



IEA Bioenergy
Technology Collaboration Programme

Country Reports 2021

Direct Thermochemical Liquefaction

(Denmark, Norway)

IEA Bioenergy: Task 34

December 2021



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ISBN, if applicable, here

Published by IEA Bioenergy

Denmark

RESEARCH ACTIVITIES

Aalborg University

Aalborg University (AAU) is among the most active institutions worldwide in the field of hydrothermal liquefaction (HTL). The activities are carried out by the group of Advanced Biofuels, operating at the Department of Energy (AAU Energy), and include several aspects of HTL, from the production of biocrude from different biomass feedstocks to the upgrading of biocrude to drop-in fuels.

The research group, led by Assoc. Prof. Thomas Helmer Pedersen, runs several number of facilities for HTL, from small scale micro-batch units to the Continuous Bench-Scale (CBS) pilot unit, run in collaboration with Steeper Energy ApS, which has a throughput of 25-50 kg/h of feed, with a biocrude production in the order of 0.3 barrels per day. Moreover, the research group runs a continuous lab-scale unit for biocrude hydrotreating.

Recently, Aalborg University has been involved in several important research projects, both at national and European level. Aalborg University has successfully concluded the Horizon 2020 projects “4Refinery” and “Hyflexfuel”, obtaining remarkable results. Among the others, production of on-specification HTL-based sustainable aviation fuel (SAF) was achieved and proved by a combustion test in an aviation lab-scale engine. Moreover, AAU is currently leading the Horizon 2020 project “Next Generation Road Fuels” and is a major partner in the project “Lowcarbfuels.dk”, funded by Innovation Fund Denmark. In these projects, HTL-based road fuels (gasoline and diesel) and aviation/marine fuels are respectively targeted, aiming at establishing feasible commercial concepts for advanced biofuels production.



Fig. 1: The Continuous Bench-Scale (CBS) pilot unit at Aalborg University. 2

Aarhus University

The research and pilot activities at Aarhus University in thermochemical liquefaction are concentrated on the hydrothermal liquefaction technology. At the Department of Biological and Chemical Engineering researchers have been operating a continuous HTL pilot plant for some years now with a capacity of 70 kg wet slurry per hour, operating at subcritical conditions (300-350 °C). Research focusses have been on upscaling the technology, energy efficiency and screening/optimization of diverse waste biomass feedstocks. Recent work has focused on urban and agricultural wastes such as sewage sludge, manures, food waste and their co-liquefaction. The team led by Assoc. Prof. Patrick Biller also have research activities in the HTL process water treatment and polymer recycling.

The work is complemented with activities in the Department of Chemistry (Assoc Prof. Marianne Glasius) where the focus is mainly on analytics of the produced products, bio-crude and aqueous phase, using advanced analytical techniques and chemometrics.



Fig. 2: HTL pilot plant at Aarhus University.

Technical University of Denmark (DTU)

The Department of Chemical & Biochemical Engineering is very active in research and development in pyrolysis based processes and pyrolysis oil upgrading. Activities include among other:

- 1) High pressure fluidized bed catalytic hydrolysis of biomass with optional downstream catalytic deep hydrodeoxygenation in a fixed bed reactor (see figure below).
- 2) Fast pyrolysis of biomass at atmospheric pressure with downstream (ex-situ) catalytic upgrading of pyrolysis vapors using acidic or alkaline catalysts.
- 3) Agricultural waste pyrolysis using fixed bed slow pyrolysis technology to maximize the char yield as a means of carbon storage, while producing a useful bio-oil. The pyrolysis reactor technology is developed and patented by DTU and licensed to the company Stiesdal Fuel Technologies working on commercializing the technology. The process is known as the SkyClean® process as it cleans the sky for CO₂.
- 4) Pyrolysis as a means of using waste as fuel at cement factories while at the same time producing surplus pyrolysis oil as a new product of the cement factory. A new technology developed by FL Smidth for waste pyrolysis in synergy with the cement production process is

being further developed to optimize the pyrolysis oil yield and obtain liquid fuels for ships and aviation.

5) Development of catalysts and processes for catalytic upgrading (hydrodeoxygenation) of fast pyrolysis bio-oil from various biomasses - in collaboration with the company Haldor Topsøe.

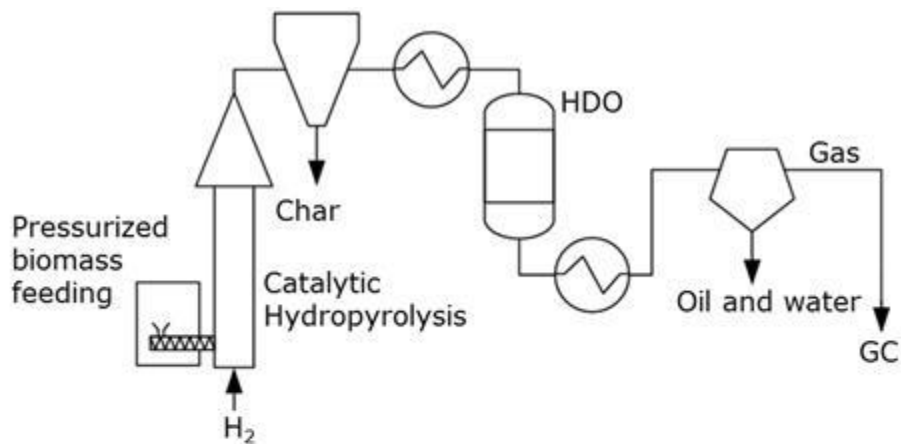


Fig: 3: Experimental setup at DTU-Chemical Engineering for catalytic hydrodeoxygenation of biomass with downstream hydrotreatment (HDO) for deep deoxygenation. Example of product directly obtained from the process is shown to the right with clean oxygen-free hydrocarbon phase on top and clean C-free water phase below. 4

DEMONSTRATION ACTIVITIES

Steeper Energy ApS

Steeper Energy ApS is a Danish-Canadian company active in the field of hydrothermal liquefaction since 2013. They have developed the Hydrofaction® process, featuring the hydrothermal liquefaction of a number of possible organic substrates at supercritical water conditions and including the recirculation of both biocrude and aqueous phase. Together with Aalborg University, Steeper Energy runs the Continuous Bench-Scale pilot unit located in Aalborg, Denmark (biocrude production: 0.3 bpd).

Steeper Energy is currently commissioning an HTL demonstration plant in Norway after a licensing deal with the Norwegian-Swedish joint venture Silva Green Fuel.

Steeper is also involved in a number of important research projects, such as Next Generation Road Fuels (EU Commission Horizon 2020) and Lowcarbufels.dk (Innovation Fund Denmark).

Circlia Nordic Aps

Circlia Nordic (previously known as Bio2Oil) is building hydrothermal liquefaction (HTL) plants that are sized to meet the market opportunity for conversion of geographically distributed wet organic wastes into biocrude oil. The plants are installed in two standard shipping containers, have a throughput of 25,000 tonnes/year of wet biomass, and produce 2,000 tonnes/year of biocrude oil. Modular design and innovations in heat exchange, pressure exchange, and product separation enable economic performance at this scale. Capacity can be increased by numbering up.

In the current quarter, Circlia Nordic finished engineering design of the first commercial HTL plant for the Sludge2Fuel demonstration project funded by the Danish Energy Technology Development and Demonstration Program (EUDP). Procurement and construction will begin in early 2022 and delivery of the plant is planned for the last quarter of 2022.

The plant will convert sewage sludge into biocrude oil at the municipal wastewater treatment plant in Fredericia, Denmark. Sludge2Fuel partners will support upstream and downstream integration of the HTL plant including feedstock logistics, biocrude oil upgrading, aqueous phase treatment, and nutrient recovery. Partners include Crossbridge Energy A/S, Fredericia Spildevand og Energy A/S, Krüger A/S, and Aarhus

University. Ecco Investment Corporation has provided seed funding to Circlia Nordic to support construction of the first support construction of the first support construction of the first of the business. 5

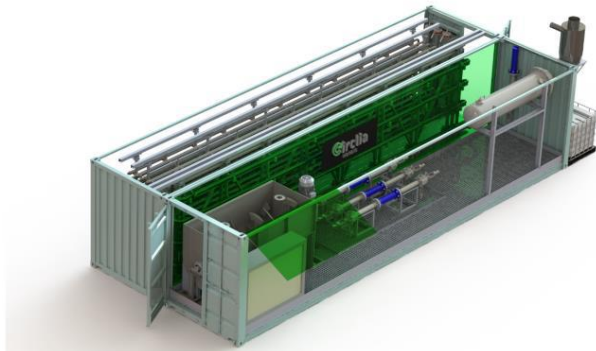


Fig. 4: Three-dimensional rendering of Circlia Nordic's hydrothermal liquefaction plant. Each plant is capable of processing 25,000 tonnes of wet biomass per year to produce 2,000 tonnes of biocrude oil.

Kvasir Technologies

Kvasir Technologies, a spin-out from The Technical University of Denmark (DTU), is commercialising a proprietary solvent liquefaction technology utilizing organic solvents. The Kvasir® liquefaction technology is capable of handling a large array of different abundant lignocellulosic feedstocks, e.g. grasses, straw, wood or nut shells, and even pure lignin. Without the need for catalytic hydrogenation a high energy recovery yield, in excess of 80%, of stable bio-oil is achieved. The oil is acid free and can be used as is as a drop in fuel for the maritime sector or alternatively be processed as a biocrude in a refinery.

Kvasir Technologies is headquartered in Denmark co-located together with Alfa Laval Copenhagen A/S. Piloting is ongoing in the United States (2021) and commissioning of a first of its kind demo plant up to 10 ton oil per day is scheduled for 2022.

Stiesdal

SkyClean® from Stiesdal is a climate technology leveraging an updraft, slow pyrolysis technology using residues from the agricultural sector to produce biochar, biocrude, gas and heat. Relying on decades of research conducted by the Technical University of Denmark we have built a 0,2 MW unit operating since August 2021. The rating refers to the heating value of the flow of biomass being processed. A 2MW pilot plant is currently during construction expected to be ready for commissioning early 2022. Commercialisation is expected to happen from 2023 in unit sizes around 10 MW. SkyClean relies on pelletized biomass to ensure a very high degree of process capability and thus quality of our biochar. Initially, the pyrolysis gas will be used to substitute fossil methane in high temperature heat applications. 6



Mash Makes

Mash Makes (known before as Mesh Energy) is an Indo-Danish company, spin-off from the Danish Technical University (DTU). The activities of Mesh Makes are mostly addressed to the shipping sector, particularly for the production of marine fuels. In this sector, Mash have produced world's first ISO 8217 and EN590 compliant bio-oil, by means of pyrolysis. They run a pyrolysis plant in Ahmedabad, India, based on an auger-type pyrolysis reactor that runs various agricultural residues. The resulting oil is ISO 8217:2019 compliant in a B11 blend with DMA or marine gas oil. By distillation of the pyrolysis product, they were able to produce an EN590 compliant fuel in a 3.8% blend.

Quantafuel

Quantafuel is a Norwegian-based company active in the field of plastic recycling. They have patented the process Catpyr®, involving catalytic pyrolysis for the chemical recycling of plastics. The core of the process is represented by a two-stage catalytic process in the gas phase, to increase the quality of the desired hydrocarbons.

Quantafuel runs a Plastic-to-liquid (Ptl) plant in Skive, Denmark, sized for a throughput of 20,000 tonnes of mixed plastic waste per year, originating from households in Denmark and Norway. Products will be delivered to BASF for the synthesis of new plastic materials and chemicals. Operations started in 2020.

A scale-up of the Skive plant has been announced and will be established in Esbjerg, in the South-West Denmark.

Reaktor ApS

Reaktor ApS is established in Frederiksværk, Denmark, and it is a relatively novel company, deriving from the previous De Nova ApS. At the moment, the company is mostly active in the pyrolysis of waste, mainly specializing in the field of plastic and rubber fractions, for the production of diesel oil from those contaminated waste that cannot be economically recycled. Among the focuses of the company there is the possibility to collect and treat plastic waste from the oceans.

Makeen Energy

Makeen Energy operates in the field of innovative and responsible energy solution for bunkering, refuelling and liquefaction. Among the others, Makeen energy is active in LPG, gas equipment, LNG/LBG, plastic waste conversion (Plastcon®), power, solar-powered street lighting (Suncil), service, facility management, project management and engineering.

As far as liquefaction is concerned, Makeen Energy runs the process Plastcon®, involving the pyrolysis of plastics mainly intended for recycling. This process can be applied to wide range of waste plastics and can produce a wide range of products. Typical yields involve 75% pyrolysis oil, to be used for new plastic production and/or as fuel for ships and trucks, 15% of combustible gases and 10% of carbon black, to be used as a coloring agent for plastics. A Plastcon module is able to treat 25 tonnes of plastic per day.

Norway

POLICY ENVIRONMENT

Norway supports the development of sustainable liquid transportation fuels primarily by setting demands for biofuel share in transportation fuels. To promote production of advanced biofuels, separate feed in demands are set for advanced biofuels. In addition, advanced count double» in the feed in calculations. Implementing increased use of biofuels in transportation is important task to reach national targets with respect to cut in CO2 emissions. In total, Norway aims for reducing national CO2 emissions by minimum 40% by 2030. The transport sector account for about 30% av total national CO2 emissions, and the target is to cut 50% of the emissions from the transport sector by 2030. For road transportation, minimum 40% biofuel share shall be obtained by 2030. By 2021, minimum 25% of road transportation fuels shall be biofuels out of which advanced biofuels shall account for minimum 9%. For aviation, the target is to obtain at least 30% biofuel share in sold aviation fuels by 2030.

RESEARCH ACTIVITIES

The main R&D actors in Norway related to thermochemical liquefaction are listed in Table 1. Here, RISE PFI (<https://www.rise-pfi.no/>) is working with fast pyrolysis, catalytic pyrolysis, upgrading and carbonization processes. SINTEF Energy (<https://www.sintef.no/sintef-energi/>) is addressing hydrothermal liquefaction whereas the chemistry department at Bergen University (<https://www.uib.no/en/kj>) is focusing on lignin solvolysis. The catalysis group at NTNU Department of Chemical Engineering (<https://www.ntnu.edu/chemeng/>) is working with catalytic pyrolysis whereas SINTEF Industry is addressing pyrolysis oil upgrading and hydrotreatment. An unique national research infrastructure within thermochemical conversion has been established through the Norwegian Biorefinery Lab (<https://norbiolab.no/>). At present, a large R&D program termed Bio4Fuels is running in Norway to develop technology and to assist industry in developing and implementing production of biofuels in Norway (<https://www.nmbu.no/en/services/centers/bio4fuels>).

Table 1: Main R&D actors within thermochemical liquefaction in Norway

Institution	Main Contact	Key activities
RISE PFI	Kai Toven	Fast pyrolysis, Catalytic pyrolysis, Upgrading, Carbonization processes
SINTEF Energy	Judit Sandquist	Hydrothermal liquefaction
Bergen University	Tanja Barth	Lignin solvolysis
Norwegian University of Science and Technology (NTNU)	De Chen	Catalytic pyrolysis
Sintef Industry	Roman Tschentscher	Upgrading, hydrotreatment

DEMONSTRATION ACTIVITIES

Silva Green Fuel

In 2015, Statkraft and Södra formed a joint venture termed Silva Green Fuel to develop and produce advanced transportation biofuels. Statkraft is a leading Norwegian company in hydropower whereas Södra is a Swedish forest owner and producer of paper pulp, sawn timber and bioenergy. After reviewing various technologies, Silva Green Fuel formed a partnership with Steeper Energy, a Danish-Canadian clean-fuel company. Here, Silva Steeper Energy will license its proprietary Hydrofaction technology to Silva Green Fuel who will build a demonstration plant with a capacity of about 4,000 liters per day at Tofte, a previous pulp mill site, in Norway. Hydrofaction® is Steeper Energy's proprietary implementation of hydrothermal liquefaction which applies supercritical water as a reaction medium for the conversion of biomass directly into a high-energy density renewable crude oil, referred to as Hydrofaction® Oil. The demonstration plant will use woody residues as feedstock that are converted to renewable crude oil which, in turn, will be upgraded to renewable diesel, jet or marine fuel. By now, the commissioning period is completed and initial testing with wood feedstock has been carried out successfully. Long-period testing will start up early 2022.



Fig. 1: Silva Green Fuel HTL demonstration plant at Tofte in Hurum county, Norway. (<https://www.silvagreenfuel.no/>)

Biozin Holding AS

Biozin Holding AS' (<https://biozin.no/>) intend to establish the first large scale production of advanced biofuel based on forest residues and by-products in Norway. Biozin AS is a wholly-owned subsidiary of Bergene Holm AS, the second-largest sawmilling and wood processing group in Norway. Pending technology qualification, Biozin Holding aims to utilize Shell's The IH² (Integrated Hydrolysis and Hydroconversion) IH2 technology for the conversion process. In June 2021, Biozin Holding entered into an agreement with Shell for financial support of their ongoing project to establish a full-scale biocrude production facility in Åmli in Agder county. The Biocrude plant shall produce 120.000 m³ of advanced bio-crude biozin® and 35.000 tons of biocarbon annually. The project aims for a final investment decision in second half 2023.



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