

# Final report

## Project details

<b>Project title</b>	<b>Advancement of Hydrofaction® Technology Platform</b>
<b>Project identification (program abbrev. and file)</b>	EUDP-2013-II, Journal number 64013-0513
<b>Name of the programme which has funded the project</b>	EUDP-2013-II, Teknologiområde: Biomasse
<b>Project managing company/institution (name and address)</b>	Steeper Energy Aps, Sandbjergvej 11, 2970 Hørsholm
<b>Project partners</b>	Institut for Energiteknik, Aalborg Universitet
<b>CVR</b> (central business register)	33383835
<b>Date for submission</b>	4. June, 2018

## Short description of project objective and results

### 1.2.1 Kortfattet beskrivelse af projektets formål og resultater (Danish version)

Projektets milestones er blevet opfyldt:

- Der er indgået en licens- og samarbejdsaftale som omfatter etablering af et Industriel Skala De-risking og Demonstrations anlæg med det Norske Selskab *Silva Green Fuel* - et joint venture mellem det Norske el selskab Statkraft og det svenske firma Södra, som er en sammenslutning af 52.000 svenske skovejere. Anlægget som har en forventet pris på DKK 377 M er under etablering på en nedlagt papirfabrik ved Tofte udenfor Oslo, og forventes idriftsat i slutningen af 2019.
- Der er gennemført test produktion med forskellige træbaserede affaldsstrømme, og gennemført en række prototype tests hos leverandører og på pilotanlægget på Aalborg Universitet. Testene har valideret masse- og energibalancer, og tilvejebragt vigtig design information for både demonstrationsanlægget og fremtidige kommercielle anlæg.

### 1.2.2 Short description of the project objective and results (English version)

The project milestones have been achieved:

- A licensing deal including establishment of an Industrial Demonstration Plant has been concluded with Silva Green Fuel (SGF). SGF is a joint venture between the Norwegian Utility company Statkraft and the Swedish company Södra, a coop of 52.000 Swedish forestry owners with extensive forestry operations and a leading producer of paper pulp, sawn timber and bioenergy. The estimated DKK 377M industrial scale demonstration plant is under establishment at Tofte, Norway and is expected to be operational ultimo 2019.
- A number of tests have been performed on wood residues, and prototype testing has been performed in vendor shops and at the pilot plant Aalborg University. The tests has validated mass- and energy balances, generated critical design data for both the industrial scale demonstration project and future commercial projects.

## Executive summary

Hydrofaction® is Steeper Energy's proprietary take on Hydrothermal Liquefaction, which cost effectively converts biomass & waste stream to liquid transportation fuels with unprecedented resource and energy efficiency.

Hydrofaction® is targeting de-carbonization of the long haul transport (heavy trucks, maritime and aviation) – The only segment where GHG emissions continues to rise despite improvements in fuel efficiency, and where efficient solutions are yet to be developed.

The overall project objective has been to advance the Hydrofaction® for commercial readiness so that an Industrial Scale Demonstration Plant could be established as a next step.

This and other objectives have been met by performing an extensive test program at the pilot plant at Aalborg University and in vendor shops allowing for establishment of consistent critical design data and validation of subcomponents for both the Industrial Scale Demonstration Plant.

The high yield and energy promised by Hydrofaction® have not only been validated, but also exceeded by 17 % with about 45 % of the input biomass (dry ash free basis), 73 % of the carbon and more than 85 % of the biomass energy ending up in the desired product. The net energy efficiency has been proven to be more than 81 % to renewable crude oil, and more than 71 % to finished transportation fuels. A "Tree to Tank" life cycle analysis has shown that these numbers converts into net CO<sub>2</sub> savings ranging from 78 % to 108 % depending on the degree of renewable electricity, and whether renewable hydrogen is utilized and/or liquid CO<sub>2</sub> is recovered from the process gas or not.

Though the renewable crude oil produced by the process has many similarities with its fossil counterparts it also have its specialities, which makes upgrading of the oil nontrivial. Significant efforts have been put into this area in order to show the pathways, marketability and value of the crude oil product. New and more efficient protocols have been developed, and "drop in" blend stocks for production of diesel complying to the existing EN590 standard ultra low sulphur diesel, and the ISO 8271 standard for low sulphur RMG180 marine fuels. Meeting existing standards means that the existing engines and the infrastructure established over the last 150 years can be reused. The concentrations of renewable transportation fuels that can be applied are per se limited to 30 % and 62 % by volume, respectively, due to density and cetane number, and flash point restrictions. Upgrading work is continuing beyond the project to push these limits.

An updated techno-economical assessment of the core process to renewable crude oil has been performed with the outset in two third party engineering studies of commercial plants performed with strategic partners (outside the project) in the project period. The updated techno-economical indicates a Capex cost of a commercial 2000 BPD wood to renewable crude oil plant in the range 160-200 MEUR (AACE class 3 estimate). This corresponds to a production cost of 40-50 USD/bbl of crude oil excl. feedstock costs or a current production cost in the range 70-90 USD/bbl incl. feed stock costs.

The critical steps for establishing Hydrofaction® as a commercial ready technology have been to attract significant strategic industrial partners and establish an Industrial Scale Demonstration plant. The project and the quality of data established have directly contributed to overcoming this difficult barrier as a licensing deal including establishment of an Industrial Demonstration Plant has been concluded with Silva Green Fuel (SGF) including establishment of an estimated DKK 377M Industrial Scale Demonstration Plant at Tofte, Norway as the first phase. Hydrofaction® was selected as preferred pathway after technology vetting of over 40 competing technologies.

## Project objectives

The overall project objective has been to advance the Hydrofaction® for commercial readiness so that an Industrial Scale De-risking & Demonstration Plant could be established as a next step.

The main milestones have been accomplished:

### **Milestone 1 (M36): Agreement related to partnership and specific site for 30-100 BPD Industrial Scale Demonstrations Plant**

A licensing deal including establishment of an Industrial Demonstration Plant has been concluded with Silva Green Fuel (SGF). SGF is a joint venture between the Norwegian Utility company Statkraft and the Swedish company Södra, a COOP of 52.000 Swedish forestry owners with extensive forestry operations and a leading producer of paper pulp, sawn timber and bioenergy. The estimated DKK 377M industrial scale demonstration plant is under establishment at Tofte, Norway and is expected to be operational ultimo 2019. Further details about the licensing deal are given in the press release (December 15, 2017: "[Steeper Energy Announces EUR 50.6 M \(DKK 377 M\) Advanced Biofuel Project with Norwegian-Swedish joint venture Silva Green Fuel in Licensing Deal](#)").

### **Milestone 2 (M36): Prototypes constructed, tested and documented**

A number of prototypes have been successfully tested and documented as further described in below. The prototype testing have allowed for selection and validation of critical unit operations for the industrial scale demonstration plant and has to a large extent been performed in collaboration with key vendors.

### **Milestone 3 (M36): Performance data for 4 feed mixtures with woody biomass as basis established**

The pilot plant in Aalborg has been used to optimize operating protocols, establish key engineering data and to produce representative oil-, water- and gas samples for detailed characterization, prototype testing (WP2), upgrading (WP4) and for evaluation by external stakeholders. Close to 400 tests have now been performed over 1750 oil production hours and a total of more than 4500 hours of hot operation. Six different feedstock with woody biomass as the basis have been tested.

High quality mass-, energy- and element balances have been established indicating an oil yield of more than 45 %, a carbon recovery in the oil of more than 73 %, and an energy recovery in the oil of more than 85 %. This translates into a net CO<sub>2</sub> saving of more than 80 %. Numbers which are unprecedented by any technology.

### **Milestone 4 (M36): Production of low sulphur marine oil according to specifications**

It has been demonstrated that the renewable Hydrofaction® crude oil is upgradable to "Drop In" blend stocks for transportation fuels meeting existing specifications with high yields. Currently diesel blends with up to 30 vol. % renewable diesel complying to the EN590 ultra low sulphur diesel and marine fuel oils complying with ISO8271 (2012) specifications have been produced. The main parameter limiting the

### **Milestone 5 (M36): Updated techno-economic feasibility study based on project results**

An updated techno-economical assessment of a greenfield 2000 BPD commercial facility located in Scandinavia indicates a Capex cost in the range DKK 160-190 MDKK (80.000-95.000 USD/BBL) not including the upgrading, and a production costs 40-50 USD/BBL excl. feedstock costs and upgrading, and a production cost of 70-90 USD/BBL including feedstock costs but including upgrading.

## Introduction to Hydrofaction®

**Hydrofaction®** is Steeper Energy's proprietary take on Hydrothermal Liquefaction, which cost effectively converts biomass wastes to liquid transportation fuels. Hydrothermal liquefaction is a thermochemical method for direct conversion of organic materials to renewable crude oil in high pressure water near the critical point. Popularly stated that "*Hydrothermal liquefaction or HTL does in minutes what nature does in 150 million of years....*"

Hydrothermal liquefaction uses water near its critical point as the reaction medium for the conversion. Under these conditions water obtains special properties that makes it an ideal medium for chemical reactions such as acid and based catalyzed reactions as well as radical reactions. Further the properties is tunable by easily controlllable paramters such as pressure and temperature.

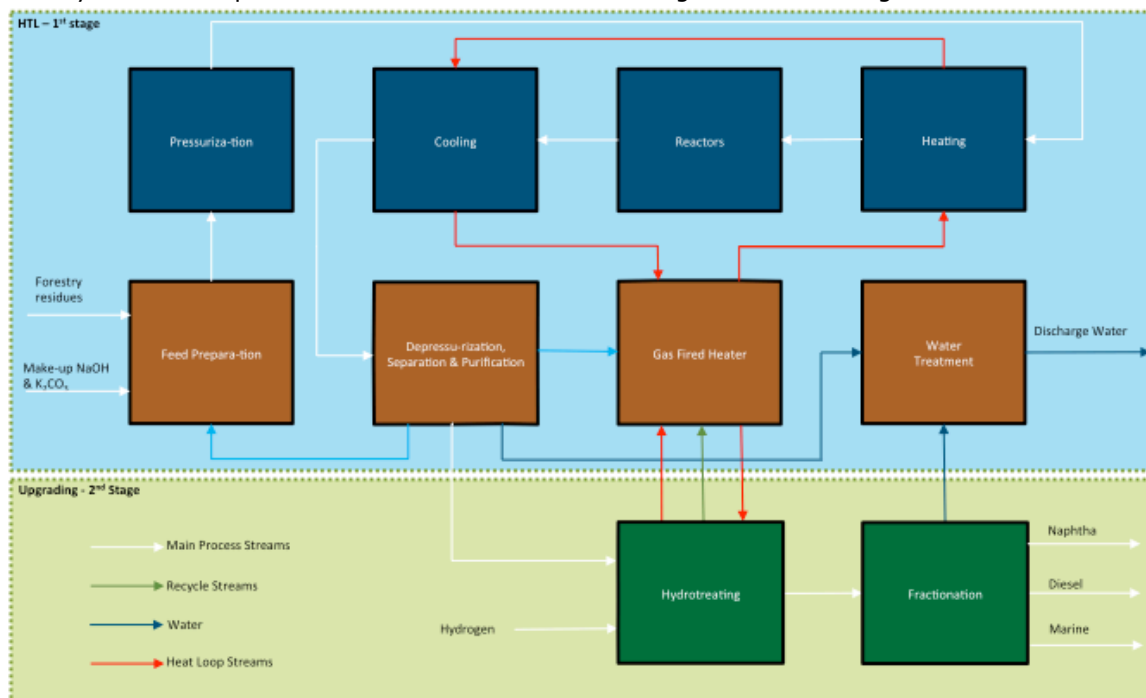
Hydrothermal liquefaction is recognized by US DOE (and others) as being an exceptionally cost, resource and energy effective with the greatest GHG mitigation, especially in heavy and long haul transport<sup>1</sup>.

The reason for this is that hydrothermal liquefaction is extremely **resource efficient** due to **very high conversion** and **high carbon efficiency into the desired product**. On contrast biological processes like ligno-cellulosic ethanol and bio-gasification (anaerobic digestion) all carbon including lignin. As 30-45 % of the carbon and 35-55 % of the energy is contained in the lignin, a significant amount of the carbon and energy and does not end up in he primary product and represents a loss for such processes though it is commonly accepted to offset the carbon- and energy balances by the recovery of byproducts for use in low value applications such as combustion. The energy efficiency is high compared to other thermochemical methods such as gasification/Fischer-Tropsch and pyrolysis as no drying of the feedstock is required due to lack of phase change (**no energy losses due to latent heat addition = wet materials can be processed**). Further the energy efficiency is maintained high as it is a **direct conversion process with high carbon efficiency, low parasitic losses**, few processing steps, and **extensive heat recovery** is possible.

Hydrofaction<sup>®</sup> differs from other hydrothermal liquefaction processes by:

- Conversion at supercritical temperatures ( $\pm 400^{\circ}\text{C}$ ) and pressures  $\pm 335$  bar,
- Use of homogeneous catalyst and capping agents
- Recovery and recirculation of catalysts & and water soluble organics
- Recirculation of oil produced
- Alkaline conditions
- High dry matter content slurries

This translates into a higher yield of higher quality crude oil, and improved energy efficiency. The Hydrofaction<sup>®</sup> process is illustrated in the block diagram shown in figure 7 below.



**Figure 1:** Hydrofaction<sup>®</sup> blockdiagram.

<sup>1</sup> [http://www.pnnl.gov/main/publications/external/technical\\_reports/PNNL-23579.pdf](http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23579.pdf)

The focus of Steeper Energy is to produce renewable "Drop In" liquid transportation fuels for long haul transport (i.e. trucks, aviation and marine ships), where electrification is not an option. Further, despite that Hydrofaction® has an inherent feedstock flexibility, the initial focus for commercialization is on woody biomass (forestry- & sawmill) residues including bark & branches as:

- It is by far the most abundant biomass stream and one of the few biomass that allow production of oil in a scale that's relevant for the petroleum industry
- Less than 40-50 % of a tree is today utilized with the residue to a large extent left in the bush (only 20 % is required to maintain nutrition value of the soil)
- Declining margins in traditional fibre markets threatens the industry in Europe & Northamerica

## **Project results and dissemination of results**

The project have been divided into the following work packages with individual milestones and deliverables

WP 1: Project Management & Dissemination

WP 2: Prototype development & demonstration

WP 3: Feedstock testing

WP 4: Oil characterization & upgrading to meet marine propulsion fuel requirements

WP5: Updated techno-economical assessment of full scale plant based on lessons learned

### ***WP1: Project Management & dissemination***

Project management has besides management and coordination of the project, included reporting and liason both via mandatory annual reports and via physical meetings. Two project changes were requested and accepted by EUDP in Spetember 2014 and December 2016.

On the dissemination side the project has resulted in one press release, 9 new patents and patent pending, 2 Ph.D. thesis's, 3 book chapters, 15 Peer reviewed articles and 16 conference presentation. The pilot plant at Aalborg University has also constituted a central piece in the dissemination and direct meetings with more than 30 stakeholders have been held centered around the pilot plant. In addition to these Steeper has contributed to the EUDP open house event at the cultural night in October 2015. Steeper has further produced a corporate video (financed by other sources) in the project period.

The major deviation compared to the original plan has been the use of press releases, which due to confidentiality arrangements has been limited to one.

### ***WP2: Prototype development & demonstration***

The project has included development, test and demonstration of a number of unit operations and subsystems in order to de-risk and further optimize the Hydrofaction® technology for future commercial plants in scale including:

- 2.1 Slurry preparation & characterization
- 2.2 Pressurization & depressurization system**
- 2.3 Heat recovery from outgoing product to incoming feed**
- 2.4 Reactors**
- 2.5 Filter-system
- 2.6 Separation system**
- 2.7 Recovery unit

Only the unit operations marked with bold were included in the original proposal. Further in the originally project plan prototypes of these systems were planned to be implemented and tested at the pilot plant in Aalborg. Initially engineering of these systems were performed according to this plan. However, on the basis of third party engineering studies of commercial plants and the Industrial Scale De-risking & Demonstration plant, a de-risking strategy where several of the unit operations were tested in representative scale at vendor shops were selected, and approved by EUDP as per project amendment dated December 8<sup>th</sup>, 2016. The results of the development, test and demonstration of the individual systems are described in further details below.

## 2.1 Slurry preparation & characterization

The main purpose of the slurry preparation is to produce of a homogeneous pumpable slurry with a high dry solid content also comprising the catalysts, recirculated oil and recirculated water phase. In general the slurry preparation comprises a size reduction and a mixing step.

The current slurry preparation system comprises a hammer mill system at the pilot plant in Aalborg, and a double screw mixer. The hammer mill is configured with a vacuum on the back side of the screen so that it can process wet feedstock such as fresh wood chips with a moisture content of 50 wt %. In a commercial system two hammer mills using different screen sizes are used.

However, the slurry preparation comprises a critical step for both the down stream process performance and process economy e.g. the higher the dry solid content the more oil and better energy balance for a given plant size. Hence, despite that a working solution is available other options has been explored.

### *2.1.1 Texturing agents*

The homogeneity of the feed mixture is a critical characteristic of the feed mixture quality and a limitation for the dry solid content that can be pumped. Lack of homogeneity may result in fluid being squeezed out of the feed mixture and leaving a solid clog when pumped i.e. the feed mixture is not pumpable.

Inspired by the food and petrochemical tests have been performed using a texturing agent or stabilizer/emulsifier as additive to the feed mixture. A further requirement to a texturing agent for use in the Hydrofaction<sup>®</sup> process is that the texturing agent is converted with the biomass in the process.

#### *2.1.1.1 Addition of stabilizers/emulsifiers*

Two texturing additives have been tested at the pilot plant in Aalborg: Guar gum a natural polysaccharide (E412) and Carboxy Methyl Cellulose (CMC, E466). Both are commonly used thickeners/emulsifiers in food industry and increasingly in oil exploitation. Both have been added on a per mille level and resulted in feed mixtures with improved homogeneity and pumpability, and in addition to this it has a viscosity lowering effect even in small concentrations. However, despite the low concentrations added guar gum proved to result in increased char formation due to early degradation to free sugar monomers an unfortunate temperature interval whereas a similar effect haven't been observed for CMC. CMC is now routinely used at the pilot plant at Aalborg University to stabilize the feed mixture and prevent sedimentation during the batch wise feed preparation at the pilot plant.

#### *2.1.1.2 Alternative texturing agents*

Some feed stocks including micro algae, distillers grain, peat has been found to have a texturing stabilizing effect on the feed mixture, and may advantageously be co-processed if feasible from an economical and availability point of view.

Another promising pathway that have been tested during the course of the project is the production of a "alkaline pulp" from part of the wood, and subsequently mixing it with the remaining wood and other ingredients afterwards. A 20 wt % pulp was produced by alkaline pulping willow chips using a ratio of NaOH to dry wood of 40 % at 180 °C for 120 minutes<sup>2</sup>. Slurries with 25 wt % and a 30 wt % dry matter was prepared by adding additional hammer milled willow to the pulp. Both feed mixtures were found to be pumpable. The 25 wt % feed mixture were processed in the pilot plant in Aalborg at Hydrofaction<sup>®</sup> processing conditions with oil yields similar to other wood runs. However, the amount of base required for the pulping by this route renders the pathway uneconomical.

### *2.1.2 Wet maceration techniques*

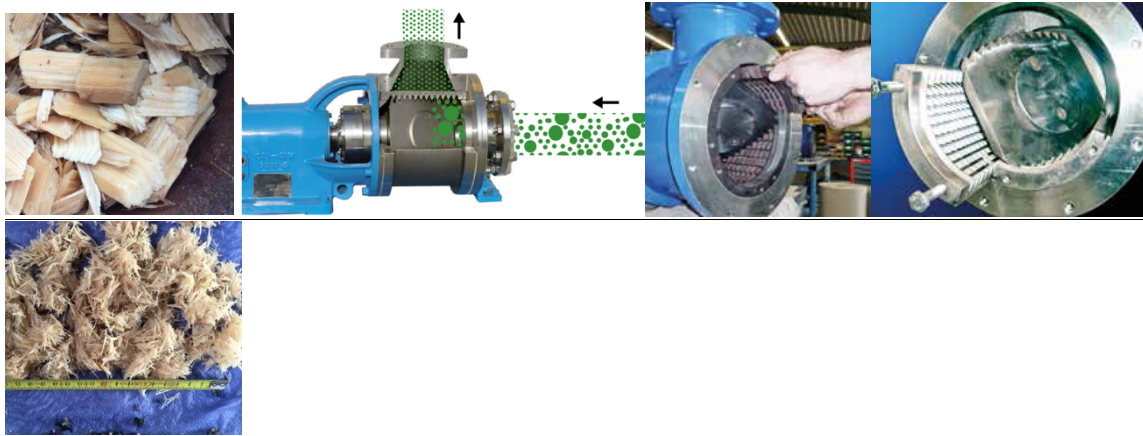
Wet maceration is an in-line technique, where whole chips is size reduced, homogenized and pumped in one step in a number of industries. Two wet maceration techniques have been tested in vendors shops during the course of the project: Gorator and Rotacut.

<sup>2</sup> 11. "Two-stage alkaline hydrothermal liquefaction of wood to biocrude in a continuous bench-scale system"/ Sintamarean, I-M, Grigoros, I, Jensen, CU, Toor, SS, Pedersen, TH & Rosendahl, LA, Biomass Conversion and Biorefinery. DOI: 10.1007/s13399-017-0247-9, 2017.

### 2.1.2.1 Gorator

Gorator is an in-line wet maceration system from the German vendor Hoelschertechnik-Gorator. A "Gorator" comprises a rotor and a stator as shown on the figures below. The particle size is controlled by the gap between the rotor and the stator.

A pilot test was performed in the vendor shop using 50 % moisture wood chips as feed stock as shown on figure 1. The tests were performed with water as milling media. As seen from figure 1, the wood chips were successfully disintegrated to a fibrous material with a fibre size of up to 20-30 mm. Further stable operation was only achieved by dilution with water to less than 10 wt % dry matter. Hence, concentration of the fibres after milling is required to achieve the desired dry matter content for the Hydrofaction® process. So whereas the Gorator technique may represent an economical pre-grinding step, the required further concentration of the milled material renders the technique less attractive.

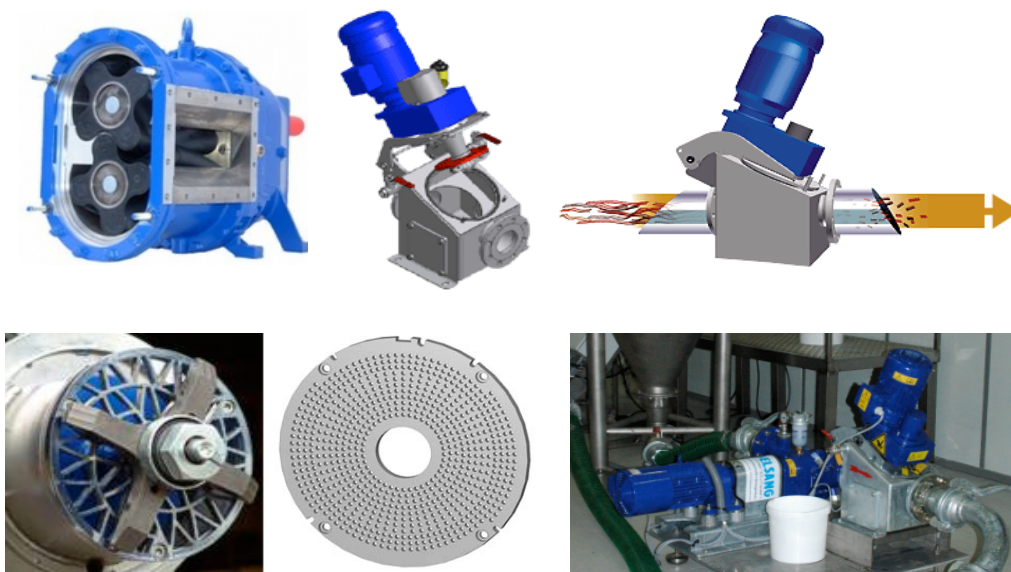


**Figure 2:** From the left: a. Fresh wood chips processed, b. Gorator principle, c. Gorator Rotor and stator, d. Gorator rotor and stator, e. Milled wood chips after dewatering.

### 2.1.2.2 Rotacut

Rotacut is an in line macerator/cutting technique from the German company Vogelsang. The system is used for fine milling and homogenization of fibrous materials and food wastes in a broad range of industries including sewage sludge, fibre fraction of manures, bio-digestion etc.

The Roatacut system consists of 1. A robust lobe pump that can pump a wide range of media, 2. An integrated stone trap and 3. A macerating/cutting step in which a rotating knife cuts the material against a static hole plate as shown in below in figure 3.



**Figure 3:** Vogelsang Rotacut system: Top left: Lobe pump, Top middle: Stone trap, Top right: Macerator/cutter, Bottom left: Rotating knife in Macerator, Bottom middle: Cutting plate/hole plate, Bottom right: Vogelsang Rotacut system.

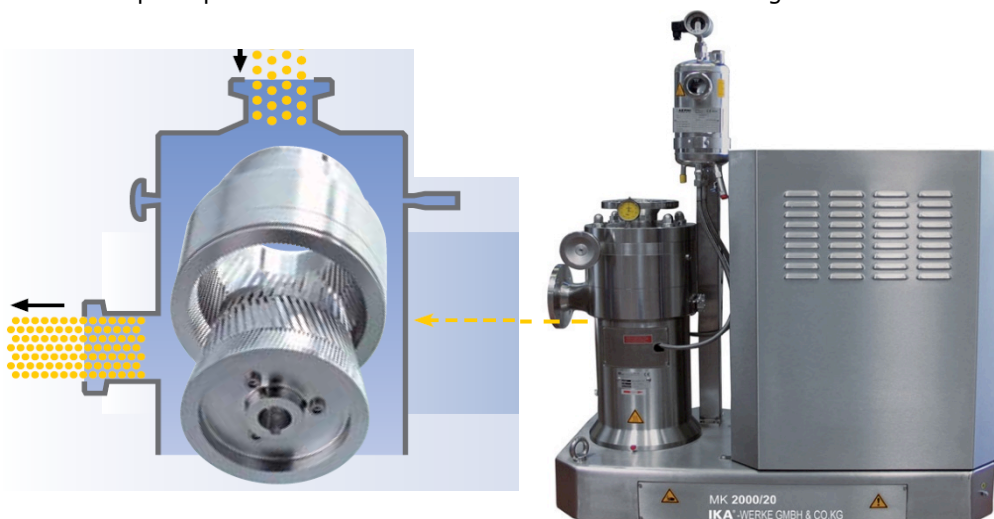


Pilot tests were performed at the vendor shop with both the whole wood chips and fresh wood chips. The tests were performed in a single stage Rotacut plant with a 12 mm cutting/hole plate. In both tests water were added in a ratio of 4:1 in order to process that material in the system. This corresponds to a dry matter content of 6-12 wt %. The output material from the Gorator tests were in both cases a material with a particle size of a few mm with a few individual fibres of up circa 5 mm. No significant improvement was observed by 15 times recirculation. For production of a finer material Vogelsang has proposed a two step system with a 4 mm cutting-/hole plate in the second stage. However, such plate was not available for the tests and has not been tested.

As for the Gorator, the Rotacut represents an economical solution with respect to both capital and operational costs. However, the technique is not suitable for viscous media and requires a dilution to 6-10 wt % in order to reduce the viscosity and the resulting pressure drop over the whole plate to acceptable levels. Hence, subsequent concentration in e.g. a screw press or a decanter centrifuge is required in order to achieve the design dry matter content of 20-25 wt %. Though such solution in principle could be combined with recirculation of the liquid from concentration step, it will result in less control with feed composition. Hence, the solution is considered inferior to the current solution for woody biomass.

### 2.1.3 Colloidal Mills

Several tests has been performed in an industrial colloidal mill at IKA in Germany. The colloidal mill is designed for fine milling and homogenization of viscous media such as production of mustard, mayonaise, marmalade and colloidal suspension of pigments. The IKA mills uses a constant circumferential velocity independently of scale and therefore results in one mill is scalable to other mills. The principle of the colloidal mill is shown below in the figure 4 and 5.



**Figure 4:** IKA colloid mill MK2000/20.

The colloidal mill is an in-line system, and further comprises a pressurized vessel with a heavy duty mixer for highly viscous media, and a circulation loop with a Seepex pump as shown in figure 4. The test set-up at IKA (MK2000/10) were limited to a max. Saw dust from softwood with a particle size of less than 5 mm was used for the tests. The system was limited to a temperature of approximately 130 °C, and didn't comprise a continuous feeding system. Hence, further addition of saw dust could not be performed without opening the lid of pressurized vessel. Nevertheless very promising results were achieved despite these limitations. Representative slurries up to 22,5 wt % were produced and a strong temperature effect was observed despite that the temperature were limited to 130 °C. To produce feed mixtures with dry matter content it were required to add the saw dust in steps i.e. cooling to about 80 °C for each addition. The tests further showed that no improvement were achieved increasing the number of recirculations above circa 5. Feed mixtures with even higher dry matter contents are considered possible, but were not produced within the available time.





**Figure 5:** Slurry preparation using colloidal mill at IKA. To the left a slurry with a dry solid content of circa 20 wt % is shown.

### 2.1.5 Slurry characterization

Detailed rheological data has been established for the slurries produced at IKA as well as 20, 25 and 30 wt% slurries produced in Aalborg. The rheological data measured represents critical design information for pump design and engineering of plants in larger scale.

## 2.2 Pressurization and de-pressurization system

A hydraulic piston pump for pressurization and/or de-pressurization has been developed. Key elements of the design are that the pump(-s) operates with actuated check valves and pressurization/de-pressurization occurs using standard pressure amplifiers/de-amplifiers driven by a hydraulic oil system. The pressurization system comprises three pressure amplifiers operating with staggered cycles, and the pump is designed so that the individual pressure amplifiers can be changed during operation. For depressurization the pump is operated in a reverse mode where the pump is operated as a brake i.e. the pressure energy from the product flow is transferred to the hydraulic oil. In a commercial system the pressurization and de-pressurization system is envisioned to be coupled via an energy reservoir on the hydraulic oil system i.e. the pressure energy is recovered and transferred to the pressurization step via the hydraulic system and in principle only a booster pump is required to compensate for losses in the system.

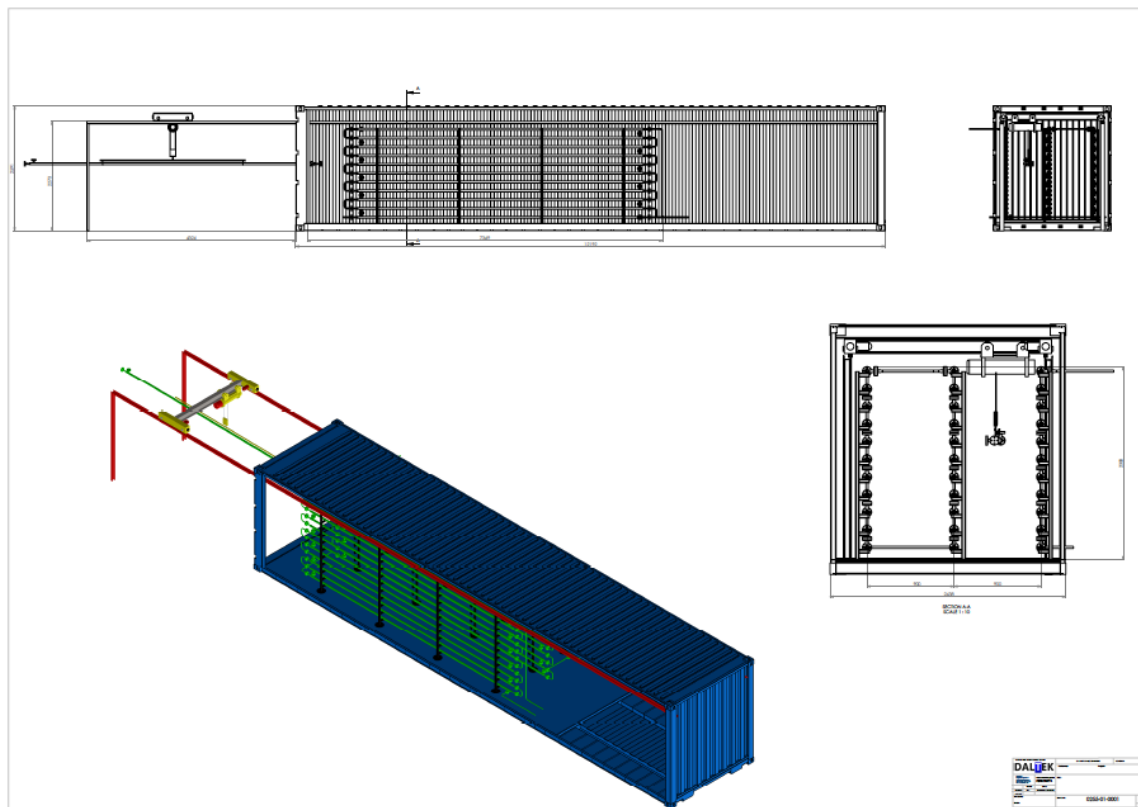
It was envisioned to install such pressurization and de-pressurization system at the pilot plant at Aalborg University. However, it was found that representative prototypes could not be produced in the scale of the Aalborg plant, and no prototyping has been performed within the project.

## 2.3 Heat Recovery Exchangers

Heat recovery from the product stream is important for the overall energy balance. Typically more than 70 % of energy required to reach the conversion temperature of the Hydrofaction<sup>®</sup> process is recovered. Valuable heat transfer design data have been established in the pilot plant at Aalborg. However, long term fouling of the tubes in the heat exchangers is a critical parameter for the sizing of heat exchangers for future commercial plants, and this is a major unknown that needs to be established in a demonstration plant before commercial plants can be build. Another weakness of these data is that they are established for small tubes with significantly lower flow velocities than for future commercial plants in larger scale.

It was originally planned to install a double tube heat recovery heat exchanger with direct heat between the incoming feed and the outgoing product flow at the pilot plant in Aalborg, and use

the existing induction heater as trim heater. The concept is shown below in figure 6.



**Figur 6:** Conceptual layout of double tube heat recovery exchanger for pilot plant at Aalborg University.

However, double tube heat exchangers are not easily cleaned on the shell side. Both the incoming feed and the outgoing product stream are considered as difficult media, and cleaning options are required. Hence, it was decided to use an indirect heat exchanger concept where heat is transferred from the product flow to the incoming feed via a heat transfer media for the future commercial plants. Such design of the heat recovery exchanger has the advantage of that both heat exchangers can flow inside tubes and thereby allow for more controlled a more controlled heat transfer and easier cleaning of he heat exchangers. Initially hot oil was chosen as heat transfer media. A further advantage of such design of the heat recovery exchanger is that the operating pressure on the shell side is reduced to approximately 10 bar, thereby allowing for a thinner shell thickness provided that suitable means for pressure release in case of a tube burst is provided. However, hot oils have a maximum operating temperature of 390-400 °C, which limits the maximum temperature of the feed mixture to 350-380 °C and requires additional trim heating of the feed mixture to reach the Hydrofaction® conversion temperature of 400-410 °C. The concept was further developed using high pressure water as the heat transfer medium and adding a trim heater to the high pressure water after being heated in the product cooler and a trim cooler to the high pressure water after being cooled in the feed mixture heater. This concept allows for increased control, operating flexibility and efficiency. The trim heater in the concept is fueled by process gas, whereby the Hydrofaction® process becomes substantially self-sustained with energy required for the heating.

However, the third party engineering studies of commercial plants with different partners as well as the basic engineering study of the industrial scale plant has revealed that it is not possible to establish representative tube dimensions and flow velocities in the current scale of the pilot plant in Aalborg, and that this defines the minimum scale of the Industrial Demonstration Plant. Hence, the first prototype will be built at the industrial demonstration plant, and establishment of the long term performance heat recovery system will be a main objective of that plant.

#### 2.4 Reactors

The main function of the reactors in the Hydrofaction® process is to maintain the feed mixture at the desired reaction temperature and pressure for sufficient time to be converted to the de-

sired level. The reactors are basically residence time chambers and the process is flexible as to how the residence time is obtained e.g. the residence time may be obtained in one big reactor, a very long tube or in several smaller reactors arranged in series and/or parallel.

It was originally planned to install a prototype of a cold walled reactor produced from mild steel with the internal ceramic insulation. However, third party engineering studies have revealed that such design will be more expensive than the current design due to the very high mechanical strength of the current construction material X10 (P91). It has further been found that the total weight of the reactors and manifolds are nearly constant and the significant savings are obtained if the diameter of the reactors are kept within standard tube dimensions i.e. at diameters up to about 80 cm in inner diameter. Due to these findings no reactor prototype has been installed and priorities have been directed to other areas.

### 2.5 Filter system

A new high pressure filter system situated after the cooling and prior to the pressure let down system was designed and implemented at the plant in Aalborg. The filter system comprises a online and offline filter. Mesh sizes from 25 to 500  $\mu\text{m}$  have been tested in the filters. The filter system has operated impeccably after implementation of traced filter eject and a back flush cleaning system with high pressure steam

### 2.6 Separation system

Dehydration and desalting of the oil product constitute a critical step for the further use or upgrading of the oil product. The oil typically contains 10-15 wt% and about 3 wt % ash after a coarse gravimetric separation which is too high for efficient upgrading with a reasonable catalyst lifetime. Hence, an extensive test program of dehydration and deashing of the Hydrofaction<sup>®</sup> oil was conducted in Aalborg and Canada as well as test conducted in collaboration vendors of separation equipment to the Petrochemical Industrial.

The tests have shown that pressure, temperature, solvents, acidification, emulsion breakers and electrical field all have a significant influence on dehydration and desalting of the oil. A manual washing procedure was successfully implemented to produce larger amounts of dehydrated and desalted oil for upgrading tests (see WP4).

Further a flexible prototype of continuous two stage solvent assisted gravimetric separation system with solvent recovery has been engineered and installed at the pilot plant at Aalborg University. The new continuous separation system is still under commissioning.

### 2.7 Recovery system

The homogeneous catalyst and water soluble organics in the Hydrofaction<sup>®</sup> process are recovered and concentrated in a recovery unit. The concentrate of homogeneous catalyst and water soluble organics are re-circulated to the slurry preparation step. Hereby a number of advantages are obtained including higher oil yields, while the water phase from the process is purified to a dischargeable level.

Proof of concept tests of the recovery unit have been performed in industrial scale test plants at vendor shops on several occasions. The water phases for these tests were produced at the pilot plant in Aalborg. Different configurations of the recovery unit were tested including 1. Evaporator only, 2. Evaporator + Coalescer, 3. Evaporator + Coalescer + Alkaline Absorber, 4. Evaporator + Coalescer + Activated Carbon, 5. Evaporator + Coalescer + Alkaline Absorber + Activated carbon, 6. Evaporator + Coalescer + Alkaline absorber + Reverse Osmosis, 7. Evaporator + Coalescer + multistage stripping. The tests showed that the homogeneous catalyst and water soluble organic compounds could be recovered with 100 % and 97 % efficiency respectively. The Total Organic Carbon (TOC) and concentration of phenols in the distillate are however too high for direct discharge. Using an alkaline absorber reduces the phenol concentration if the water phase is acidic, whereas the effect is marginal if the process water is alkaline, which is the normal conditions in the Hydrofaction<sup>®</sup> process. The tests with the activated carbon filter (4 and 5) as polishing technology showed that both TOC and phenols can be reduced to concentrations, which are more than 100 times the discharge limits. Two step reverse osmosis as polishing so-

lution showed good retention for phenols, but limited effect on low boiling components like methanol and ethanol requires an additional polishing step for these compounds. The evaporation and multistage stripping proved to be able to reduce the TOC and phenol levels distillate to dischargeable levels.

A bleed stream of approximately 15 % of the water phase concentrate is required to prevent accumulation of compounds due to the recirculation. The limiting factor is chloride concentration. Proof of Concept tests of an chloride selective ion exchanger have shown the chloride can be removed from the concentrate with high efficiency and that the bleed requirements and related losses of homogeneous catalyst and water soluble organics can be reduced to 5 % by installing such bleed treatment technology.

### WP3: Feedstock testing and biooil production

The pilot plant at Aalborg has been used to optimize operating protocols, establish key engineering data and to produce representative oil-, water and gas samples for external tests of separation (dehydration & desalting), recovery unit, detailed characterization and upgrading of oil to finished "Drop In" fuels as well as production of samples for evaluation by external stakeholders. Close to 400 tests have been performed during 1750 oil production hours and a total of 4500 hours of hot operation.

Woody biomass in the form of forestry- and timber mill residual wastes is the feedstock for the Industrial Demonstration Project and first commercial plants. Woody biomass is by far the most abundant biomass resource and has formed the basis for all tests. Wood species tested included spruce, pine, birch, energy wood (road cuttings), coppiced willow and combinations thereof. Further bark and glycerine have been processed with softwood in various ratios.

Key results are shown in the table 1-3 and figure 8 and further described in details in the references [11], [12], [13], [16], [18], [21], [22], [26], [27]:

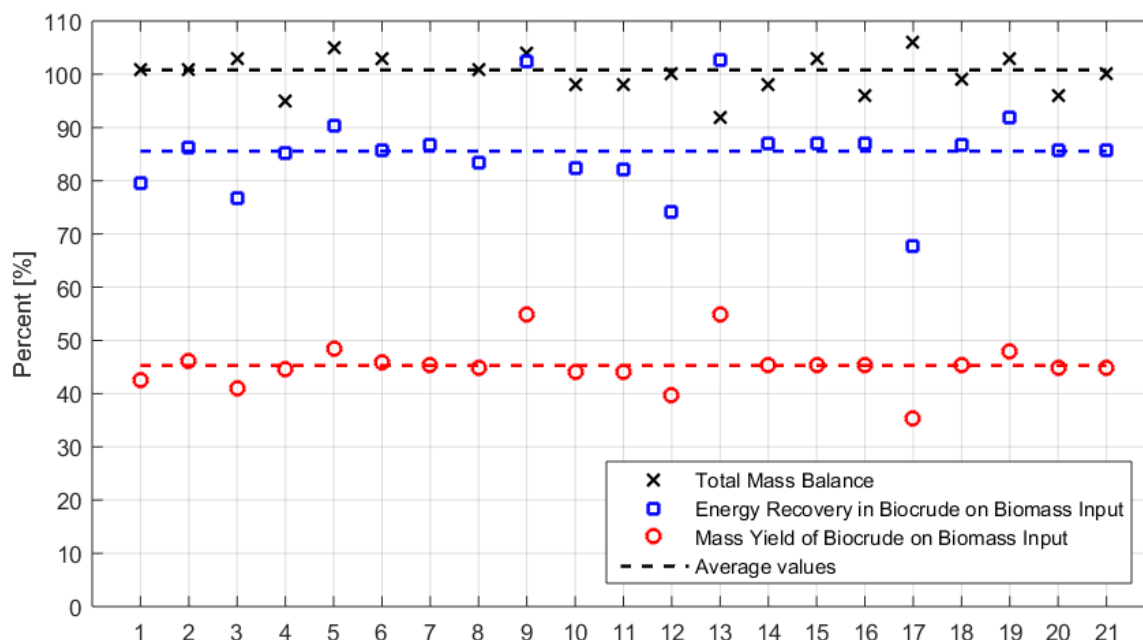
**Table 1:** Typical operating conditions for test of woody biomass.

Operating conditions	
Feedstock	50/50 Spruce/Pine
Dry matter content, wt %	17-24
Oil to wood ratio, kg/kg	0.8-1.0
Particle size, mm	< 2
Feed flow rate, kg/h	20-22
Reactor pressure, bar	300-340
Temperature, °C	390-410
Heating rate, °C/min	350-450

**Table 2:** Mass-, Energy- and elemental balances based on the average values presented in figure 7.

		Feed (Wood)	Oil	Off gas	Water <sup>†</sup>	Total out
<b>Mass and Energy balance</b>						
Mass	wt.%	100	45.3	41.2	13.8	100.3
Energy	%	100	85.6	15.8	0	101.4
<b>Elemental balance</b>						
C	wt.%	100	73.7	26.2	0	99.9
O	wt.%	100	10.5	61.1	28.4	100.0
H	wt.%	100	63.8	25.4	25.1	114.3

<sup>†</sup>Determined based on 100% oxygen balance



**Figure 7:** Key numbers on efficiency for steady state production of renewable crude oil. Total mass balance reflect overall mass balance closure of input and output streams. Energy recovery expresses how much of the energy in the incoming wood is recovered in the renewable crude oil and does not include external utilities. Note that the mass balances presented do not include runs with less than 5 consecutive recycling of oil and water.

**Table 3:** Steady state composition of product gas.

Component	vol.% <sup>a</sup>	wt.% <sup>a</sup>	HHV (MJ/kg)	Standards
H <sub>2</sub>	25.79	1.69	2.40	SS-ISO 6974
CO <sub>2</sub>	61.14	87.27	0.00	SS-ISO 6974
CO	0.32	0.29	0.03	SS-ISO 6974
CH <sub>4</sub>	7.20	3.75	2.08	SS-ISO 6974
Ethene	0.17	0.16	0.08	SS-ISO 6974
Ethane	2.36	2.31	1.20	SS-ISO 6974
Propene	0.29	0.40	0.19	SS-ISO 6974
Propane	1.02	1.46	0.74	SS-ISO 6974
Sum C <sub>4</sub>	0.68	1.25	0.62	SS-ISO 6974
Methanol	0.44	0.46	0.10	SS-ISO 6974
Ethanol	0.29	0.43	0.13	SS-ISO 6974
Acetone	0.28	0.53	0.17	SS-ISO 6974
Total	100	100	7.73	

The gas analyses were performed by the certified analysis laboratory at SP Technical Research Institute of Sweden, Sweden. The gas samples were supplied to the laboratory in special designed sample bags dedicated for gas samples. Based on the given composition, the elemental content of the gaseous product is 32 wt.% C, 3.8 wt.% H, 0.0 wt.% N, and 64.1 wt.% O

<sup>a</sup> Air free

**Table 4:** Hydrofaction<sup>®</sup> oil characteristics

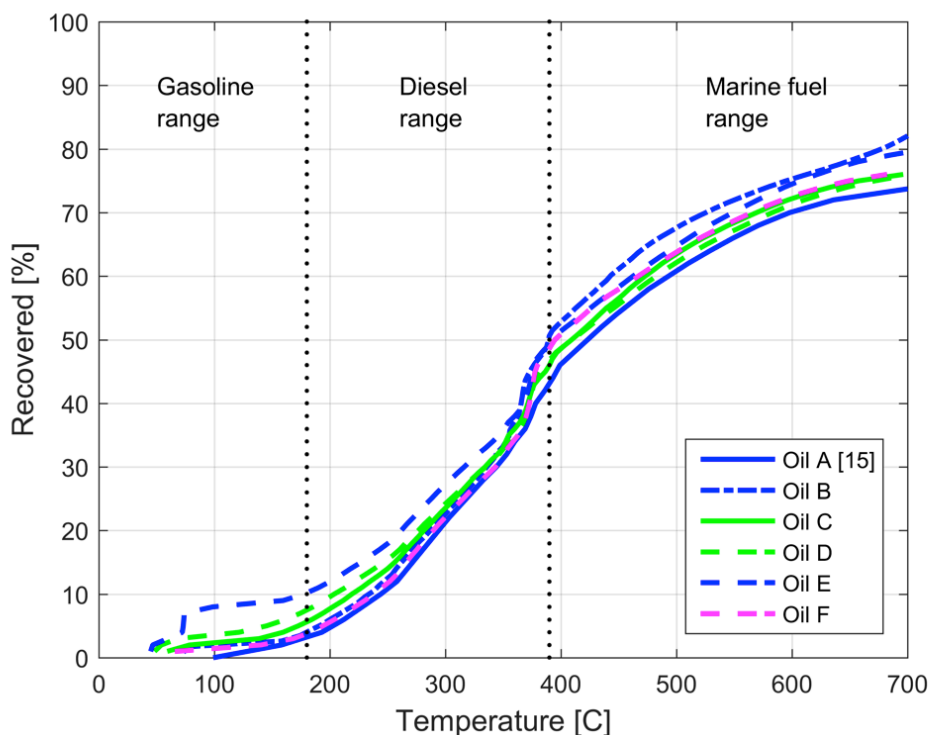
Test	Unit	Hydrofaction <sup>™</sup> oil	Standard
Elemental analysis (DAF)	wt.%		
C		81.4	ASTM D5291
H		8.7	ASTM D5291
N		0.095	ASTM D5291
S		0.01	ASTM D2622
O		9.8	By difference
H/C mole ratio (DAF)	–	1.28	Calculated
HHV (DAF)	MJ/kg	38.6	ASTM D4809
Water content	wt.%	0.8	ASTM D6304
Density	kg m <sup>-3</sup>		
At 40 °C		1,057.2	ASTM D4052
At 50 °C		1,050.3	ASTM D4052
At 60 °C		1,043.5	ASTM D4052
At 70 °C		1,036.8	ASTM D4052
Kinematic viscosity at 40 °C	mm <sup>2</sup> /s	17,360	ASTM D445
Kinematic viscosity at 60 °C	mm <sup>2</sup> /s	1,545	ASTM D445
Total acid number	mg KOH/g	8.8	ASTM D664
Strong acid number	mg KOH/g	<0.01	ASTM D664
Pour point	°C	24	ASTM D97
Flash point	°C	59	ASTM D97

All analyses of the oil were performed by the certified oil laboratory at Saybolt Nederland B.V. Dehydration of the oil by distillation (ASTM D2892) was also done by Saybolt Nederland B.V., and the oil characteristics reflect the dehydrated oil

**Table 5:** Basic properties of renewable crude oils produced by Hydrofaction<sup>®</sup> from various woody biomass sources.

Start-up oil	Feedstock	Viscosity <sup>a</sup>	HHV <sup>b</sup>	MCR <sup>b,c</sup>	C <sup>b</sup>	H <sup>b</sup>	N <sup>b</sup>	S <sup>b</sup>	O <sup>d</sup>	H/C
		[cP]	[MJ/kg]	[wt.%]	[wt.%]	[wt.%]	[ppm]	[ppm]	[wt.%]	[-]
CTO	Pine/Spruce	17360	38.6	21.0	81.4	8.6	1124	100	9.8	1.26
CTO	Pine/Spruce	714	38.0	16.4	80.4	9.0	822	195	10.4	1.34
CTO	Birch	813	38.0	15.6	80.8	9.1	2635	215	9.8	1.34
DTO	Birch	2084	37.7	18.6	80.2	9.2	2201	159	10.4	1.37
DTO	Pine/Spruce	3313	37.2	19.7	80.0	9.0	1447	104	10.9	1.34
DTO	10% Bark in Pine/Spruce	1954	37.9	18.1	81.4	9.7	973	100	8.8	1.42





**Figure 8:** Simulated distillation of crude oils given in table 5 (pine/spruce: blue), birch (green), 10 % bark in pine/spruce (pink).

As seen from the results, the core Hydrofaction<sup>®</sup> process results in an mass yield of circa 10 % oxygen crude oil of about 45, a carbon recovery in the oil of more 73 % and a bruttoenergy yield in the oil of circa 85 %.

#### **WP4: Oil characterization & upgrading to meet marine propulsion fuel requirements**

As for conventional crude oils the renewable oil from the renewable crude oil produced by Hydrofaction<sup>®</sup> needs to be upgraded/refined before it can be used in its final applications e.g. as transportation fuels. Though the renewable crude oil has a low oxygen and high calorific value compared to other bio- oils, and in many ways resembles its fossil counterparts oils, however it also have its specialities that needs to be addressed during the upgrading process including:

- Huge difference in boiling point and viscosity with and without oxygen
- High exotherms due to high oxygen content can lead to high temperature increase that can not be managed in a conventional way of oil recycling with interim cooling. Hence, reaction rates needs to be carefully controlled
- High boiling point and viscosity due to oxygen content
- Low sulphur content deactivates normal sulphided catalysts if the sulphur content is less than 200 ppm e.g. sulphur spiking is required to maintain the activity many conventional sulphided CoMo and/or NiMo type catalysts or non-sulphided catalysts must be used
- Crude oil not fully blendable with upgraded oil which may results in operational problems and reactor clogging if not managed properly

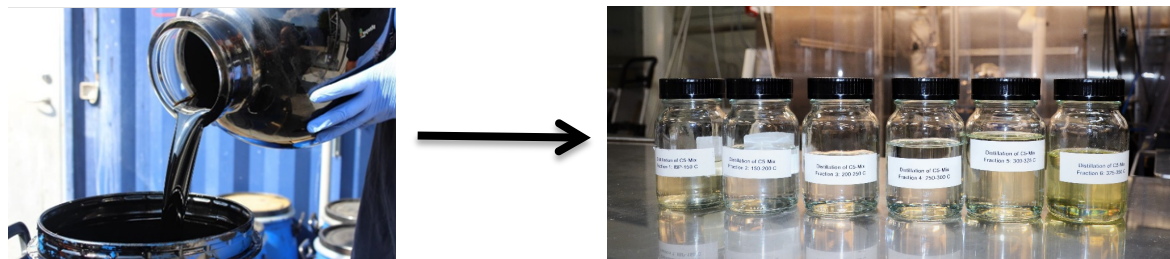
An extensive program for characterizing and upgrading the crude oil to "Drop in" transportation fuels or blend stocks has been performed using leased facilities at University of Calgary in Canada as well as in a new facility established at Aalborg University (financed outside the project), which became operational in the last part of the project.

This program has been important to understand the characteristics of the oil, demonstrate its upgradability and market value. The aim has been to maximize the yield of transportation fuels for long haul transport with renewable diesel as the main product while meeting existing standards for such fuels so that the infrastructure and engines established over the last 150 years can be reused.

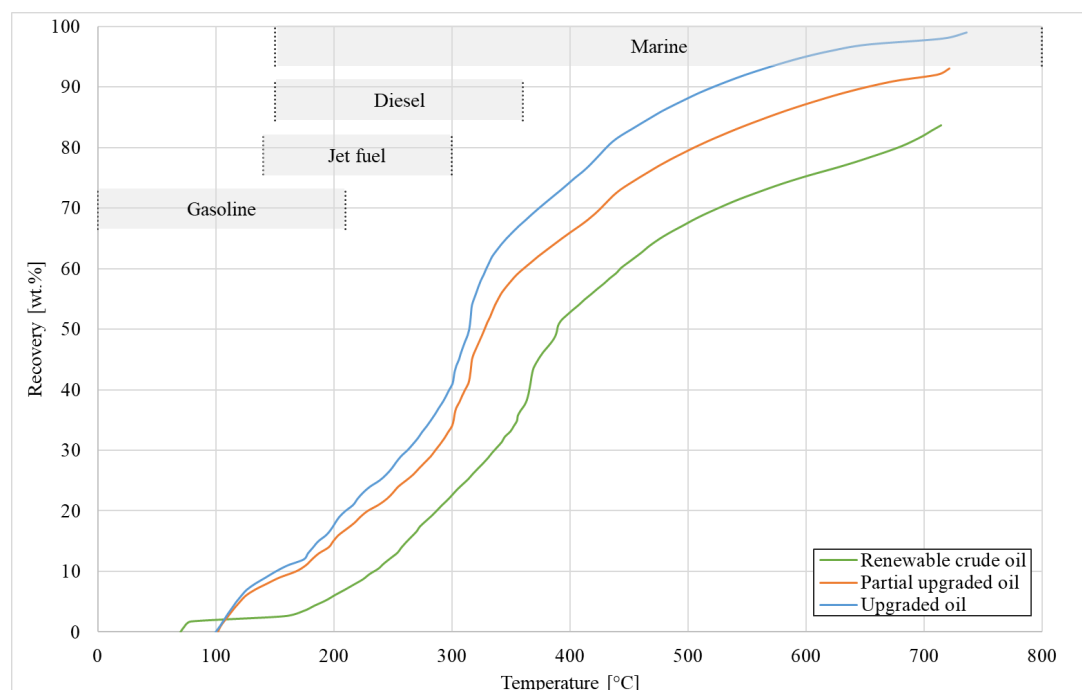


Different upgrading strategies, catalysts, reactor configurations, temperatures and pressures has been tested both in screening experiments and in longer term stability tests in durations of more than a month (>700 hours) have proven that the oil are upgradable if the upgrading process is designed for the oil specialities rather than adapting conventional upgrading processes to the oil.

Key results are shown below in figure 9-12 and the tables 6-7 and further described in details in [3], [10], [12], [13],[31]-[33], [43]-[46].



**Figure 9:** Photos of crude oil and the clear fractions of the upgraded product.



**Figure 10:** Boiling point curves (SIMDIST) for renewable crude oil, partial upgraded and upgraded oil.

**Table 6:** Comparison of key properties for renewable crude oil, partially upgraded oil and upgraded oil.

	Renewable crude oil	Partial Upgraded Oil	Upgraded oil
Density at 15 °C [kg/m <sup>3</sup> ]	1051	926	903
Aromatic content [mol%]	-	21.1	17.7
TAN [mgKOH/g]	55.7	1.4	<0.1
HHV <sup>a</sup> [MJ/kg]	37.6	43.9	44.3
C, wt % (daf)	81.4	87.4	87.3
H,wt % (daf)	8.5	12	12.7
O, wt %	10.1	0.6	0
H/C	1.25	1.64	1.73
IBP-350 °C distillate [%]	32	64	67
Residue > 550 °C	28.0	16.3	7.9

As seen from figure 10 and table 6, a significant reduction of boiling point and residue is obtained even by partial upgrading of the oil e.g. the fraction from the initial boiling point (IBP) to 350 °C is more than doubled by the upgrading process, and the residue (BP > 550 °C) is reduced from 28 % to 7.9 %. Also it is worth noticing that the total acid number and oxygen content is reduced to below detection level for the fully upgraded oil, and the hydrogen to carbon ratio has been increased from 1.25 to 1.73. Table 7 shows properties of the different fractions after true distillation according to ASTM D2892.

**Table 7:** Properties of upgraded oil and distillation fractions.

	Upgraded Oil	F1	F2	F3	F4	F5	F6	F7
Temperature range [°C]	-	54-150	150-200	200-250	250-300	300-325	325-350	350+
Yield [wt.%]	-	7.1	10.2	9.1	12.0	17.8	10.8	31.6
Density at 15 °C [kg/m <sup>3</sup> ]	903	770	814	863	872	866	921	1033
HHV <sup>a</sup> [MJ/kg]	44.3	44.8	45.1	45.0	45.2	45.4	44.3	43.1
Aromatic content <sup>b</sup> [mol.%]	17.7	3.4	8.2	11.8	12.8	10.6	19.6	33.0
Flash point [°C]	37.5	<25	44.5	82	117	151	169	NA
CCI <sup>c</sup>	-	-	35	32	44	59	46	NA
S <sup>d</sup> [ppm]	30	54	19	23	10	15	34	NA
C [wt.%]	87.3	85.0	85.5	86.4	86.5	86.2	87.3	89.4
H [wt.%]	12.7	15.0	14.5	13.6	13.5	13.8	12.7	10.6
O <sup>e</sup> [wt.%]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H/C	1.73	2.10	2.02	1.87	1.86	1.91	1.73	1.42

<sup>a</sup> dry basis; <sup>b</sup> by C13-NMR; <sup>c</sup> estimated from density and distillation data; <sup>d</sup> deviation: up to 50 ppm; <sup>e</sup> by difference.

As seen from table 7 the Jet- and diesel fractions F1-F5 have H/C ratios in the range 1,73-2.02 and higher heating values of about 45 MJ/kg. These values are similar to what are obtained found for conventional gasoline and diesel. It should also be noted that the 350+ °C residue has a higher aromatic content and for the same reason has a higher density and H/C ratio.

About 7 wt % percent of upgraded product ends up as a gasoline. Due to the low flash point it has been found difficult to blend out with other fractions while complying to an existing standard. The gasoline has been found to be compatible with fossil gasoline in any concentration, and may be and is considered as by-product.

Various diesel and marine fuel blends were physically produced from the Jet/diesel fuel fraction and the 350+ residue fraction °C based on predictions from optimized blending models for compliance with the EN590 (2013) ultra low sulphur diesel standard and the residue fraction (BP 350+) was blended with marine oils to produce a blend complying ISO 8271 (2012) specifications for low sulphur marine fuel oil. The results are shown in table 8-9, and in figure 11.

**Table 8.** Comparison of properties of diesel comprising 30 vol % upgraded renewable oil (150 < BP < 350 °C fraction with the EN590 Ultra Low Sulphur Diesel standard (2013).

	Blendstocks					Ultra Low Sulfur Diesel Blend	ULSD (EN 590)	
	HT Kero	HCK Diesel	HT ULSD	HT HSAGO	HT Steeper Diesel <sup>d</sup>		Minimum Spec	Maximum Spec
Density, g/mL	0.798	0.8692	0.8439	0.851	0.8496	0.845	0.82	0.845
Sulfur, ppm	0.960	12.000	8.000	45.000	0.000	10.000	-	10
Flash Pt,	58	97.8	70	95	60.41	67.96	55	200
Cetane Index	45.7	47.4	58.1	49.1	34.9 <sup>a</sup>	46.127	46	-
Cetane Number	43.6	66	56	60	36.9	51.000	51	-
Cloud Pt,	-56	-25.9	-25	-12	-8.8	-36.74	-	5
Cold Filter Plug Pt,	-56	-26	-25	-12	-10	-36.79	-	5
Viscosity at 40 °C, cs	1.2	5.3	2.98	3.7	1.83	2.526	2	4.5
CCR in 10% Btms, wt %	0.000	0.000	0.000	0.100	0.100	0.042	-	0.3
Ash, wt %	0.000	0.000	0.000	0.010	0.000	0.001	-	0.01
Water & sediment, vol %	0.000	0.000	0.000	0.010	0.000	0.001	-	0.002
Aromatics vol %	4.5	13	9	22	25.6	15.723	-	30
PolyAromatics vol %	0	4.5	0	0.7	0.3	1.079	-	8
% vol	14.3%	20.1%	23.5%	12.2%	30.0%	100		



**Figure 11:** Left: 30 Renewable Diesel blend complying with the EN590 Ultra low sulphur standard. Right: Vial and Spot Test of the marine fuel blend (compatible).

As seen from table 8 a diesel comprising 30 vol % renewable blend stock complying with EN590 Ultra low sulphur diesel standard. The amount of renewable blend stock that can be added is currently limited to 30 vol % due to restrictions on the cetane number and density of the F2-F6 fractions, which is caused by the residual aromatic content. Work is ongoing to further improve these properties of the upgraded oil, and push these limits.

A series of blending tests utilizing the 350+ °C residue fraction in a low sulphur RMG180 marine fuel formulation complying with ISO 8271 (2012) utilizing an optimized marine fuel blending model for such fuels. Physical blends were produced and the compability and the stability of the blends were evaluated by vial and spot tests shown in figure 11 as well as microscope studies. A marine fuel blend. Table 9 compares the properties of a RMG 180 marine fuel blend comprising 62 % by volume of the 350+°C fraction complying with the ISO 8271 (2012) standard for low sulphur RMG180 marine fuels.

**Table 9:** Comparison of properties for marine fuel comprising 62 % by vol of the 350+°C fraction complying with the ISO 8271 (2012) standard for low sulphur RMG180 marine fuel.

	Blendstocks			Low sulfur RMG 180 Blend	RMG 180 <0.1 wt% S	
	ULSFO	RMG 380 HSFO	Steeper HF		Minimum Spec	Maximum Spec
Density, kg/m <sup>3</sup>	888	990	1033	979.9	-	991
Sulfur, wt %	0.10	2.49	0.02	0.096	-	0.10
Flash Pt, °C	91	90.5	125	104	60	-
Pour Pt, °C	9	-9	24	19.7	-	30
Viscosity at 50 °C	14.2	371.5	6757	172.9	160	180
Ash, wt %	0.005	0.100	0.12	0.082	-	0.100
Con Carbon, wt %	1.89	15.8	14.46	10.4	-	18.0
Water & sediment, vol %	0.10	0.50	0.21	0.2	-	0.50
Total Sediment Potential, wt %	0.01	0.03	-	0.00	-	0.1
Vanadium, ppm w	1	189	-	4.1	-	350
Aluminum+Silicon, ppm w	15	60	-	6.1	-	60
ULO-Zinc, ppm W	1	0	-	0.3	-	15
ULO-Phosphorus, ppm w	1	0	-	0.3	-	15
ULO-Calcium, ppm w	6	4	-	2.0	-	30
Acid Number, mg KOH/g	0	0	0	0.0	-	2.5
Sodium, mg/kg		28	-	0.6	-	100
Asphaltenes, wt %	0	0	-	0.00	-	10
H <sub>2</sub> S, mg/kg	0.4	0.6	-	0.1	-	2
CCAI	797	851	-	849.6	-	860
BMCI	38.7	75.2	-	72.2	70	-
vol %	36.0%	2.0%	62.0%	100.0%		

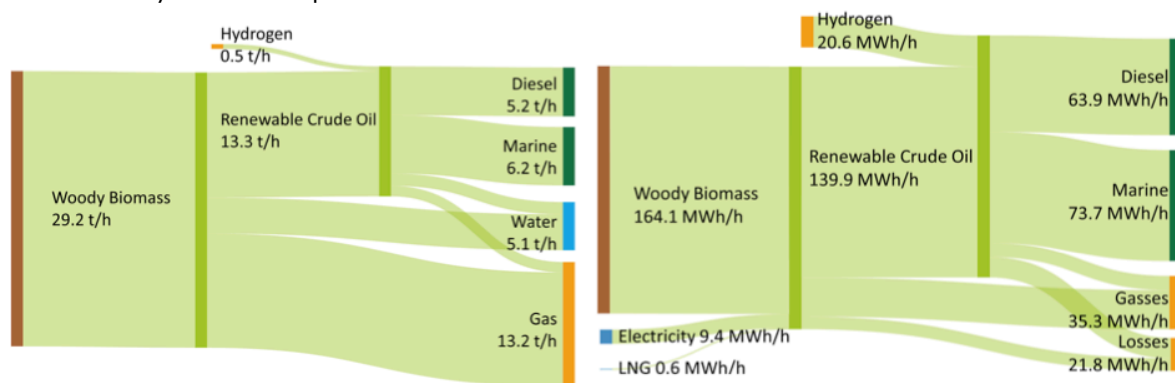
As seen from table 9 a blend complying with existing ISO 8271 (2012) standard for low sulphur RMG180 marine fuel can be produced with up to 62 % by volume from the 350+°C fraction. As it complies with an existing standard it can be used in existing engines without engine modifications required.

**WP5: Updated techno-economical assessment of full scale plant based on lessons learned**

During the project period two third party engineering studies of 2000 BPD commercial plants (100.000 TPA oil export) with industrial partners have been performed outside the project. These studies have focused on the conversion of forestry residues to renewable crude oil by Hydrofaction® i.e. the upgrading part of the process has not been included. The studies have been performed according to AACE International 18R-97 Cost Classification System, Estimate Class 3). With the outset in these studies Steeper Energy has performed an updated techno-economical assessment of a green field 2000 BPD commercial facility for production of renewable crude oil located in Scandinavia. The indication from the study is that a first of a kind 2000 BPD Hydrofaction® plant for production of renewable crude oil will have a Capex cost in the range DKK 160-200 MEUR, and that the production costs are in the range 40-50 USD/BBL excl. feedstock costs, and a current production cost of 70-90 USD/BBL including feedstock costs not including the upgrading costs.

*Life Cycle GHG emissions of Hydrofaction®*

The sustainability of a renewable drop-in fuel is highly dependent on the energy efficiency of the production as well as the GHG emissions reduction associated with use of the particular fuel. A life cycle evaluation GHG emission reductions associated with Hydrofaction® products has been performed in parallel with the present project. The estimation is based on a 2000 barrels per day (BPD) Hydrofaction® plant using forestry residues as feedstock and producing diesel and marine drop-in renewable fuels. Figure 12 visualises the overall mass- and energy flows for the 2000 BPD Hydrofaction® plant assessed in the GHG emissions calculation.



**Figure 12:** Sankey diagrams showing the mass- and energy balances for a 2000 BPD Hydrofaction® plant on a dry ash free basis.

The significant heating energy that is available through the gaseous products from Hydrofaction® is illustrated in the Sankey diagrams. In steady state operation, combustion of these gaseous products is sufficient to make the overall process self-sustained with heat. However, an external LNG stream is included to cover start-up operations. Based on the energy balance, the net energy recovered in the “drop in” fuels can be calculated to 71%.

The location of the Hydrofaction® plant assessed is the province of Alberta, Canada. Forestry residues are abundant in the region and fuel distribution infrastructure is widely available because extraction, refining and distribution of oil sands and derived products is the largest industry in Alberta. Table 10 lists the emission intensities used in the GHG analysis of the Hydrofaction® plant located in Alberta, Canada. Emission factors given in by the government of Alberta have been used whenever possible<sup>3</sup>. The plant applies forestry residues as feedstock that would have otherwise been disposed in permanent wood waste stockpiles. The methane emissions from decomposition of such wood waste stockpiles in the baseline scenario have been calculated based on the guidelines in. It is assumed that the feedstock is transported on average 200km from the harvesting site. The gaseous Hydrofaction® products are combusted to provide process heat, and the emission intensities of CH<sub>4</sub> and N<sub>2</sub>O combustion products are assumed equal to that from combustion of liquefied natural gas (LNG). LNG is purchased to cover any additional heat requirements related to process start-up. The effect of using standard grid electricity

<sup>3</sup> Gary, JH, Handwerk, GE, Kaiser, MJ. Petroleum Refining, technology & economics. %th ed. CRC Press, 207, ISBN:=-8493-7038-8.

versus renewable grid electricity has been tested. Heat, electricity and make-up HTL catalysts requirements are based on the engineering studies for a 2000 BPD Hydrofaction<sup>®</sup> plant. Upgrading catalysts are assumed to be changed once every year and transportation of all make-up catalysts to site is assumed to be on average 1000km by heavy truck. Hydrogen consumption during upgrading is defined to a conservative 4 wt.% (oil feed basis); The upgraded Hydrofaction<sup>®</sup> oil is fractionated into 50 vol.% renewable drop-in diesel fuel used to displace petroleum diesel and 50 vol.% drop-in marine fuel used to displace heavy fuel oil. Emissions related to distribution and dispensing of the finished fuels is left out of the calculation, because it is assumed to be the same and independent of the carbon origin of the fuel. Finally, GHG emissions related to construction of the plant are assumed negligible over the lifetime of the plant.

**Table 10.** Emissions intensities used in the GHG emissions analysis of Hydrofaction<sup>®</sup> products [13]

Emission source	Unit	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub> e <sup>a</sup>
Feedstock harvesting and transportation (200m), 15.9 L diesel/tonne	(kg/tonne)	4.2E+01	2.1E-03	6.4E-03	
Combustion of liquefied natural gas (LNG)	(kg/m <sup>3</sup> LNG)	1.9E+00	3.7E-04	3.3E-05	
Emission factor for grid electricity	(kg/kWh)	BNA			6.4E-01
Emission factor for renewable grid electricity	(kg/kWh)	BNA			0.0E+00
Hydrogen emission intensity	(kg/kg H <sub>2</sub> )	BNA			8.9E+00
K <sub>2</sub> CO <sub>3</sub> emission intensity	(kg/kg)	BNA			2.7E-01
NaOH emission intensity	(kg/kg)	BNA			4.7E-01
Upgrading catalyst emission intensity	(kg/kg)	BNA			5.5E+00
Catalyst transportation by truck, 1000km	(kg/kg)	BNA			4.9E-02
Emission intensity of fuel extraction and production	(kg/L)	1.4E-01	1.1E-02	4.0E-06	
Combustion of diesel	(kg/L)	2.7E+00	1.3E-04	4.0E-04	
Combustion of heavy fuel oil	(kg/L)	3.1E+00	3.4E-05	6.4E-05	
Emission intensity from decomposition of wood waste stockpile	(kg/tonne)	Biogenic	2.0E+01		

<sup>a</sup> 1 kg CH<sub>4</sub> = 25 kg CO<sub>2</sub>e; 1 kg N<sub>2</sub>O = 298 kg CO<sub>2</sub>e; [15] BNA, breakdown not available.

Table 11 lists the GHG emissions related to a 2000 BPD Hydrofaction<sup>®</sup> plant producing diesel and marine fuel as compared to a baseline scenario where petroleum derived diesel and heavy fuel oil products are refined and used in Alberta, Canada. The GHG emissions reduction associated with using Hydrofaction<sup>®</sup> products as compared to petroleum derived products is 77%.

**Table 11:** GHG emissions reduction associated with displacement of diesel and heavy fuel oil by renewable Hydrofaction<sup>®</sup> products [13].

Emission source	Amount	CO <sub>2</sub> (kg/h)	CH <sub>4</sub> (kg/h)	N <sub>2</sub> O (kg/h)	CO <sub>2</sub> e* (kg/h)
<b>2000 BPD Hydrofaction<sup>TM</sup> plant</b>					
Feedstock collection and transport	29.2 tonne/h	1.2E+03	6.2E-02	1.9E-01	1295
Combustion of HTL process gas	3436 m <sup>3</sup> LNGe/h	Biogenic	1.3E+00	1.1E-01	66
Combustion of purchased LNG for heat	60.9 m <sup>3</sup> /h	1.2E+02	2.3E-02	2.0E-03	118
Purchased electricity	9362 kWh/h	BNA	BNA	BNA	5992
Purchased hydrogen	530 kg/h	BNA	BNA	BNA	4717
Drop-in diesel fuel usage	6.5 m <sup>3</sup> /h	Biogenic	8.6E-01	2.6E+00	791
Drop-in marine fuel usage	6.5 m <sup>3</sup> /h	Biogenic	2.2E-01	4.1E-01	129
Make-up catalysts	1087 kg/h	BNA	BNA	BNA	443
CO <sub>2</sub> sequestration	0 tonne/h	BNA	BNA	BNA	0
Hydrofaction <sup>TM</sup> GHG emission total					13550
<b>Petroleum baseline</b>					
Extraction and refining of petroleum diesel and fuel oil	12.9 m <sup>3</sup> /h	1.8E+03	1.4E+02	5.2E-02	5313
Diesel combustion	6.5 m <sup>3</sup> /h	1.7E+04	8.6E-01	2.6E+00	17974
Heavy fuel oil combustion	6.5 m <sup>3</sup> /h	2.0E+04	2.2E-01	4.1E-01	20287
Wood waste stockpiling, decomposition	29.2 tonne/h	Biogenic	5.9E+02		14642
Baseline GHG emission total					58216
GHG emission reduction					44666
GHG emission reduction relative to baseline					77

The base case scenario is based on purchase of all hydrogen required for upgrading, use of standard grid electricity (coal intensive in Alberta) and where the biogenic CO<sub>2</sub> from the HTL gaseous products is all emitted. It is clear that the major contributions to GHG emissions are related to the purchased electricity and hydrogen, covering 44% and 35% of the total emissions respectively. Based on that, the following four additional scenarios were tested in the LCA.

**Case 1:** The base case is modified so hydrogen produced in-situ during 1<sup>st</sup> stage Hydrofaction<sup>®</sup> is applied during upgrading of the renewable crude oil to lower the amount of hydrogen



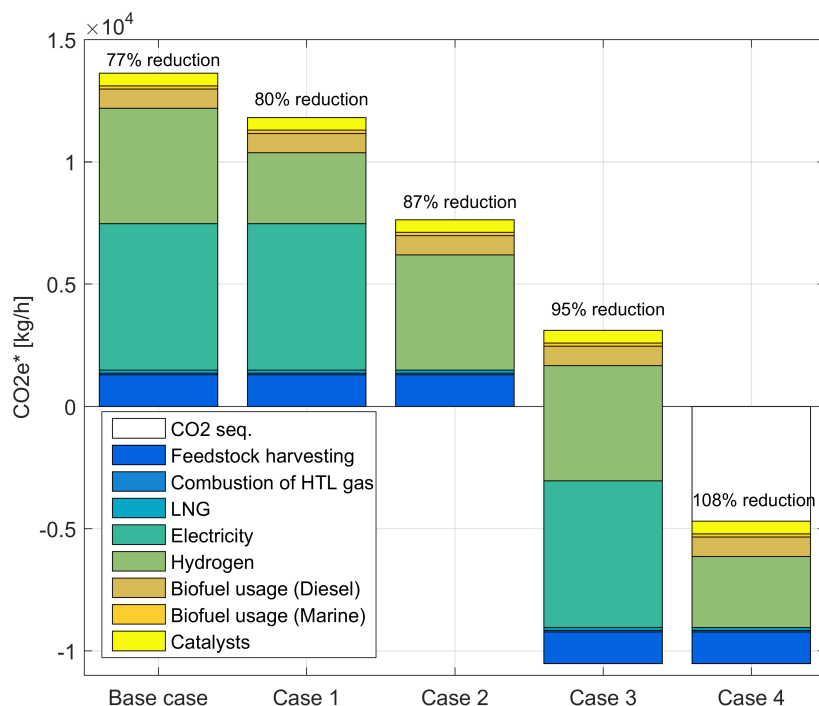
that need to be purchased. No additional LNG need to be purchased, because there is sufficient heating value in the remaining gaseous products after hydrogen separation. Additional electricity demand is not accounted for.

**Case 2:** The base case is modified so renewable grid electricity is used to reduce the emissions intensity of electricity, but at the expense of a higher cost.

**Case 3:** The base case is modified so all the biogenic CO<sub>2</sub> from the HTL gaseous products is extracted (before combusting the gaseous products with air) and sequestered. Additional electricity demand is not accounted for.

**Case 4:** The base case is modified to include all of the above.

The GHG emissions from the different scenarios and the resulting emissions reduction are compared below in figure 12.



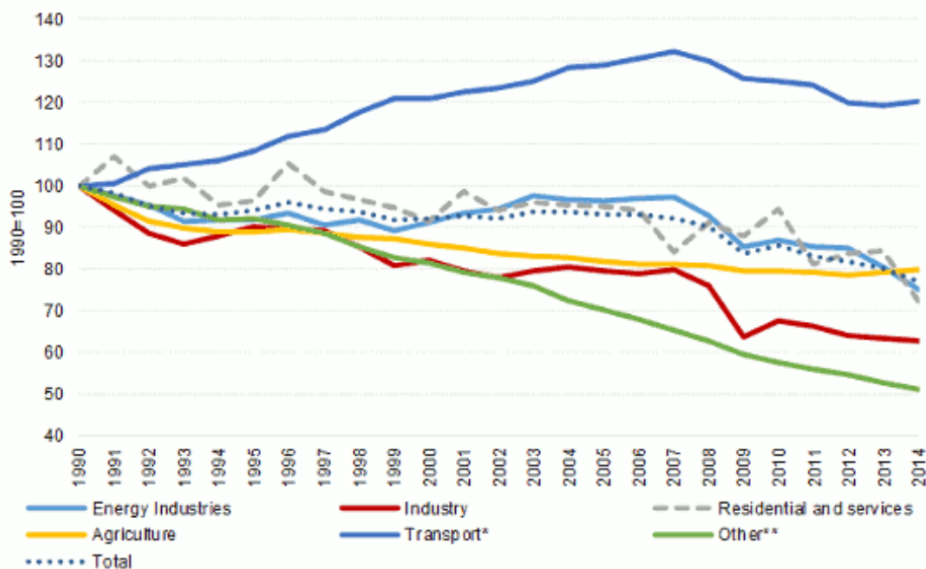
**Figure 12.** GHG emissions intensity of different Hydrofaction<sup>®</sup> cases

The effect of utilizing in-situ produced hydrogen in Case 1 is minor, but this process modification is likely to be cost efficient, since hydrogen is an expensive utility. The use of renewable electricity instead of standard grid electricity in Case 2 has a major effect on the GHG emissions, which is because power generation in Alberta is relative carbon intensive due to coal fired power plants. The cost-efficiency of Case 2 depends on carbon legislation and the additional price of renewable electricity. The possibility of sequestering CO<sub>2</sub> from the gaseous products is also worth considering as illustrated with Case 3, since CO<sub>2</sub> is a major product from the 1<sup>st</sup> stage Hydrofaction<sup>®</sup> HTL and sequestration can significantly enhance the project's GHG emission savings. The right-most column of figure 12 includes all the modifications to show the potential GHG emissions reduction associated with Hydrofaction<sup>®</sup> products. The result is a 108% GHG emissions reduction, which implies a process that is not only CO<sub>2</sub> neutral but actually CO<sub>2</sub> negative.

## Utilization of project results

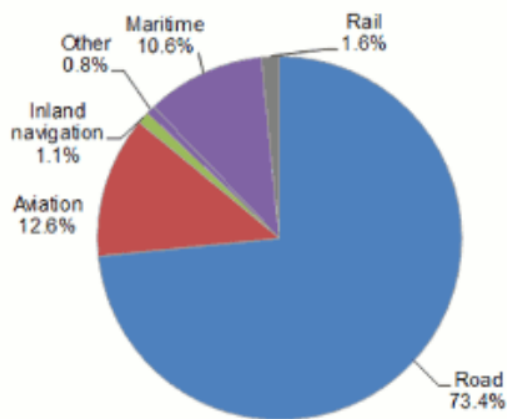
### Market & policies

EU and Denmark have set ambitious goals of reducing the total emissions of Green house gas emissions by 60 % compared to 1990 ([https://ec.europa.eu/clima/policies/strategies/2050\\_en](https://ec.europa.eu/clima/policies/strategies/2050_en)). About 25% of the total GHG emissions comes from transport, which is the only sector where the CO<sub>2</sub> emissions are still significantly higher than the 1990 levels (20 %) as shown figure 13 and 14. [https://ec.europa.eu/clima/policies/transport\\_en](https://ec.europa.eu/clima/policies/transport_en).



Note: \* Transport includes international aviation but excludes international maritime; \*\* Other include fugitive emissions from fuels, waste management and indirect CO<sub>2</sub> emissions  
Source: EEA.

**Figure 13:** Development in CO<sub>2</sub> emissions from different transport sectors.



**Figure 14:** CO<sub>2</sub> emissions from transport segments in 2014

As seen from figure 14 the contribution from road transport constitutes 73,4 %, maritime 10,6 % and aviation 12,6 % of the of the total CO<sub>2</sub> emissions from transport. Whereas emissions from light vehicles and buses can be reduced by improvements in fuel efficiency, electrification, hybrid cars, bioethanol, such options currently do not exist for heavy trucking, maritime and aviation, where emissions keep rising, and are predicted to continue to increase. ([https://ec.europa.eu/clima/policies/transport\\_en](https://ec.europa.eu/clima/policies/transport_en)).

Globally 1.9 B odt/y (EU: 200 Modt/yr) of "non-food" non "merchantable" biomass residue is available, which by the yields obtained in he present project corresponds to 14 M barrels per day (bpd) or 32% of the world's total transport fuel demand<sup>5</sup>, which again potentially corresponds to more than 2500 million t CO<sub>2</sub> emission savings per year globally. These numbers are of the same order of magnitude as the amount of raw materials required to decarbonize the long haul transport sector. Hence, the Hydrofaction® may get a very significant impact both locally in Denmark, within EU and globally.

The Hydrofaction technology and the project therefore contributes to fulfilling both the EU and Danish policy goals in relation to energy security, climate, environment, and independency of fossile fuels by 2050 by addressing a large and unsaturated market, where no good solutions exist per se.



**Utilization project results and roll out plans**

The project has directly contributed to advancing the Hydrofaction® technology so that the Norwegian company Silva Green Fuel (a joint venture between the Norwegian utility company Statkraft and the Swedish company with extensive operation within forestry, sawmill and pulp and paper company Södra) has licensed Steeper Energy’s Hydrofaction® technology as the preferred pathway after technology vetting of more than 40 competing technologies for conversion of forestry residues to drop in transportation fuels for long haul transport. As part of the license agreement a DKK 377M Industrial Scale Demonstration plant will be established in Tofte outside Oslo in Norway as a first phase. The Industrial Scale Demonstration plant is a scale down of a 2000 BPD (100.000 TPA oil export) commercial plant, and subject to the Industrial Demonstration Plant meeting certain success criteria a 2000 BPD commercial plant at the same site in a second phase and subsequently be rolled out to other locations in Norway and Sweden. It is the ambition that to establish 10 commercial plants in Norway and Sweden, and it is estimated that these will result in circa 30 % of the CO<sub>2</sub> reduction targets in Norway and Sweden by 2030.



**Figure 15:** Silva Green Fuel project site in Tofte, Noway with existing building hosting the Industrial Demonstration plant.

The Industrial Demonstration Plant represents the critical path to commerciality and further roll out is dependent on the Silva Green Fuel demonstration project. Steeper Energy has about a dozen large scale forestry residue projects in the early phase of project development, where the resource, site and partners have been identified, and which is expected to take off once the technology & business have been proven in scale. These projects include in the originally proposed project at the Port of Frederikshavn. Table 10 shows the top 10 jurisdictions of forestry residues.

**Table 10:** Top 10 jurisdictions of forestry residues and potential number commercial Hydrofaction® plants based on availability of forestry residues.

Country	Potential Residue for production (46% of production), Million Tonnes	Potential number of 2000 BPD Hydrofaction™ Plants
USA	714.6	1429
Russian Federation	155.8	311
Brazil	82.3	164
Canada	78.4	156
China	77.2	154
Indonesia	35.1	70
Sweden	33.2	66
India	27.8	55
Finland	26.0	52
Germany	23.6	47
<b>Total</b>	<b>1254</b>	<b>2504</b>

IEA, 2015 (Baruya): Estimates based on assumption that 46% of harvested wood not utilized in primary product.

### Extension beyond wood

The Industrial Scale Demonstration Plant is not economically viable with forestry residues as feedstock as feedstock. However, it represents a commercial and profitable scale for urban waste streams such as sewage sludge, sources sorted municipal solid waste etc. as a gate fee is associated with such feed stocks. Hence, they are profitable in a similar scale as industrial scale demonstration plant. Steeper is poised to enter into this market segment, where the challenge will more be adaption of the technology to the specific feedstock rather than a technology scale up experience.

### Other effect of project results

The project has indirectly resulted in 9 new patent families being filed in the project period (financed by other sources). Steeper Energy’s current patent portfolio now comprises more than 100 patents and patents pending divided into 21 patent families.

An indirect result of the successful advancement of Hydrofaction® technology and securing a license agreement with a significant industrial player has further resulted in Steeper Energy managing to raise USD 10M in new capital from existing investors.

### Job creation

As a direct result of the project result Steeper Energy has doubled the number of employees in the project period, and further expect to increase the number of employees by 50 % in 2018, and another 50 % in 2019.

Each 2000 BPD Hydrofaction® facilities will each create 30 direct and up to 680 indirect jobs. The majority of the indirect jobs would come from the construction of the plants and from the whole feedstock supply chain, including the supporting logistics operators, machinery suppliers, contracted equipment suppliers, etc.

Table 11 and figure 11 shows an estimate of jobs created by the envisioned plant roll out for 32 x 2000 bpd commercial Hydrofaction® facilities to 2032. It should be noted that this deployment plan corresponds to 1,3 % of the forestry residue resources available in the top 10 jurisdictions in table 15 above, and do not include urban waste plants, and other candidate materials such as ag residues. The plants are expected to be rolled out in the Baltic sea region first, and thereafter Northamerica. The ratio of direct to indirect jobs is based on the WASTED, 2014<sup>4</sup> European study on advanced biofuel industry impacts.

**Figure 16:** Jobs created by the envisioned deployment of Hydrofaction® wood to oil plants to 2032.

	Commercial facilities (number)	Hydorfaction™ Oil production (bbl/d)	Direct employees (Full time equivalents)	Indirect employees (Full time equivalents)	GHG savings (tCO2e/yr)
2022	1	2000	30	678	254,539
2023	1	2000	30	678	254,539
2024	2	4000	60	1357	509,078
2025	4	8000	120	2713	1,018,156
2026	6	12000	180	4070	1,527,234
2027	8	16000	240	5427	2,036,312
2028	12	24000	360	8140	3,054,468
2029	16	32000	480	10853	4,072,624
2030	20	40000	600	13567	5,090,780
2031	24	48000	720	16280	6,108,936
2032	32	64000	960	21707	8,145,248

<sup>4</sup> <http://europeanclimate.org/wp-content/uploads/2014/02/WASTED-final.pdf>

## Project conclusion and perspective

The project and the Hydrofaction® technology targets the production of transportation fuels for long haul transport (i.e. heavy trucks, maritime and aviation). A segment where CO<sub>2</sub> emissions keeps rising despite gains in fuel efficiency, and where no good solutions exists and yet have been identified. As a significant further growth of the segment is predicted towards 2050, the international 2050 climate targets of 2 °C can not be met without good decarbonisation solutions for this significant segment<sup>5</sup>. Hence, the project are an important contribution to the Danish energy policies and goals related to green transition, climate, energy security, environment, cost efficiency and independency of fossil fuels by 2050.

The project has contributed to advancing the technology to commercial readiness and to creating a Danish strength position within the attractive emerging technology space of hydrothermal liquefaction. Steeper Energy is today considered a global leader with a very strong intellectual property position within this field. Further the facilities and know how build around the pilot plant at Aalborg University are unprecedented at any university in the world. EUDP has contributed to establishing this unique position by supporting the successful private-public-partnership both in the present project and the previous EUDP project (EUDP 2012-II, J.Nr. 64012-0004).

Any organic material can in principle be converted to crude oil by Hydrofaction® including wet feed stocks and combinations of feed stocks. However, the project has focused on the conversion of forestry residues typically fresh wood residues with a moisture content in the range 40-60 %. The rationale behind this is that forestry residues is by far the most abundant biomass feed stock on earth, only a small part of a three is utilized in high value application today and most of it left in the bush, and allows for Hydrofaction® plants to be build in a scale where the oil production is meaningful also in a petroleum context = real impact is created. Further the pulp and paper industry in Europe and North America is threatened and need to reinvent their value chain or shut down in a foreseeable future as eucalyptus trees in Brazil or Southeast Asia in 5-7 years to grow the same amount of biomass that requires 50-70 years on the Northern Hemisphere. The commercial size of Hydrofaction® plants for forestry residues has been identified to be have a minimum production capacity of 2000 BPD. For perspective, the Danish oil production in the North Sea was 165.000 BPD in 2015 and keeps declining. Hence, the renewable crude oil production from a single 2000 BPD plant is measured in per cent of the total Danish oil production. The potential impact is further illustrated by ten expected 2000 BPD plants in Norway and Sweden by 2030 is forecasted to be covering 30% of the CO<sub>2</sub> reduction targets in these countries by 2030.

High quality and consistent mass-, energy and elemental balance data have been established for the core process not only validating, but exceeding the high yield numbers established in the previous EUDP project by more than 15 %. The renewable crude oil per dry ash free tonne of wood have been 453 kg (45,3 %) corresponding to an energy- and carbon recovery in the desired product of more than 85 % and 73 %, respectively. The net CO<sub>2</sub> reduction (Tree to Tank) are in the range 77-108 % depending of whether renewable electricity, renewable hydrogen and CO<sub>2</sub> is recovered as by-product or not<sup>6</sup>. These numbers are unprecedented for woody biomass and are besides the application of HTL due to the proprietary process schemes and operating protocols of Hydrofaction®. Volumes of renewable crude oil and water streams for upgrading tests, evaluation by external stakeholders and testing of prototypes have been produced at oil. This has allowed for test and validation of subcomponents at the pilot plant and at vendor shops, and thereby providing a key contribution to advancing the technology to commercial readiness.

Though the renewable crude oil produced has many similarities with its fossil counterparts it also has its specialities, which makes upgrading to finish transportation fuels nontrivial. New and more efficient process schemes and operating protocols have been developed and it has been proven that "drop in" blend stocks for production of diesel complying to the existing EN590 standard ultra low sulphur diesel, and the ISO 8271 standard for low sulphur RMG180

<sup>5</sup> [https://ec.europa.eu/clima/policies/transport\\_en](https://ec.europa.eu/clima/policies/transport_en)

marine fuels. Meeting existing standards means that the existing engines and the infrastructure established over the last 150 years can be reused. The concentrations of renewable transportation fuels that can be applied are per se limited to 30 % and 62 % by volume, respectively, due to density and cetane number, and flash point restrictions. Upgrading work is continuing beyond the project to push these limits.

An updated techno-economical assessment of the core process to renewable crude oil has been performed with the outset in two third party engineering studies of commercial plants performed with strategic partners (outside the project) in the project period. The updated techno-economical indicates a Capex cost of a commercial 2000 BPD wood to renewable crude oil plant in the range 160-200 MEUR (AACE class 3 estimate). This corresponds to a production cost of 40-50 USD/bbl of crude oil excl. feedstock costs or a current production cost in the range 70-90 USD/bbl incl. feed stock costs.

The critical steps for establishing Hydrofaction® as a commercial ready technology have been to attract significant strategic industrial partners and establish an Industrial Scale Demonstration plant. The project and the quality of data established have directly contributed to overcoming this difficult barrier as a licensing deal including establishment of an Industrial Demonstration Plant has been concluded with Silva Green Fuel (SGF) including establishment of an estimated DKK 377M Industrial Scale Demonstration Plant at Tofte, Norway as the first phase. Hydrofaction® was selected as preferred pathway after technology vetting of over 40 competing technologies.

The Industrial Scale Demonstration Plant represents a commercial scale for gate fee materials such as sewage sludge, source sorted municipal solid waste, etc. Steeper Energy is poised to enter this attractive market segment to benefit from the momentum gained by the Industrial Scale Demonstration Plant and speed up the commercialization process.

## Annex

### 1. Publications

#### 1.1 Press Releases

1. December 15, 2017: [Steeper Energy Announces EUR 50.6 M \(DKK 377 M\) Advanced Bio-fuel Project with Norwegian-Swedish joint venture Silva Green Fuel in Licensing Deal](#)

#### 1.2 Patents

2. **"Feed mixture for producing hydrocarbons"**/Steen Brummerstedt Iversen, Göran Olofsson, International patent application WO2015/050113, May 2015.

3. **"Process for producing low sulphur renewable oil"**/ Steen Brummerstedt Iversen, Göran Olofsson, Sergios Karatzos, Claus Uhrenholt Jensen, Julie Katerine Guerrero Rodriguez, International patent application WO2018/00011, July 2016.

4. **"Pressurization in high pressure processing system"**/Steen Brummerstedt Iversen, Henrik Egholm, Danish patent no. PR 179314, International Patent application no. WO2018/053179 filed Feb. 8, 2017.

5. **"Pressure reduction in high pressure processing system"**/Steen Brummerstedt Iversen, Henrik Egholm, Danish Patent no. PR 179391, International patent application no. WO2018/053179 filed Feb. 8, 2017.

6. **"Heating System for high pressure processing system"**/ Steen Brummerstedt Iversen, Claus Uhrenholt Jensen, Andrew Ironside, Göran Olofsson, International patent application no. WO2018/055445 filed Mar. 7, 2017.

7. **"Separation System in High Pressure Processing System"**/ Steen Brummerstedt Iversen, Claus Uhrenholt Jensen, Julie Katerine Guerrero Rodriguez, Göran Olofsson, International patent application no. WO2018/011139A1 filed Mar. 30, 2017.

8. **"Modular Processing System"**/Steen Brummerstedt Iversen, Danish patent application no. PA201770842, filed Nov. 9., 2017.

9. **"Recovery system for high pressure processing system"**/ Steen Brummerstedt Iversen, Danish patent application no. PA201770844 filed Nov. 10, 2017.

10. **"Process for upgrading oxygen containing renewable crude oil"**/Steen Brummerstedt Iversen, Julie Katerine Guerrero Rodriguez, Claus Uhrenholt Jensen, Danish patent application no. PA201800011 filed Jan. 10, 2018.

#### 1.3 Ph.D. thesis's

11. **"Feedstock Preparation and Physico-Chemical Characterization – Optimization of feedstocks for continuous HTL and optimum Yield"**/ Iulia Mairia Sintamarean, Ph.D. Thesis, University of Aalborg, ISSN/eISSN: 2446-1636/978-87-7112-943-4, 2017.

12. **"PIUS-Hydrofaction™ Platform with Integrated Upgrading Step"**/Claus Uhrenholt Jensen, Ph.D. Thesis, University of Aalborg, ISSN/ISBN:2446-1636/978-87-7210-134-7.

#### 1.4 Book chapters

13. **"Hydrofaction™ of Forestry Residues to Drop-in Renewable Transportation Fuels"**/ Claus Uhrenholt Jensen, and Julie Katerine Rodriguez Guerrero, Sergios Karatzos, Göran Olofsson, Steen Brummerstedt Iversen, In Lasse Rosendahl: "Direct Thermochemical Liquefaction of Biomass for Energy Applications", Elsevier 2018, ISBN 978-0-08-101029-7 / 978-0-08-101025-9.

14. **"Recipe-based co-HTL of biomass and organic waste"**/ Toor, S.S., L. Rosendahl, & I. Sintamarean, in *Direct Thermochemical Liquefaction for Energy Applications*, Rosendahl (ed.), Woodhead Publishing Series in Energy, Elsevier 2018, ISBN 978-0-08-101029-7 / 978-0-08-101025-9.

15. **"Coproprocessing of pyrolysis oil in refineries"**/Castello, D. & L. Rosendahl, in *Direct Thermochemical Liquefaction for Energy Applications*, Rosendahl (ed.), Woodhead Publishing Series in Energy, Elsevier 2018, ISBN ISBN 978-0-08-101029-7 / 978-0-08-101025-9

## 1.5 Articles

16. **"Alkaline pre-treatment of lignocellulosic biomass for continuous HTL process"**/ Sintamarean, Iulia-Maria; Rosendahl, Lasse Aistrup; Pedersen, Thomas Helmer; Toor, Saqib Sohail, *Renewable Energy*, 2016.

17. **"Characterization of liquid products from hydrothermal liquefaction (HTL) of biomass via solid-phase microextraction (SPME)"** / Arturi, Katarzyna Ratajczyk; Hansen, Kathrine Regine; Nielsen, Rudi Pankratz; Rosendahl, Lasse Aistrup; Sogaard, Erik Gydesen. *Biomass & Bioenergy*, Vol. 88, 05.2016, p. 116-125.

18. **"Continuous Hydrothermal Co-liquefaction of Aspen Wood and Glycerol with Water Phase Recirculation"**/ Pedersen, Thomas Helmer; Grigoras, Ionela; Hoffmann, Jessica; Toor, Saqib Sohail; Daraban, Iulia Maria; Jensen, Claus Uhrenholt; Iversen, Steen B.; Madsen, René; Glacius, Marianne; Arturi, Katarzyna Ratajczyk; Nielsen, Rudi Pankratz; Sogaard, Erik Gydesen; Rosendahl, Lasse Aistrup, *Applied Energy*, Vol. 162, 01.2016, p. 1034–1041.

19. **"Co-processing potential of HTL bio-crude at petroleum refineries – Part 1: Fractional distillation and characterization"**/ Hoffmann, Jessica; Jensen, Claus Uhrenholt; Rosendahl, Lasse Aistrup, *Fuel*, Vol. 165, 02, 2016, p. 526–535.

20. **"Co-processing potential of HTL bio-crude at petroleum refineries. Part 2: A parametric hydrotreating study"**/ Jensen, Claus Uhrenholt; Hoffmann, Jessica; Rosendahl, Lasse Aistrup, *Fuel*, Vol. 165, 02.2016, p. 536–543.

21. **"Pretreatment methods to obtain pumpable high solid loading wood–water slurries for continuous hydrothermal liquefaction systems"**. /Dârăbana, Iulia-Maria; Rosendahl, Lasse Aistrup; Pedersen, Thomas Helmer; Iversen, Steen Brummerstedt. *Biomass & Bioenergy*, Vol. 81, 10, 2015, p. 437–443.

22. **"Fundamentals of Hydrofaction™: Renewable crude oil from woody biomass"**/ Claus Uhrenholt Jensen, Julie Katerine Rodriguez Guerrero, Sergios Karatzos, Göran Olofsson, Steen Brummerstedt Iversen, *Biomass Conversion & Biorefinery*, p. 1-15, ISSN/eISSN 2190-6823, 2017 (DOI 10.1007/s13399-017-0248-8).

23. **"Full characterization of compounds obtained from fractional distillation and upgrading of a HTL biocrude"**/ Pedersen, Thomas Helmer; Jensen, Claus Uhrenholt; Sandström, L.; Rosendahl, Lasse Aistrup, *Applied Energy*, 202, 408-419. DOI:10.1016/j.apenergy.2017.05.167

24. **"Fracking biomass: Steeper Energy and the pursuit of renewable hydrocarbons"**/Jim Lane, *Biofuels Digest*, February 2, 2017, Washington, USA, <http://www.biofuelsdigest.com/bdigest/2017/02/02/fracking-biomass-steeper-energy-and-the-pursuit-of-renewable-hydrocarbons/>)

25. **"Application of Algae as Co-substrate To Enhance the Processability of Willow Wood for Continuous Hydrothermal Liquefaction"**/ Sintamarean, I-M, Pedersen, TH, Zhao, X, Kruse, A & Rosendahl, LA, *Industrial & Engineering Chemistry Research*, vol 56, no. 15, pp. 4562-4571. DOI: 10.1021/acs.iecr.7b00327, 2017.

26. **"Two-stage alkaline hydrothermal liquefaction of wood to biocrude in a continuous bench-scale system"**/ Sintamarean, I-M, Grigoras, I, Jensen, CU, Toor, SS, Pedersen, TH & Rosendahl, LA, *Biomass Conversion and Biorefinery*. DOI: 10.1007/s13399-017-0247-9, 2017.

27. **"Impact of nitrogenous alkaline agent on continuous HTL of lignocellulosic biomass and biocrude upgrading"**/Jensen, CU, Rosendahl, LA & Olofsson, G 2017 *Fuel Processing Technology*, vol 159, pp. 376–385. DOI:<http://dx.doi.org/10.1016/j.fuproc.2016.12.022>, 2017.



28. **"Renewable hydrocarbon fuels from hydrothermal liquefaction: A techno-economic analysis"**/ Pedersen, T. H., Hansen, N. H., Pérez, O. M., Cabezas, D. E. V. and Rosendahl, L. A., *Biofuels, Bioprod. Bioref.*. doi:10.1002/bbb.1831, 2017.
29. **"Effect of biomass pretreatment on the product distribution and composition resulting from the hydrothermal liquefaction of short rotation coppice willow"**/ Grigoras, I.F., R.E. Stroe, I.M. Sintamarean, L.A. Rosendahl, *Bioresource Technology*, Volume 231, pp 116-123, ISSN 0960-8524, 2017  
<http://dx.doi.org/10.1016/j.biortech.2017.01.056>.
30. **"The Silver in Silva: The story of Steeper Energy and SGF's \$59M advanced bio-fuels project in Norway"**/Jim Lane, *Biofuels Digest*, January 16, 2018, Washington, USA, <http://www.biofuelsdigest.com/bdigest/2018/01/16/the-silver-in-silva-the-story-of-steeper-energys-59m-advanced-biofuels-project-in-norway/>

## 1.6 Conference contributions

31. **"Hydrofaction™ – The path to renewable drop-in biofuels"**/ Jensen, Claus Uhrenholt, In proceedings for TCS 2016 - Symposium on Thermal and Catalytic Sciences for Bio-fuel and Biobased Products, 1-4th November 2016, Chapel Hill, USA.
32. **"Continuous Hydrotreatment of Hydrofaction™ Oil to Drop-in Diesel"**/Jensen, Claus Uhrenholt, Rodriguez, Julie Katerine, GOPE 2016 - International Conference on Gas, Oil and Petroleum Engineering, 14-16th November 2016, Las Vegas, USA.
33. **"Recent Advancements in Upgrading of Hydrofaction™ Oil"** /Claus Uhrenholt Jensen, Julie Katerine Rodríguez Guerrero & Ling Li, In proceedings of the 24th European European Biomass and Exhibition 2016, Amsterdam June 6-9., 2016.
34. **"Hydrofaction™: Renewable fuel oils from Steeper Energy's HTL Technology – Game Changing Economics to Power and Decarbonize the Transport Sector"**/Perry Toms,, 24th European European Biomass and Exhibition 2016, Amsterdam June 6.-9., 2016.
35. **"Biomass to Hydrocarbon: HTL's Progress to Commercial Application"**/Perry Toms, Thermochemical Lignocellulose Conversion Technologies, Chalkidiki, Greece, May 18-20, 2016.
36. **"Hydrofaction™: Renewable fuel oils from Steeper Energy's HTL Technology – Game Changing Economics to Power and Decarbonize the Transport Sector"**/Perry Toms, 13th Annual World Congress on Industrial Biotechnology, San Diego, USA, Apr 17-20, 2016
37. **"Renewable Fuel for the Heavy & Long-Haul Transport Sector"**/Perry Toms, 2016 Cleantech Forum Europe, Lyon, France, Apr 11-13, 2016.
38. **"Hydrotreatment and Compound Identification of Distillate Bio-crude Fractions from Continuous Hydrothermal Liquefaction of Wood"**/ Jensen, Claus Uhrenholt, TC Biomass 2015 - The 4th International Conference on Thermochemical Biomass Conversion Science, 2-5th November 2015, Chicago, USA.
39. **"Hydrofaction™ as a sustainable pathway to "Drop In" Biofuels"**/Lasse Rosendahl and Steen Brummerstedt Iversen, *Lignofuels 2015*, Madrid Jan. 21.-22., 2015.
40. **"Technology validation through collaborations"**/Sergios Karatzos, 6th Annual Bio-industrial Meeting: Bioindustrial Innovations- Unlocking Value & tackling Climate Change, Edmonton Canada, Nov 22.-25., 2015.
41. **"Renewable Diesel from Lignocellulosic Feedstocks through Hydrofaction™"**/Bob Moll, Canadian Bioeconomy Conference: Biofuels to Bioeconomy, Vancouver, Canada, Nov 30 - Dec 2 2015.
42. **"Roundtable discussion in the Bar Room Chat session"**/ Perry Toms, World Bio Markets, Amsterdam, the Netherlands, Mar 14-17, 2016.



43. **"Renewable Fuel from Biomass for the Heavy & Long-Haul Transport Sector"**/Sergios Karatzos, Resource Industries Suppliers Association, Edmonton, Canada, November 23, 2016.

44. **"Lignocellulosic to Jet Fuel through Hydrofaction™"**/Bob Moll, WestJet Renewable Aviation Fuels Forum, Calgary, Canada, November 22, 2016.

45. **"Hydrofaction™ Oil: A Solution for Decarbonizing Long-haul Transport"**/Perry Toms, Advanced Bioeconomy Leadership Conference 2017, March 3, 2017, Washington, USA.

46. **"Hydrofaction – The Path to Renewable Drop-in Biofuels"**/Claus Uhrenholt Jensen, Julia Katerine Rodriguez, International Conference on Gas, Oil and Petroleum Engineering, Las Vegas, USA, November 15, 2016.

#### **1.7 Steeper Energy Corporate video (not financed by project)**

47. <https://www.youtube.com/watch?v=1MWgqQRqsu4&feature=youtu.be>