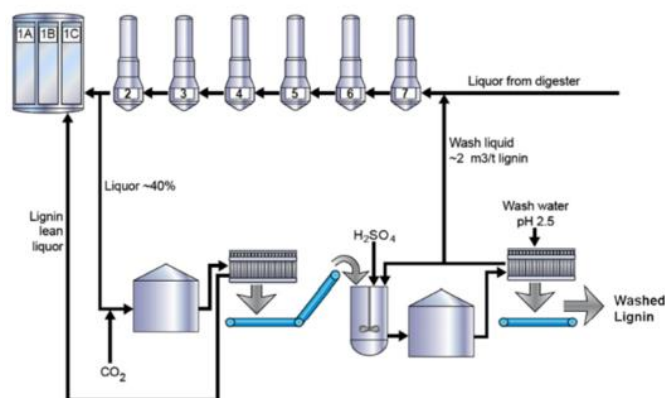


FIGURE 3: A SIMPLIFIED LAYOUT OF THE LIGNOBOOST PROCESS

The amount of lignin possible to extract from the black liquor varies greatly from mill to mill due to different process conditions and each case should be evaluated separately. Literature sources reports a wide range of 5-36 % of available lignin extraction without compromising the operation of the mill [15-17]. Valmet, the owner of LignoBoost, states that many mills can extract around 25 % of the lignin and that the 50,000 annual tons LignoBoost plant in Sunila, Finland, extracts 22 % of the available lignin [18].

3.2.4 Other types of lignin

Apart from kraft lignin, there are of course other sorts of lignins on the market, with different qualities and purities, stemming from other upstream processes, treatments, and raw materials. The most notable of these, in terms of amounts produced, are lignosulphonate, which is extracted from the spent liquor at sulfite mills. The typical commercial applications for lignosulfates are as surfactants, bonding agents, dispersant etc. Hydrolysis lignin is mostly originating from biorefineries such as bioethanol plants and its availability is expected to rapidly increase in the future. Soda and Organosolv lignin are two other types, which are free from sulfur. Soda pulping has mostly been adopted in Asia and South Africa for non-woody biomass. The soda lignin is used for production of phenolic resins, animal nutrition and polymer synthesis. Organosolv lignin is produced using an organic solvent treatment process and is still not really commercialized due to high capital investment and expensive solvent recovery.

Different lignins produced using different processes have different properties such as purity, molecular weight, and functional groups. Table 1 summarizes the main properties of the different lignins. The data shows how a separation process can significantly alter properties of the lignin. Both kraft and Organosolv lignin have high purity which makes them suitable for a wide range of applications. Hydrolysis lignin has the lowest purity and contains high quantity of residual carbohydrates.

Production of sulfur free lignin such as Organosolv, soda and lignin from second generation biorefineries is still small and not comparable with kraft and lignosulfonates. Lignosulfonate production in 2015 was 1.1 Mt [15] and by that dominated (and still dominates) the market of produced lignins. However, since the kraft process is by far the most common pulping process in the world, the capacity potential of kraft lignin supply is the most interesting from a mass production perspective.

TABLE 1: CHEMICAL AND PHYSICAL PROPERTIES OF DIFFERENT COMMERCIAL LIGNINS [19].

Type	Sulfur content (wt.%)	Sugar content (wt.%)	Ash content (wt.%)	Purity scale	Molecular weight (g/mol)	Polydispersity	Elemental analysis			T_g (°C)
							N (wt.%)	H (wt.%)	C (wt.%)	
Kraft	1.0–3.0	1.0–2.3	0.5–3.0	High	<25,000	2.5–4	0.9	5.8	62.8	108–165
Lignosulfonate	3.5–8.0	-	4.5–8.0	Low	<15,000	4.2–9.0	0.2	3.7	47.9	127–154
Soda	0	1.5–3.0	0.7–2.3	Medium-high	<15,000	2.5–3.5	0.9	5.9	61.9	150–155
Hydrolysis lignin	0–1.0	10.0–22.4	1.0–3.0	Medium-high	5,000–10,000	1.5–3.0	0.5	6.2	47.8	75–90
Organosolv	0	1.0–3.0	~1.7	Very high	<5000	1.5–2.4	0.3	5.9	61.1	89–97

3.2.5 Global and Swedish kraft lignin availability

In 2019, about 144 million ADt (Air-dried tonnes, i.e. 90 % dryness) out of the total amount of pulp produced globally (183 MADt) was kraft pulp [20, 21]. The corresponding kraft pulp production in Europe and Sweden for 2019 was around 26 out of the total 38 MADt pulp [20] and 8 out of the total 12 MADt pulp [22] respectively. These production numbers include both bleached and unbleached softwood (SW) and hardwood (HW) pulp as well as pulp produced for the market and for integrated paper/board production.

To estimate the global, European, and Swedish availability of kraft lignin several reference values and assumptions were applied. A rough pulp yield of 50.0 % to even out the, in general, higher yields of Eucalyptus species with the lower yields of softwood species was assumed. The lignin composition in wood varies between 20-30 wt % (dry) depending on species, where softwoods are on the higher end, eucalyptus species somewhere in the middle and other hardwoods, e.g. birch, at the lower end [23]. An average wood lignin content of 25 wt% was assumed in the calculations. The amount of lignin dissolved in the digester varies greatly depending on the sort of species and the cooking conditions (chemical charge, temperature, time etc.) but a plausible number that was used in the calculations is a 95 % dissolution [10]. This means that roughly 95 % of the lignin in the woody feedstock ends up in the black liquor and the global annual amount of that available lignin was estimated (with the above inputs) to ~62 Mt. Literature suggests the corresponding number to be 50-70 Mt/y [24]. Furthermore, it was assumed that the extractable fraction of available lignin in the black liquor should be considered as a range from 15-25 %. After applying the above numbers and assumptions the resulting estimated amount of kraft lignin available worldwide and in Europe and Sweden would be 9.2-15.4, 1.7-2.8 and 0.5-0.9 Mt per year, respectively. This worldwide potential compares relatively well with other references; 3.5-14 Mt/y [15, 25]. The global, European and Swedish kraft pulp productions and their respective kraft lignin and downstream ABC Salt jet fuel potential capacities are summarized below in Table 2 and Table 3. The conversion efficiency of kraft lignin to jet fuel according to the ABC Salt process is 61 % (see Table 7). The global jet fuel demand for 2019 was 331 Mt/y. Thus, less than 3 % of the global 2019 jet fuel consumption could have been provided through the ABC-Salt process. The jet fuel consumption in Sweden on the other hand was roughly 1 Mt/y. Thus, up to half of the Swedish jet consumption could be provided through the ABC-Salt process.

TABLE 2: SUMMARY OF ESTIMATED KRAFT LIGNIN AND CORRESPONDING ABC SALT JET FUEL POTENTIALS BASED ON 2019 GLOBAL, EUROPEAN AND SWEDISH KRAFT PULP PRODUCTIONS.

	2019 kraft pulp production [Mt/y]	Kraft lignin available in black liquor [Mt/y]	Kraft lignin potential [Mt/y] ^a
World	144	61.6	9.2-15.4
Europe	26	11.4	1.7-2.8
Sweden	8	3.6	0.5-0.9

^a The range is based on 15-25 % of lignin extracted from the black liquor.

TABLE 3: 2019 JET FUEL DEMAND AND POSSIBLE CONTRIBUTION THROUGH THE ABC-SALT PROCESS.

	Jet fuel potential ^a [Mt/y]	Jet fuel demand [Mt ₂₀₁₉ /y][26]	Jet Potential/ Jet Demand [%]
World	5.6-9.4	331	1.7-2.8
Europe	1-1.7	80	1.3-2.1
Sweden	0.3-0.55	1	30-55

^a Jet fuel potential based on dry lignin fed to the ABC-Salt process with a conversion efficiency of 61 %, assuming that the whole oil fraction can be used as jet fuel.

3.3 Product Properties and Specifications

The product derived from representative runs is investigated with respect to its applicability as jet fuel. Hydrotreated liquid products were produced from the ABC-salt integrated unit commissioned at RUG, Groningen, with Lignoboost as feedstock. Lignoboost was depolymerized to a liquid product by continuous hydrolysis in molten salts. The hydrolysed oil was hydrotreated using commercial pre-sulfied NiMO catalyst in a packed bed reactor to achieve a final product with a very low oxygen content. Process conditions of the individual steps: hydrolysis and hydrotreatment, were optimised to achieve an overall carbon yield, from lignin to hydrotreated product, of around 78 C%. The hydrodeoxygenated product was distilled in the temperature range of 100-260 °C to arrive at a fraction that is aimed to be in the middle distillate range. Almost one litre of distilled product was made available from the experimental setup.

Jet fuels typically compose of different alkanes (n-, iso-, cyclo-) and aromatics. It is worth noting that hydrocarbons containing heteroatoms (O, N, S only traces allowed) as well as olefins (less than 1 % is allowed as unsaturated molecules lead to gum formation) are unacceptable for the use in jet fuel engines [4]. Each of the allowed molecular subgroups adds to the global properties of the fuel (see Table 4). Alkanes have a higher specific energy, but lower energy density, and less particulate matter is formed in the combustion process [4]. N-alkanes have drawbacks regarding the low density, hence energy density and poor freezing/flashpoints [4]. A combination of iso-alkanes and cycloalkanes enables a high

specific energy, good thermal stability, low freezing points, a high (energy) density and may also provide a seal-swelling property which is usually provided by aromatics [4].

TABLE 4: QUALITATIVE PROPERTIES OF DIFFERENT HYDROCARBON GROUPS THAT ARE FOUND IN JET FUEL [4]

		<i>n</i> -Alkanes	Iso-Alkanes Weakly Branched	Iso-Alkanes Strongly Branched	Cycloalkanes Monocyclic	Cycloalkanes Fused Bicyclic	Aromatics
Performance	Specific energy	++	++	++	+	0	-
	Energy density	-	-	-	+	++	++
	Thermal stability	+	+	+	+	+	
	Sooting	++	++	++	+	+	--
Operability	DCN	++	+	-			-
	Density	-	-	-	+	++	+
	Freeze point	-	+/-	+	+	+	+
	Sooting	++	++	++	+	+	--

The full set of properties is listed in ASTM 7566-20b. As the process under investigation in this project is not listed as an Annex in this ASTM the data from Table 1 “Detailed Requirements of Aviation Turbine Fuels Containing Synthesized Hydrocarbons” is used in order to benchmark the ABC-Salt product. The properties investigated in this deliverable are shown in Table 5. The results indicate a very good agreement of the final ABC-Salt product properties compared with the target jet fuel specifications. 15 out of 19 of the product properties are in line with the target specifications. Small adjustments in the distillation and by applying the maximum applicable blending ratio of 50 % further improved the results (18 out of 19 of the properties reached for the blend). However, further investigations are necessary to reach the target flash point, which is important for safe fuel handling. It was estimated that, in order to reach the specification, the maximum allowable blending ratio is 7 %. However, this is only an estimation through an empirical approach (from [27]). As small amounts may already affect the flash point significantly it is advised to separate fractional amounts of the lightest fraction and analyze the flash points of the remaining product. This may lead to a product that has the appropriate flash point without significant impact on the other properties. It may be concluded that despite the low TRL, the analysis of the product indicates the suitability of the ABC-Salt product as SAF.

TABLE 5: PRODUCT PROPERTIES OF THE ABC-SALT PRODUCT IN COMPARISON TO THE ASTM SPECIFICATION FOR JET FUEL AND AN EXEMPLARY SET OF TYPICAL JET A PROPERTIES.

Parameter	Method	Specifications ASTM D7566-20b			Jet A	ABC Salt Final product	CPK-O/IH2
		Min	Max				
Basic and Extended Requirements							
<i>Composition</i>							
Acid number	ASTM D3242 :2011		0.1	mgKOH/g	0.01	0.009	0
Aromatics	ASTM D8267 :2019	8	25	vol.-%	16.4	8.35	<0.2
Sulfur, mercaptan	ASTM D3227: 2016		0.003	wt.-%	0.001	<0.001	0
Sulfur, total	ASTM D2622:2021		0.3	wt.-%	0.0376	0.00711	0.0014
<i>Volatility</i>							
T10	ASTM D86		205	°C	155	110.4	161
T50	ASTM D86	Report			205	130.9	190
T90	ASTM D86	Report			244	253.2	249
Final boiling point	ASTM D86		300	°C	271	304.3	271
Distillation loss	ASTM D86		1.5	vol.-%	0.5	0.6	0.5
Distillation residue	ASTM D86		1.5	vol.-%	1.4	1.3	1.2
T50-T10	ASTM D86	15		°C	50	20.5	29
T90-T10	ASTM D86	40		°C	89	142.8	88
Flash point	DIN EN ISO 3679 :2015	38		°C	48	5	40
Density at 15 °C	ASTM D4052 :2018	775	840	kg/m3	803	809	832
<i>Fluidity</i>							
Freezing Point (Jet A/Jet A-1)	ASTM D5972 :2016		-40/-47	°C	-51	-39.4	-61
Viscosity at -20 °C	ASTM D7042 :2020		8	mm2/s	4.6	2.624	4.6



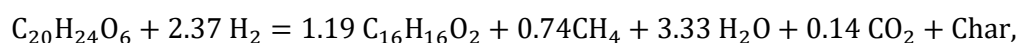
Table continued							
<i>Combustion</i>							
Net heat of combustion	ASTM D4809 :2018 mod.	42.8		MJ/kg	43.1	42.54	43.1
Smoke point	ASTM D1322 :2019	18		mm	26	26.7	28
Naphthalene	ASTM D1840 :2007		3	Vol.-%		0.38	
<i>Corrosion</i>							
Corrosion, copper strip (2h at 100 °C)	ASTM D130 :2019		1	No.	1a	1a	1b
<i>Thermal Stability</i>							
2.5 h at 260°C, Tube rating	ASTM D3241 :2020 Annex 4		3		260	Not enough sample	325
2.5 h at 260°C, Filter pressure drop	ASTM D3241 :2020 Annex 4		25	mm Hg	0		0
<i>Contaminants</i>							
Existent gum	IP 540 :2008		7	mg/100ml	<1	5.4	<1
<i>Lubricity</i>							
Lubricity	ASTM D5001 :2019		0.85	mm	0.61	0.59	0.8

3.4 Net Production Cost and Efficiency

A flowsheet model is set up in Aspen Plus based on the experimental outcome and advances of the project. Figure 4 shows the general configuration of the base case V7 flowsheet model. Lignin (8 wt.-% moisture, 3.53 t/h [28],[29]) and molten salt #4. The feed is liquefied and pumped to the hydrolysis (HP) reactor (the liquid state is secured by dedicated measures). Additionally, fresh hydrogen and recycled hydrogen from a membrane unit are fed into the HP reactor. The HP product is separated in a flash in order to separate the liquid fraction from the gases. The gaseous components are fed to a membrane unit in order to recover unreacted hydrogen. The bottom fraction containing oil, aqueous phase, salt and char is further processed through the addition of acidic water to separate the salt containing aqueous phase from the oil fraction. The oil fraction continues to the first hydrodeoxygenation step (HDO-1). There again pure and recycled hydrogen from the membrane unit enter the HDO-1 unit. The HDO-1 product is separated in several flashes targeting the separation into several streams, at least one consisting mainly of gaseous components that are fed to the membrane unit for hydrogen recovery and one fraction that contains the target product to be fed to the final HDO-2 step. The HDO-2 product is separated into three fractions – a gaseous fraction, an aqueous fraction and the (oily) product fraction. Again, the gaseous fraction, consisting of reaction products and unreacted hydrogen, is fed to a membrane unit for hydrogen recovery. The permeate from this membrane unit is recycled while the retentate continues to the pulp mill for heat/steam generation. In order to avoid accumulation of inert gases, 2 wt.-% of the permeate is assumed to be purged. This purge gas also continues to the pulp mill.

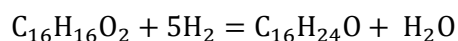
The stoichiometric equations (i-v) used in the Aspen Plus simulation are:

- i. Hydrolysis (100 % conversion)

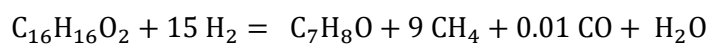


with Char(wt%) = 75.3 % C, 6.3 % H, 18.4 % O

- ii. HDO-1 – Hydrogenation of lignin oil (92 % conversion)



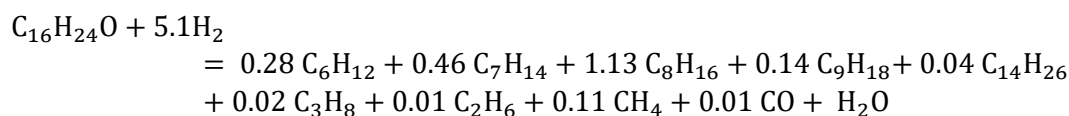
- iii. HDO-1 – Hydrocracking of lignin oil (8 % conversion)



- iv. HDO-2 – Hydrotreatment of lignin oil to aromatics (25 % conversion)



- v. HDO-2 – Hydrotreatment of lignin oil to cycloalkanes (75 % conversion)



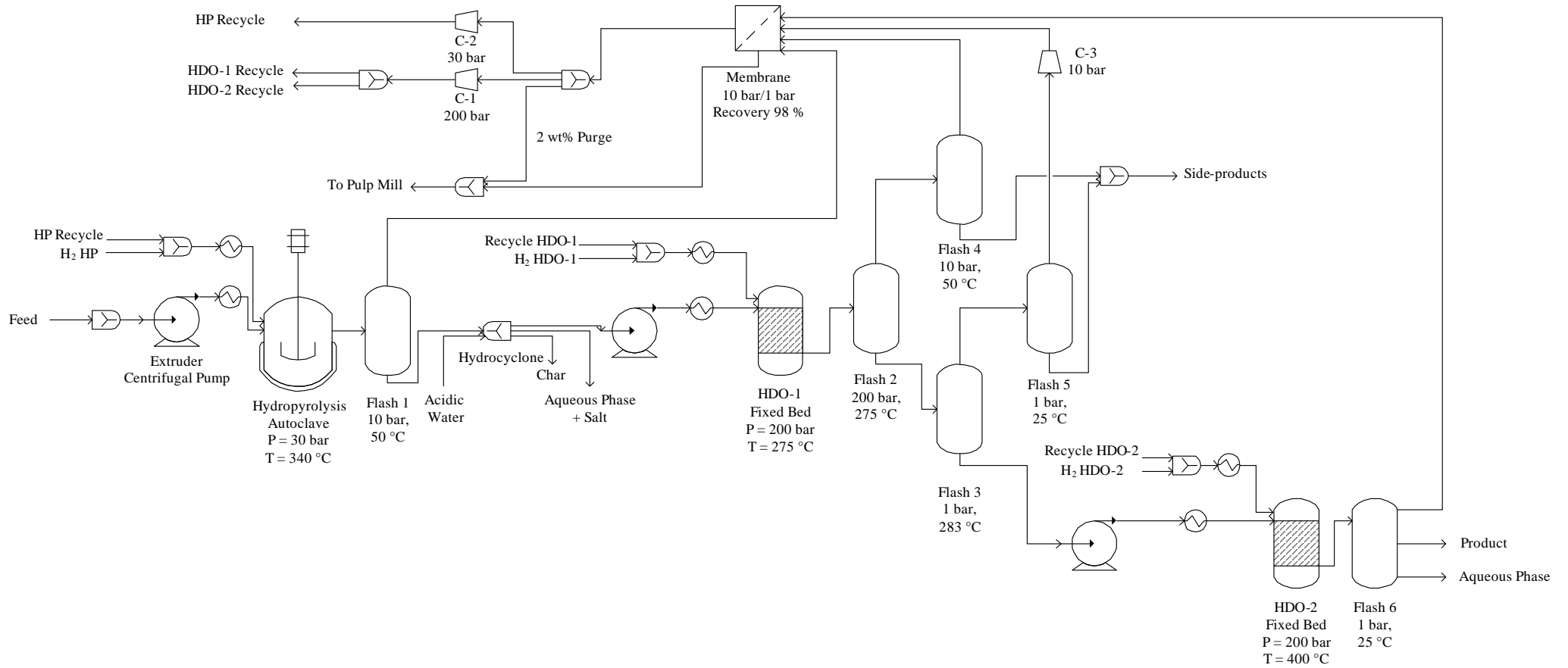


FIGURE 4: FLOWSHEET BASE CASE MODEL V7. THE PLANT PROCESSES 3.53 T/H OF LIGNIN.

The ABC-Salt process is thermally and materially integrated into a pulp mill process. Therefore, drying and steam generation section are allocated at to the pulp mill and the gaseous by-products from the membrane unit and the resulting char are provided from the ABC-Salt process to the pulp mill. It is assumed that the gaseous components, char and if applicable heat/steam are transferred free of charge between pulp mill and ABC-salt process. The resulting lignin cost are calculated based on this material integration. Lignin is usually burned in the pulp mill for electricity generation. Thus, the lignin extraction from the pulp mill leads to a loss in power production. This loss is reduced through the char and gas input from the ABC-Salt process to the pulp mill. Therefore, the lignin price is lower in case of the ABC-Salt process integration. The resulting lignin price is 362 EUR/t_{lignin}. The reference lignin price without the depicted ABC-Salt integration is 412 €/t_{lignin} (LignoBoost only).

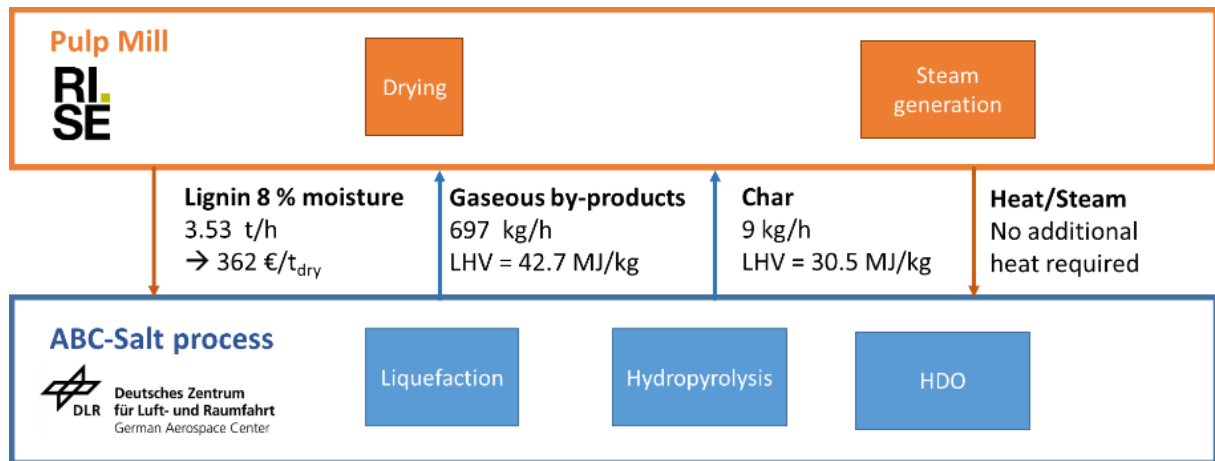


FIGURE 5: PULP MILL AND ABC-SALT PROCESS - MATERIAL AND THERMAL INTEGRATION.

Table 6 shows the results for a set of defined technical key performance indicators and properties. The lower heating values (LHV) are determined in the Aspen Plus simulation by fully combusting (adiabatic) the dry lignin/ the product stream with O₂. LHV_{Lignin} is slightly higher compared to literature data (softwood LignoBoost: 25 MJ/kg, [30]). The LHV of fossil diesel and Jet-A1 is 42-44 MJ/kg. The lower heating value of the ABC-Salt product is in good agreement with the desired product heating value (42 MJ/kg).

Four efficiencies are defined according to the following equations:

- $\eta_{H2+BtL} = \frac{\dot{m}_{Product} \cdot LHV_{Product}}{\dot{m}_{H2} \cdot LHV_{H2} + \dot{m}_{Lignin,dry} \cdot LHV_{Lignin}}$
- $\eta_{energy} = \frac{\dot{m}_{Product} \cdot LHV_{Product}}{Q_{ext} + \sum P_{el} + \dot{m}_{H2} \cdot LHV_{H2} + \dot{m}_{Lignin,dry} \cdot LHV_{Lignin}}$
- $\eta_C = \frac{\dot{m}_{C,Product}}{\dot{m}_{C,Lignin,dry}}$
- $\eta_H = \frac{\dot{m}_{H,Product}}{\dot{m}_{H2} + \dot{m}_{H,Lignin,dry}}$

The carbon efficiency is 78.2 % in the base case, meaning that 78 % of the carbon entering the ABC-Salt plant in form of lignin is incorporated in the fuel products. The low 'loss' in carbon is mainly as gas (almost 20.8 % of carbon ends up in gas, see Table 7) and to an even smaller extent as char and in the aqueous phase produced. Overall, the process is exothermic, meaning that more heat is produced than is required which results in zero external heat demand (Q_{ext} = 0). Remarkably, the hydrogen+biomass-to-liquid efficiency is high, around 67 % and the overall energy efficiency is 60 %. The hydrogen efficiency is 51 %, meaning that

51 % of the hydrogen incorporated in the dry lignin plus hydrogen that is added to the process ends up in the liquid fuel fraction. Most of the remaining hydrogen ends up either in the gas, that is transferred to the pulp mill, or in the aqueous phase, in the form of water as well as small amounts of organics that dissolve in water. Ideally, from the stoichiometry of the reactions, 244 kg/h of hydrogen are consumed by the reactions. Thus, 15 % more hydrogen is required in comparison to an ideal, full conversion. This arises from the fact that the reactions are conducted over-stoichiometrically, hence, more hydrogen is fed to each of the reactors than is actually required for the reaction. In order to still have a high hydrogen efficiency, 98 % of the hydrogen are recovered in the membrane reactor and the retentate proceeds to the pulp mill. Therefore, the actual hydrogen demand is higher than the hydrogen demand from the stoichiometry of the reaction equations. The overall amount of gas that is recycled to the plant is 1068 kg/h consisting of 91 wt.-% H₂, whereas the retentate to the pulp mill is 675 kg/h containing little over 3 wt% of H₂.

TABLE 6: OVERVIEW TECHNICAL KPIs AND PRODUCT PROPERTIES BASE CASE V7

LHV _{Lignin}	27.8	MJ/kg
LHV _{Product}	42.0	MJ/kg
η_{H_2+BtL}	67	%
η_{energy}	60	%
η_c	78	%
η_H	51	%

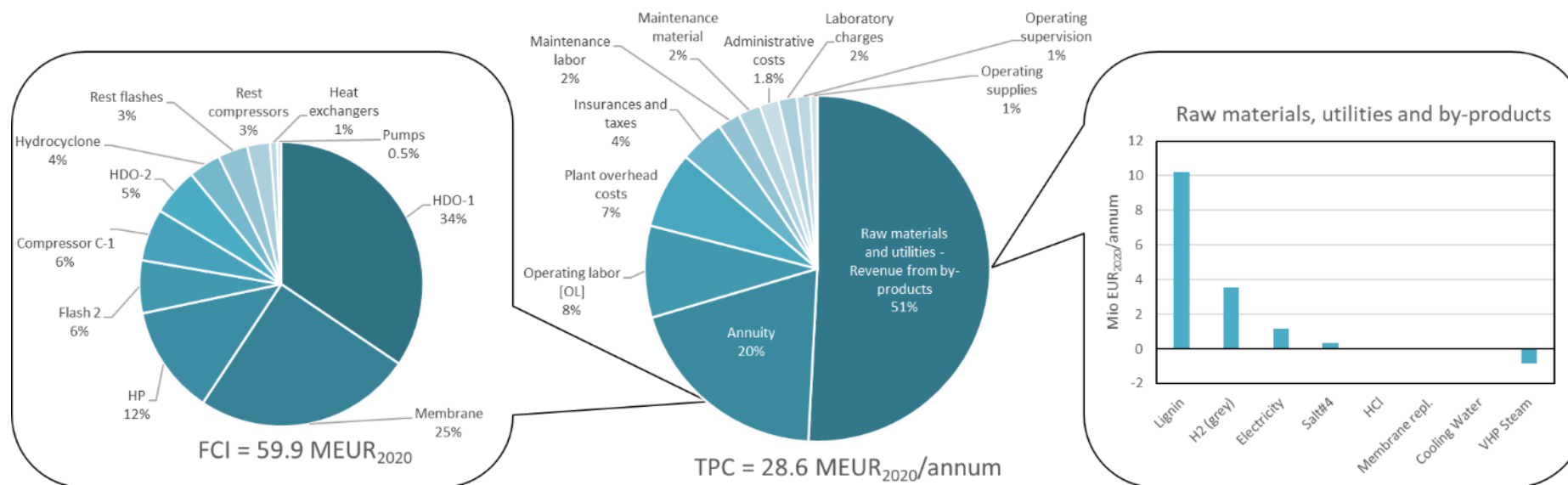
TABLE 7: HYDROGEN, CARBON AND OVERALL MASS BALANCES BASE CASE V7

Hydrogen Balance					
In	kg/h		Out	kg/h	
Lignin dry	216	40.8%	Fuel	254	47.9%
Hydrogen	281	52.9%	Aqueous Phase	126	23.8%
Moist. Lignin	31	5.9%	Gas to Pulp Mill	150	28.2%
			Char	1	0.1%
Carbon Balance					
In	kg/h		Out	kg/h	
Lignin dry	2166	100.0%	Fuel	1693	78.2%
Hydrogen	0	0.0%	Aqueous Phase	16	0.7%
Moist. Lignin	0	0.0%	Gas to Pulp Mill	451	20.8%
			Char	7	0.3%

Mass Balance					
In	kg/h		Out	kg/h	
Lignin dry	3250	85.2%	Fuel	1974	51.8%
Hydrogen	281	7.4%	Aqueous Phase	1135	29.7%
Moist. Lignin	283	7.4%	Gas to Pulp Mill	696	18.3%
			Char	9	0.2%

Figure 6 summarizes the key results of the economic analysis. The total production cost TPC is 28.6 MEUR₂₀₂₀ per year. The two largest contributors are the direct OPEX (raw materials + utilities – revenue from very high-pressure steam) with 51 % and the annuity with 20 %. Labor cost in Sweden accounts for 8 % and the remaining indirect OPEX add up to 21 %. Raw materials and utilities sum up to 15 MEUR per year whereas the main contributor is the lignin cost (67 %). Hydrogen (1.58 €/kg_{H2} [31] → 3.6 MEUR/a) and electricity (48.8 €/MWh [32] → 1.5 MEUR) further add to the cost, while the cost for the salt, hydrochloric acid, membrane replacement and cooling water are comparably low and can be neglected. The annuity cost is closely related to the fixed capital investment FCI. Overall, the CAPEX is 59.9 MEUR. The two reactors make for almost half (46 %) of the FCI. Another major contributor is the membrane cost that strongly correlates with the hydrogen recovery assumed (here: 98 %) as higher recovery rates require larger membranes while reducing the hydrogen cost. Overall, the net production cost is 1.81 EUR/kg_{Product} with the main contributors being the lignin (36 %) and the hydrogen (12 %) cost.

A sensitivity analysis is conducted to identify further cost reduction potentials through further process optimization. The results show that the optimum hydrogen recovery is dependent on the hydrogen price (base case: 1.58 €/kg_{H2}), with recoveries of 90-95% showing good results throughout the whole investigated hydrogen price range. Additionally, the NPC could potentially be reduced by a further optimization. The technical feasibility of this reduction, however, remains yet to be proven. Through optimization, it is likely that equipment cost can be drastically reduced (FCI_{Base} = 60 MEUR vs. FCI_{Opt} = 28 MEUR). The higher hydrogen cost, because of the lower recovery, is to a certain extent outweighed by the lower lignin price and cost for compression work. Overall, this optimization leads to 1.56 €/kg_{Product} which is in the range of the the latest jet fuel price development (1.65 €/kg_{jet fuel}, 143.5 USD/barrel [5] converted with a density of 800 kg/m³ and an exchange rate of 1.1 EUR/USD).



NPC: 1.81 EUR/kg _{Product} or 1.45 EUR/L _{Product}					
NPC	€/kg	NPC	€/kg	NPC	€/kg
Lignin	0.647	Membrane	0.088	Administrative cost	0.032
H2 (grey)	0.225	Maintenance	0.076	Laboratory charges	0.031
Labor cost	0.179	Insurances and taxes	0.076	Salt losses	0.022
Plant overhead cost	0.130	Electricity	0.071	Flash 2	0.021
HDO-1	0.122	HP	0.044	Rest	0.046

FIGURE 6: KEY ECONOMIC RESULTS FOR THE BASE CASE MODEL

3.5 Ecological Impact

The life cycle assessment (LCA) is based on the same Aspen Plus process simulation as the techno-economic assessment which was described in the previous section 3.4. The thermal and material integration of the ABC-Salt process into a kraft pulp mill process was taken a step further for the LCA. The ABC-Salt process not only delivers char and gaseous by-products to the pulp mill for electricity generation but also receives electricity required for various pumps, compressors and the extruder from the pulp mill's generated electricity. Since the pulp mill produces multiple products (pulp, tall oil, turpentine, electricity) besides lignin, energetic allocation was performed, which allocated 5.5% of the impacts from the pulp mill operation with lignin extraction to lignin. In the base case green hydrogen is supplied to the ABC-Salt process, which is generated through alkaline electrolysis (AEL) with Swedish hydro power.

Figure 7 displays the resulting global warming potential (GWP) of 1 MJ (LHV) product produced in the ABC-Salt process and the main contributors to the impact. The GWP is benchmarked against the project goal of an 80% reduction compared with fossil fuel and the REDII limit of a 65% reduction. The REDII fossil fuel value of $94 \text{ g}_{\text{CO}_2\text{-eq}}/\text{MJ}_{\text{product}}$ was used as the comparator [33]. In the base case the ABC-Salt product achieves a GWP reduction of 82% compared with fossil fuel. If grey hydrogen from fossil sources (methane steam reforming) [34] has to be used instead of green hydrogen, the GWP reduction decreases to 39%. Blue hydrogen with 93% carbon capture and storage and a methane emission rate of 1.5% [35] can reduce the GWP of the ABC-Salt product by 71%, which does not reach the project goal yet but meets the REDII limit. Besides hydrogen a major contributor to the GWP of the ABC-Salt product is the lignin production at the pulp mill. The impact mainly stems from the production of various chemical that are used in the pulp mill as well as pulp wood harvesting and transport of these inputs.

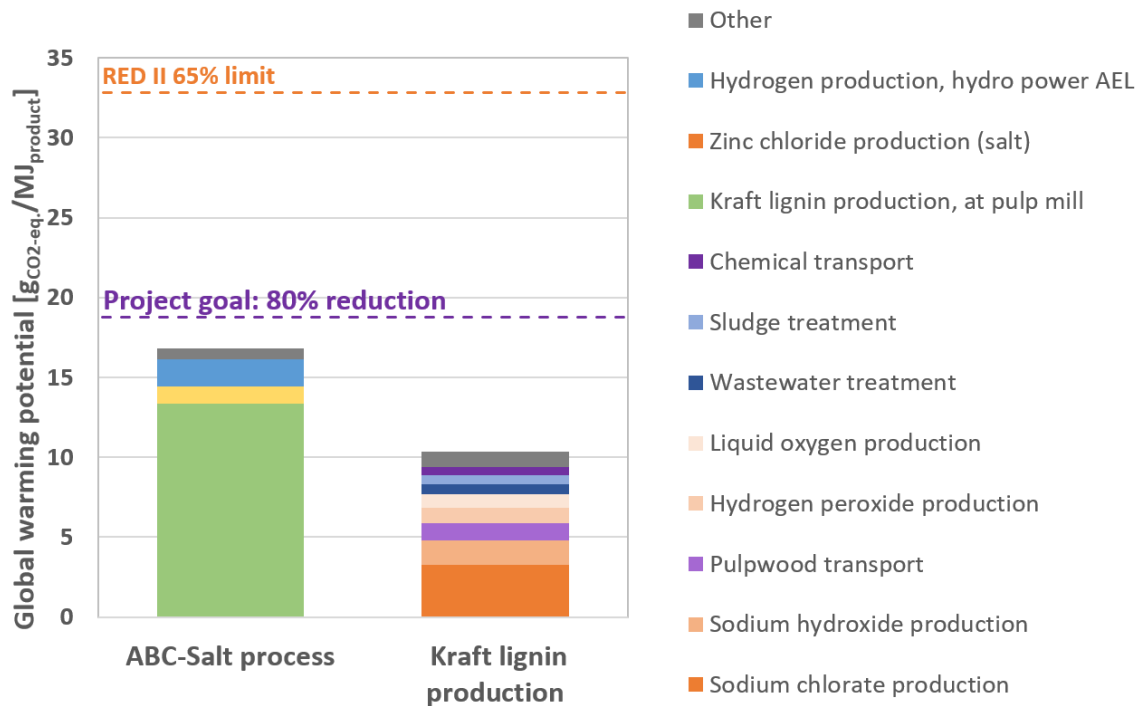


FIGURE 7: GLOBAL WARMING POTENTIAL OF THE ABC-SALT PROCESS AND KRAFT LIGNIN PRODUCTION PER MJ OF PRODUCED PRODUCT

The lignin production is also the main contributor for most of the 16 other categories considered (see Figure 8). Other important contributors are the zinc chloride and hydrogen production. Reductions in global warming potential naturally have some trade-offs with impact increases in other impact categories. In comparison with fossil kerosene there are some categories where an impact increase was to be expected due to the utilisation of biomass and a more complex production chain, e.g., land use, water use and resource use of minerals and metals. Other impact increases like particulate matter formation, freshwater eutrophication, freshwater ecotoxicity and carcinogenic human toxicity need to be investigated in more detail and could be further improved.

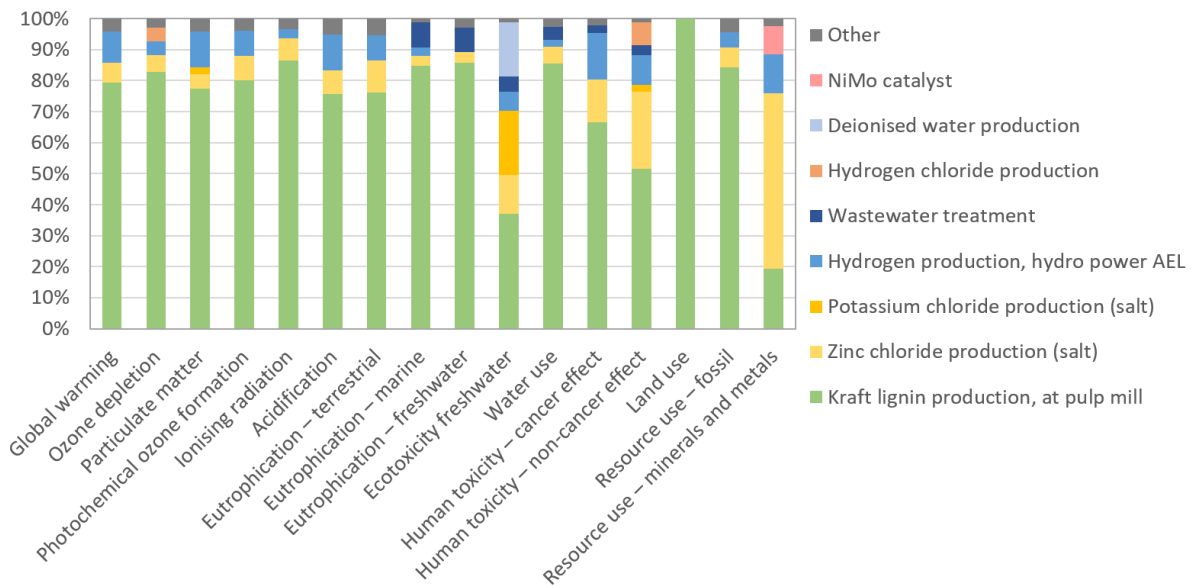


FIGURE 8: IMPACT CONTRIBUTIONS OF THE ABC-SALT PROCESS FOR 16 IMPACT CATEGORIES FROM THE ENVIRONMENTAL FOOTPRINT METHOD

Sensitivity studies regarding the hydrogen recovery showed that high hydrogen recovery rates are more favorable for the GWP even though less gaseous by-products can be sent to the pulp mill for power production. The project goal for the GWP reduction can be reached with hydrogen recovery rates as low as 62% in combination with green hydrogen. The base case assumption was a hydrogen recovery rate of 98%. Blue and grey hydrogen are not able to achieve an 80% GWP reduction for the ABC-Salt product. However, blue hydrogen can be used with hydrogen recovery rates down to 85% to reach the REDII 65 % limit.

3.6 Social Analysis

To make the transition towards renewable and sustainable energy possible, there is a need to make new relevant technologies more acceptable and accepted. This is the case of biofuels too. In order to achieve such a goal, appropriate leveraging is needed for: the perception of the biofuels technology's features; the perception of its context of adoption (in terms of both economics and politics); and finally, the perception that the adopting persons have about a number of their own social-psychological features. Too often end-users resist biofuels technologies due to inherent unconvincing technology characteristics; or to a general skepticism toward the adoption context; as well as to some skeptical personal features by the adopters themselves. This means that to act in favor of biofuels at 360° needs improving both their perceived technological features, and the surrounding context supporting their adoption, as well as some social-psychological features of the target adopters. Achieving the ultimate goal of biofuels adoption thus requires a holistic approach in order to foster this new energy technology acceptability and acceptance considering several biofuels features.

To do this, the Integrated Sustainable Energy Technology Acceptance Model (i-SETA) was developed and tested (Bonaiuto *et al.*, in preparation), also by means of some new piloted tools to measure the relevant biofuels beliefs profile (Ariccio *et al.*, 2022). The results revealed the importance of beliefs belonging to each one of the different considered domains (that is,

about technological, contextual, and personal variables): Several of them directly impact on the cognitive and affective biofuels evaluation, and subsequently on biofuels acceptability and acceptance, both for EU laypeople and expert stakeholders (total sample $N > 1000$).

Main results from the model's statistical test, integrated with those from the preliminary qualitative study (Dessi *et al.*, 2022), thus revealed that very specific beliefs, across all the three beliefs classes, can be identified as either barriers or drivers with respect to the aim of boosting biofuels acceptability and acceptance (as summarised in Figure 9), in view of biofuels' future adoption.

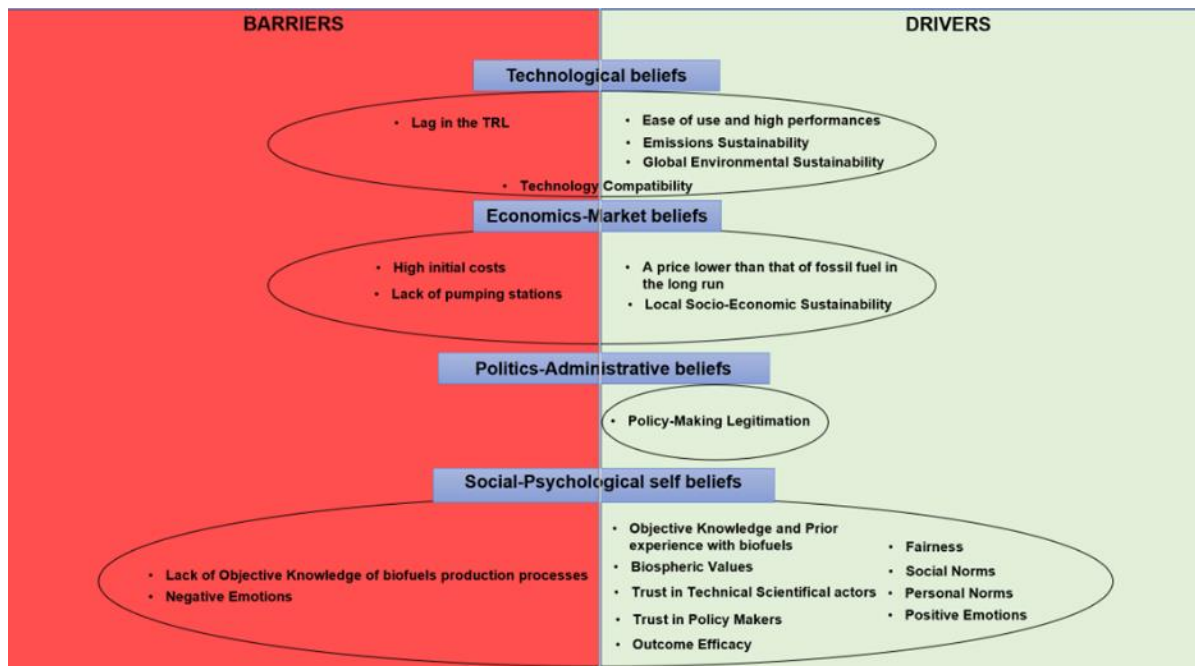


FIGURE 9: SYNTHESIS OF BARRIERS AND DRIVERS FOR BIOFUELS ACCEPTABILITY AND ACCEPTANCE

The biofuels beliefs that emerged as barriers to biofuels acceptability and acceptance are summarised below.

- 1) Technological beliefs as barriers:
 - A lag in the TRL.
- 2) Economic-market beliefs as barriers:
 - Higher initial costs in comparison with fossil fuels or other sustainable energy technologies;
 - The lack of pumping stations.
- 3) Social-psychological self-beliefs as barriers:
 - The lack of objective knowledge of biofuels production processes;
 - "Negative Emotions" elicited by biofuels.

The biofuels beliefs that emerged as drivers for biofuels acceptability and acceptance are summarised below.

- 1) Technological beliefs as drivers:
 - Ease of use and high performances compared with other sustainable energies;
 - "Emissions Sustainability" (emissions decrease because of the use of biofuels vs. fossil fuels);
 - "Global Environmental Sustainability" (positive global environmental effect of biofuels);
 - "Technology Compatibility" (the resulting degree of integration of biofuels into existing infrastructure without requiring changes and without drastically transforming the auto market) can be a driver, which however implies a coherent lower availability to pay (thus a barrier in terms of willingness to pay).
- 2) Economic-market beliefs as drivers:
 - A price lower than that of fossil fuel in the long run;
 - "Local Socio-economic Sustainability" (local economic benefits from biofuels use).
- 3) Political-administrative beliefs as drivers:
 - "Policy-making Legitimation" (support from policy makers initiatives to biofuels).
- 4) Social-psychological self-beliefs as drivers:
 - "Objective Knowledge" about biofuels and Prior experience with biofuels;
 - "Biospheric Values" (oriented toward the preservation of the environment and nature);
 - "Trust in Technical Scientific Actors" (regarding their actions toward biofuels);
 - "Trust in Policy Makers" (trust in political action taken toward biofuels by politicians);
 - "Outcome Efficacy" (perceived effectiveness of biofuels outcomes);
 - "Fairness" (the fairness perceptions of the various decision-making processes involved in the implementation of biofuels);
 - "Social Norms" (perceived social influence based on what are the behaviours and thoughts of the people around us);
 - "Personal Norms" (the moral obligation to perform or abstain from specific actions);
 - "Positive Emotions" elicited by biofuels.

Some very general indications about starting ideas to spark tentative implementations – on how to cope with the above-mentioned barriers and how to capitalise on the above-mentioned drivers – have been summarised in in **Deliverable 2.10** ("Public report on new knowledge regarding acceptance and resistance in European population towards new technology for biofuel production").

4 Conclusions and Outlook

Feedstock availability and product properties: Product samples of representative runs are analysed and compared against target specifications (ASTM D7566 - Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons). Despite the low TRL, the results are analysed to monitor the general suitability of the ABC-Salt product as middle distillate, or more specific jet fuel and also to create ideas on how the product could be further processed/tailored in order to achieve close to jet fuel specifications. The results indicate a very good agreement for pure and blended products, with 15 and 18 out of 19 of the target specifications met, respectively. However, more detailed investigations regarding the flash point are necessary. Lignin is investigated as the feedstock derived from the pulp industry. The analysis indicates an availability of 0.5-0.90 Mt/y in Sweden, 1.7-2.8 Mt/y in Europe and 9.2-15.4 Mt/y on a global scale. With a conversion efficiency of 61 % it would only be possible to supply less than 3 % of the total global jet fuel demand in 2019. However, around half the jet fuel consumed in Sweden in 2019 could have been provided from the amount of lignin available in Sweden.

Techno-economic analysis: The conducted techno-economic process analysis allows to investigate the process with respect to material and energy efficiencies as well as to identify the main cost contributors and the resulting net production cost. The technical analysis indicates a high carbon efficiency of 78 % and an energy efficiency of 60 %. The ABC-Salt process model is thermally and materially integrated into a pulp mill process. The lignin price is calculated based on this integration. The base case ABC-Salt net production cost is calculated to 1.81 €/kg_{Product} at a derived lignin price of 362 €/t. Lignin is the main cost contributor. Further theoretical process optimization yields 1.56 €/kg_{Product} which is still a little higher than the latest jet fuel price development (1.24 €/kg_{jet fuel}). However, the technical feasibility of this optimization remains yet to be proven.

Ecological analysis: The performed life cycle assessment enables the determination of the environmental impacts of the ABC-Salt process, especially the global warming potential, and the identification of key impact drivers. Lignin, zinc chloride and hydrogen production are key impact drivers in all investigated impact categories. The global warming potential of the base case ABC-Salt product is 16.8 g_{CO₂-eq./MJ_{product}}, which is equivalent to an 82% reduction compared with fossil fuel. The project goal of an 80% GWP reduction can still be achieved even when the hydrogen recovery rate is decreased from 98% in the base case down to 62%. However, the global warming reduction potential strongly depends on the hydrogen source. If blue or grey hydrogen is utilised instead of green hydrogen, the GWP reduction at 98% hydrogen recovery decreases to 71% and 39%, respectively.

Social analysis: A methodological side result of the social-psychological study is the creation of standardised tools to measure people's beliefs towards biofuels: this is useful in order to standardise the measurement of potential predictors for biofuels marketability. The main result is represented by the list of 5 barriers and 16 drivers for biofuels acceptability and acceptance (see Figure 9): This dashboard contains all the specific social-psychological targets for any initiative devoted to help biofuels marketability. Possible implementations include a wide array of various means (for some first examples, see **Deliverable 2.10**), which could be further elaborated by means of interdisciplinary collaborations too. The general implication can be a 360° plan of activities to set the stage in order to reach the target of improving both general public's and expert stakeholders' affective and cognitive evaluations of biofuels, thus heightening biofuels acceptability (i.e., positive attitudes) and acceptance



(i.e., favourable intentions) from their part. This would prepare the ground capable of maximising the probability for a future final biofuel adoption by both public and stakeholders.

5 Literature

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