IEA Bioenergy
Technology Collaboration Programme

Country Reports 2023

Direct Thermochemical Liquefaction

(Canada, Germany, United States)

IEA Bioenergy: Task 34

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Canada

DIRECT THERMOCHEMICAL LIQUEFACTION (DTL) WITHIN CANADIAN POLICY FRAMEWORK

Canada's liquid fuel mandate is primarily directed by The Canadian Net-Zero Emissions Accountability Act, which became law on June 29, 2021. This act enshrines Canada's commitment to reduce GHG emissions to 40-45% below 2005 levels by 2030 and to achieve net-zero emissions by 2050. The Pan Canadian Greenhouse Gas Offsets Framework has set minimum carbon pollution price at $ 65 per tonne CO_2e in 2023 which will increase to $ CAD 170/tonne CO_2e by 2030.

In 2022, Canada published its Clean Fuel Regulations (CFRs). These regulations are an important off shoot of Canada's climate change mitigation strategy. The CFRs take a performance-based approach and require primary suppliers, producers and importers of gasoline and diesel, used in mobile equipment to reduce the carbon intensity (CI) of these fuels. The Regulations are designed to incentivize innovation and adoption of clean technologies and expand the use of low carbon intensity fuels throughout the economy without adhering to any specific pathways or any specific fuels. The Regulations give fuel suppliers flexibility to meet the requirements in a cost-effective way that works best for them. More specifically, the CFRs aim to gradually reduce the CI of surface transportation fuels: by 3.5 g CO_2e/MJ in 2023, up to 14 g tCO_2e/MJ in 2030 when compared to 2016 CI levels. The CFRs also establish a credit market whereby the annual CI reduction requirement could be met via three compliance categories: (1) reducing the CI of the fossil fuel production throughout its life cycle, (2) blending low-carbon fuels (e.g., ethanol and biodiesel equivalents), and (3) specified end-use fuel switching in transportation. At a more comprehensive national level, it should be noted that most provinces have renewable fuels mandates and policies in place, for example British Columbia has a unique low carbon fuel standard (LCFS), all of which will complement the CFRs. For details one can refer to Canada Gazette Part II - Clean Fuel Regulations.

This implies that Canada will need around 2.2 billion liters of additional low CI diesel equivalent, and 700 million litres of additional ethanol equivalent liquid biofuels compared to current supply of 1.60 billion litres of biodiesel and 460 million litres of ethanol equivalent biofuels.

KEY RESEARCH ACTIVITIES

CanmetENERGY

CanmetENERGY is a branch of Natural Resources Canada. It has three labs across Canada with a mission to lead the development of energy S&T solutions for environmental and economic benefit of Canada. CanmetMATERIALS is another sibling lab which provides materials related R&D support in development of energy conversion processes.

CanmetENERGY-Ottawa continues to operate its' 5-10 kg/h fast pyrolysis facilities in support of direct thermochemical liquefaction and valorization of liquid as well as byproduct streams derived from low quality agriculture, forestry, and municipal solid residues. These facilities include, ablative centrifuge pyrolysis reactor, fluid bed pyrolysis reactor and screw reactor. CanmetENERGY-Ottawa is also pursuing research in hydrothermal conversion process using their h with 1 L and 40 L hydrothermal reactors.

Furthermore, CanmetENERGY-Ottawa is collaborating with several universities and research organizations by providing pyrolysis derived liquids and byproducts sourced from Canadian agriculture, forestry and municipal solid residues.

CanmetENERGY-Ottawa also operates:

- 50 kW_{th} waste oil furnace modified for bio-oil and biocrude combustion furnace for developing technical

data on the combustion performance of bio-oils and biocrudes,

• various systems for developing data on the handling of bio-oils and biocrudes (e.g., filtration and materials exposure),

• and operates a variety of catalytic upgrading equipment to assist technology development of viable routes to fungible hydrocarbon fuels including sustainable aviation fuel (SAF).

In support of Canadian mandate on low carbon intensity liquid fuels,

- CanmetENERGY-Ottawa and CanmetENERGY-Devon continue to develop methods and expertise for the advanced characterization and standardization of these pyrolysis liquids.
- CanmetENERGY-Devon works extensively with the oil & gas industry in Canada to establish technology, standards and guidelines for the co-processing of bio-oils and biocrudes.
- CanmetENERGY-Varennes supports research related to process integration, life cycle and techno-economic analysis of biomass liquefaction within the Canadian pulp and paper industry.
- CanmetMATERIALS develops technical data and provides expertise on materials for biomass thermochemical processes and applications for the products derived from these processes.

National Research Council

The National Research Council (NRC) has developed a pilot scale (5 kg/hr) HTL facility and is pursuing research on hydrothermal liquefaction of wet bio-feedstocks including food wastes, manures and algae. NRC is developing customized solutions for gas turbine and diesel engine application of waste derived HTL bio-crude. The NRC partners with CanmetENERGY for upgrading, coprocessing trials of HTL bio-crude and has been working with industrial clients requiring HTL bio-crude as an input to their specific upgrading processes. Other ongoing research at NRC involves HTL bio-crude characterization, catalyst development to improve the HTL processes and upgrading to SAF.

Université du Québec à Trois-Rivières

The mission of the Institut d'innovations en écomatériaux, écoproduits, écoénergies at Universite du Quebec a Trois-rivieres is the analysis, optimization and application to a specific local context of the key technologies necessary for the development of a regional bioeconomy with a view to accelerating its establishment and contributing significantly to the development of a regional bioeconomy. The production and modification of pyrolytic oils for specific applications, i.e., “drop in” type biofuels”, is one of the technologies being evaluated. The institute has been part of a major initiative related to bio-oil, i.e., Bioénergie La Tuque (BELT), to produce biofuels from residual forestry biomass. However, recently, there has not been further updates.

University of New Brunswick

Researchers in University of New Brunswick (UNB) are investigating:

-reducing bio-oil oxygen content via in-situ catalytic deoxygenation and hydrogen production

-the opportunities for using bio-oil and byproducts from fast pyrolysis, such as biochar in asphalt applications.

University of Toronto

The University of Toronto’s combustion and propulsion research focuses on analyzing the combustion characteristics of biofuels, including pyrolysis oil. Recent work includes application of second-generation waste derived bio-oil in industrial applications and power generation systems (i.e., gas turbine, lime kiln, etc.) for reducing their carbon footprint. This work enhances understanding of pyrolysis liquid spray formation and combustion with the help of various experimental tools. It also covers the effect of

pyrolysis liquid rheological characteristics on its spray formation.

Western University

The Institute for Chemicals and Fuels from Alternative Resources (ICFAR) at Western University, is one of the major research groups in Canada working on pyrolysis. Their ongoing work includes the conversion of biomass, residues and wastes into value-added products from pyrolysis; the production of bio-oils, biochar and gas from biomass; bio-oil and biochar upgrading and applications, including the use of bio-oils as pesticides, antioxidants and adhesives; biochar as a soil amendment, in carbon sequestration, adsorbent and other uses and the separation and purification of valuable chemicals from bio-oils. In collaboration with CanmetMATERIALS, ICFAR is also investigating reaction Kinetics and corrosion-resistance performance of candidate alloys for hydrothermal liquefaction (HTL) reactors.

KEY DEMONSTRATION ACTIVITIES

Abri-Tech

ABRI-Tech Inc. is a partnership between the Leggett family and Peter Fransham (Ph. D.). Abri-Tech has been developing biomass pyrolysis and drying technologies. ABRI-Tech's objective is to add value and convert these byproducts into bio-oil, which can serve as an alternative to fossil fuels. ABRI-Tech Inc has been actively focussed on biomass dryers and auger pyrolysis systems since 1988. The company's line of products includes an auger pyrolysis system using steel shot as a heat carrier. The entire system of dryer, reactor, char management and condensation consists of seven modules that can be relocated easily and quickly. As per the previous country report in 2020, the largest modular plant is 50 dry tonnes per day. Plants have been installed in Canada and Russia. A 1 tpd plant at their facility in Namur, Quebec, Canada offices is available for feedstock testing. Currently no further updates are available on Abri-Tech.

Bio-TechFar

BioTechFar (BTF) is a biorefinery technology provider for the conversion of biomass into energy and non-energy products through an innovative mechanically fluidized reactor (MFR) pyrolysis process. BTF has an initial focus on processing 2nd Generation biomass feedstock, i.e., derived from non-food biomass such as lignocellulosic materials and waste / byproducts from forestry, agriculture, industry and households. Unlike other thermochemical conversion processes with a "single product output", the MFR pyrolysis system enables the production of all three products (oil, char and gas) with both energy and non-energy value potential for improved ROI potential. The founders of the company are also associated with the Institute for Chemicals and Fuels from Alternative Resources (ICFAR), Western University. BTF has no recent updates available through their website.

Arbios Biotech

Arbios Biotech is a joint venture between technology pioneers Licella and integrated forest products company Canfor. Arbios Biotech uses cutting edge technology to convert end-of-life wood and biomass into renewable biofuels and biochemicals. Licella is the global leader in the field of Hydrothermal Liquefaction (HTL). The company has dedicated over a decade to developing its patented Cat-HTR™ ('Catalytic Hydrothermal Reactor') platform that produces low-carbon biocrude (a renewable and sustainable bio-oil for the circular economy), from which low-carbon transportation fuels and chemicals can be produced.

Arbios Biotech claims to have world's first small-scale commercial HTL plant (CS-1) with the ability to process 5000 tonnes per annum of post-consumer and residue biomass (producing 10,000 barrels per annum of renewable bio-oil), using commercial scale reactors. In May 2021, Shell Catalysts & Technologies ("SC&T") and Arbios Biotech announced a new global alliance aimed at utilizing SC&T's upgrading technology capability in pursuit of a low-carbon intensity, circular-bioeconomy focussed biorefinery. In October 2021, Canfor also announced its positive final investment decision in support of the construction

of the first phase of Arbios Biotech's (Arbios) innovative biomass to low carbon biofuel plant in Prince George, British Columbia. The plant will use first-of-a-kind technology to convert 25,000 dry metric tons of sawmill residues, primarily bark, into 50,000 barrels of sustainable high value renewable biocrude which can be further processed in refineries to produce low-carbon transportation fuels. In August 2022, the commercial facility was named as Arbios Biotech Chuntoh Ghuna that means "The Forest Lives". Originally it was scheduled to start producing renewable biocrude in the first half of 2023, however, currently no further updates are available.

ONYM Groupe (*Pyrobiom Énergies inc.*)

In 2017, ONYM Group, through its subsidiary Pyrobiom Énergies inc. installed its first forest residue recovery plant, a 50 ton/day auger pyrolysis technology, at a softwood sawmill located in Parent, Québec. This project, which benefited from financial support from the Technoclimat program of the government of Quebec, makes it possible to process bark, sawdust and shavings to produce bio-oil and bio-char.

In 2022, ONYM Group has also started work on its second unit which will be installed in the east of Montreal to produce bioenergy and bioproducts, through the valorization of urban forestry residues. The plant is located inside a petrochemical facility that will consume bioenergy to reduce its GHG emissions. The project is a technological showcase, and it benefits from significant financial support from the Government of Quebec.

Pyrovac Inc

Pyrovac is developing, designing and constructing industrial pyrolysis plants for various applications including forestry and agricultural biomass, waste plastics, used tires and bituminous waste materials. Given the increasing demand for biocarbon, Pyrovac has diversified demand for pyrolysis products, its approach on the conversion of various wastes into valuable products such as wood vinegar, bio-oils, biochar, pyrolytic carbon black and different kinds of chemicals. In 2019, Sustainable Development Technology Canada (SDTC) provided $3 million grant to Pyrovac for a project to develop a plastic-to-fuel pyrolysis technology that avoids the production of conventional diesel and reduces plastic waste in landfills.

In 2021, Pyrovac, partnered with Polynergy, opened a pilot plant in Saint-Lambert-De-Lauzon, Quebec, with a 50kg/hr conversion of plastic waste to pyrolytic diesel. As per claims, when mixed with petroleum derived diesel used in buses and in industrial trucks, pyrolytic diesel reduces greenhouse gas (GHG) emissions. The production of pyrolytic diesel generates 68% less GHG than petroleum diesel, based on the ISO 14064-2 standard.

Steeper Energy

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. It is claimed that Hydrofaction® biocrude can be used directly or upgraded for use as a renewable marine, diesel, or aviation fuel.

In April 2023, Steeper Energy and Invest Alberta Corporation announced to develop first-of-its-kind Hydrofaction commercial plant in Alberta. Steeper's first plant in Alberta will specifically focus on the large volumes of forestry waste that would otherwise need to be burned to manage forest fire risk.

Vancouver Metro

The City of Vancouver has a hydrothermal processing pilot project underway, using the Genifuel process, that was developed by the USDOE Pacific Northwest National Laboratory. A pilot facility has been planned at the city's Annacis Island Wastewater Treatment Plant to convert wastewater biomass solids from treatment plants into biocrude oil that can be refined to a low carbon transportation fuel. The Parkland

Fuel was hoping to co-process the bio-crude from the HTP unit at its Burnaby, B.C. refinery. The project was expected to be operational in 2024. However, there are no further updates available.

Ensyn

Ensyn has provided their RTP technology (fast pyrolysis) for commercial operations in Rhinelander, Wisconsin (3 x 30 - 40 dry tons per day), in Renfrew, Ontario (70 dry tons per day) operated by the Kerry Group and Côte-Nord, and in Port-Cartier, Québec (200 dry tons per day) operated by BioÉnergie AE Côte-Nord under a partnership with forestry companies. Their major products include food flavourings, renewable fuel oil, and refinery feedstocks. The company continues to provide support for commercial operations and develop new commercial projects.

In Dec. 2022, ArcelorMittal Mining Canada G.P. has won an EnviroLys Award in the ICI+ Green Project category for introducing the use of pyrolytic oil at its Port-Cartier plant. So far, they have utilized three million litres of pyrolytic oil at the Port-Cartier pellet plant. As per reports, the energy efficiency of the pyrolytic oil, which is manufactured by BioÉnergie AE Côte-Nord, exceeded expectations.

Vyterra Renewables Inc. which is Ensyn's wholly-owned Canadian subsidiary is developing Nova Scotia Project, a 40 million litre/year (10 million gallon/year) low carbon fuel production facility in central Nova Scotia.

The project will produce low-carbon fuel oil, which will be supplied to local institutional and industrial clients for heating purposes. In addition, the site is strategically located in proximity to the Port of Halifax, allowing for shipment of biocrude to international customers. In December 2023 Michelin North America (Canada) Inc. and Vyterra announced the completion of a successful low carbon fuel oil (LCFO) combustion trial at Michelin’s Waterville, Nova Scotia plant.

NOVA Chemicals

Calgary based plastic producer NOVA Chemicals has partnered with Plastic Energy to transform up to 146 million pounds of scrap plastic each year. Currently a feasibility study for Sarnia, Ontario as the primary location is underway. If successful, this will be largest of its kind (of pyrolysis) plant in Canada. Plastic ENERGY uses pyrolysis to make TACOIL™, a branded oil that can be used to make fresh plastic within the context of a circular economy framework.

Germany

Major stakeholders in Germany around DTL technologies are compiled in Table 1. All of these stakeholders have been actively researching and/or promoting DTL technologies in 2023.

Table 1: DTL Stakeholders in Germany

Institution	Main Contact	Key activities
German Biomass Research Center (DBFZ)	Dr. Benjamin Herklotz	Hydrothermal Processes
Fraunhofer Institute UMSICHT	Dr. Andreas Apfelbacher	Intermediate Pyrolysis (TCR®)
Hamburg University of Applied Sciene (HAW)	Thomas Willner	Solvolytic reactive distillation, READi process
Karlsruhe Institute of Technology-IKFT	Nicolaus Dahmen	Fast pyrolysis, hydrothermal and solvothermal liquefaction, bioliq® process
Nexxoil	Thorsten Dunker	Solvolytic reactive distillation, READi process
Thermophil	Dietrich Meier	Consultant FPBO analytics and fast pyrolysis
Thünen Institute of Wood Research	Jörn Appelt	FPBO analytics, FPBO upgrading

DTL WITHIN THE NATIONAL POLICY FRAMEWORK

Germany is following the blend in mandate of biofuels according to EU legislation and has no legislation/

incentives in place beyond that specifically targeting 2nd generation biofuels. There is a moderate CO_2 price raised for heat and transportation fuels of 30 €/t in 2023 (which is constantly increasing in the coming years). Germany has a strong policy to instead promote power-based fuels (PtX), specifically for use in transportation to meet GHG reduction targets in the transportation sector imposed by European legislation. By 2026, a share of 0.5% PtX fuels should be implemented which raises to 2% by 2030 (equivalent to roughly 200k t.p.a. power-based fuels).

The previously extremely successful German Renewable Energy Sources Act grants subsidies for combined heat and power generation only (with special rules for combined heat & power generation) and DTL technologies cannot compete against other bioenergies (such as anaerobic digestion and wood combustion) in this sector, yet.

Notably, there are efforts to develop a national biomass strategy to align policies that direct the use of (national) biogenic resources and also a carbon management strategy to align policies in the field of carbon capture and storage. The former has already been framed by several governing principles. It is very clear that sustainable biomass supply will be the core of this strategy and that there will be a focus on biogenic residues, consequently. Purpose grown biomass should be reserved for material use, ideally in a cascaded approach. Some of these principles have already been included in the current 8th energy research program of the German government in that bioenergy should only be produced by biogenic residues and even then material use should be priorized.

There has been a concerted study by the German Energy Agency to develop a national roadmap for achieving a climate neutral society by 2045. This roadmap considered all energy aspects (power, heat, and transportation) as well as other carbon demand in industry. This study anticipates a high share of power-based fuels of 176 TWh by 2045 compared to roughly 40 TWh bio-based fuels. Consequently, a low increase in bio-based fuels is assumed since today's biofuels used in transportation represent 30-35 TWh. Nevertheless, renewable carbon input to the future German carbon cycle is anticipated to be governed by 105 Mio t CO_2-eq from national biomass sources in contrast to 10 Mio t CO_2-eq local CCU applications. In this scenario, 24 Mio t CO_2-eq CCS are anticipated and a significant import of renewable carbon via 40 Mio t CO_2-eq power-based transportation fuels and 25 Mio t CO_2-eq synthetic hydrocarbons (both biogenic and power-based) for the chemical industry.

RESEARCH ACTIVITIES

DBFZ

The DBFZ is running a 'Biorefinery Laboratory' consisting of several technologies and a wide variety of equipment around hydrothermal processing of biomass. DBFZ has established an annual symposium on hydrothermal processing, which is German based but bilingual (www.htp-inno.de) and usually takes place around early autumn in Leipzig/ Germany.

Fraunhofer UMSICHT

The main focus of Fraunhofer UMSICHT (location Sulzbach-Rosenthal) is developing the TCR® process, which is based on intermediate pyrolysis. They operate units up to a TRL of 7. Main focus is on conversion of agricultural residues, such as e.g. digestate, and sewage sludge. EN 590/ EN 228 compatible Diesel/ Gasoline is achieved via hydrodeoxygenation of bio-oil. Active research involves using H2 derived from by-product syngas and investigation of suitable catalysts.

Latest achievement was successful demonstration of sewage sludge conversion to approx. 50,000 litres bio-oil as precursor for gasoline, diesel, and kerosene production within the EU H2020 TO-SYN-FUEL project (www.tosynfuel.eu)

HAW Hamburg

The research of the Hamburg University of Applied Sciences (HAW Hamburg) in the field of DTL focuses on

solvolytic approaches, such as solvolytic reactive distillation (SRD) and solvolytic reactive stripping (SRS). The basic approach of both variants is using a self-regenerating heavy-oil sump phase as a solvolytically acting reaction medium. The main challenge is the stabilization of the sump phase in continuous long-term operation. Previous research results have confirmed that the sump phase can develop towards a stable state over time as intended, with the exception of the formation of small proportions of solid residues (char). These solids must be separated continuously to prevent them from accumulating in the reactor.

SRD: The SRD variant is called READiTM process indicating "Reactive Distillation" in the name. It is working at low pressures in the range of usually 1 to 5 bar. The reaction temperature is also the boiling point of the reaction medium. Thus, the cracked product molecules are continuously removed by distillation from the sump phase. Cracking reactions are accompanied by deoxygenation reactions. Contents of other heteroatoms such as sulphur or nitrogen, if present, are also reduced significantly. The separated and condensed product is free of heavy-oil molecules. All these effects are expected to be cost reducing by minimizing further refining and hydrotreating efforts. Furthermore, the process is a non-catalytic approach. Thus, it is resistant to impurities in the feedstock as no catalyst can be contaminated or deactivated. The SRD approach has been successfully applied on the one hand to liquid feedstock such as oils and fats, used cooking oil, different heavy-oil residues and others, and on the other hand to solid waste material such as plastic waste mixtures.

SRS: The SRS approach is also a sump phase concept, but in contrast to the SRD variant applying pressurized hydrogen. The elevated pressures result in an increase of the boiling temperature of the liquid sump phases (solvent) far above reaction temperatures. Therefore, volatile reaction products are stripped out by a hydrogen flow (SRD → SRS). The use of catalyst is again avoided because catalyst deactivation in long-term operation is promoted by the conditions in the sump phase and the use of waste feedstocks. To enable the reactivity of hydrogen without catalyst, temperatures around 400 °C and above are required. The research aims to develop a process with hydrogen serving as a radical scavenger shifting the product distribution from heavy bio-crude to light bio-oils easier to handle and upgrade. However, heavy oil should still be produced sufficiently to regenerate the sump phase contributing to the light oil yield at the severe operation conditions. One typical field of application is solid lignocellulosic biomass the HAW Hamburg research is focussing at.

KIT

There is both research on fast pyrolysis as well as HTL at KIT. Fast pyrolysis research is focusing on solutions for DTL of (ash-rich) biogenic residues. KIT operates a lab-scale (100 g/h feed capacity) bubbling fluidized bed reactor and a pilot scale (10 kg/h feed capacity) twin-screw mixing reactor. The bioliq® pilot unit has been put out of operation and will be dismantled after having demonstrated this technology for both wheat straw and miscanthus as feedstock. Research continues to focus around auger reactor design (design, simulation, and scale up), condensation of pyrolysis vapours (fractionated condensation, phase equilibria, condensation design), and process design (simulations and concepts). Alternative uses of the condensates are investigated with a focus on mild hydrodeoxygenation, water removal, and use of CO2 to enhance downstream processing of FPBO. Research on HTL has recently focused around lignin degradation pathways/ kinetics to bifunctional monomers and oligomers within a lignocellulose biorefinery, integration with microalgae utilization by extraction of lipids and/or proteins or amino acids, and the fate of nitrogen containing species.

Current participation in large research projects includes H2020/ Horizon Europe projects FLEXI-GREEN Fuels (https://flexigreenfuels.eu), Black Liquor to Fuel (www.bl2f.eu) and PYRAGRAF (www.pyragraf.eu) as well as the federal funded REF4FU project (http://www.ref4fu.de) with participation of the largest German crude oil refinery (see highlight box).

REF4FU Project

To date, renewable fuels for road, aviation, and marine transport cannot be produced selectively using a single process route. They are usually produced in different proportions together with other by-products-

The REF4FU project aims to develop, validate and evaluate sustainable refinery concepts that can meet the future demand for renewable liquid fuels. The fuels that are currently used in fleets and will be required in the foreseeable future will be produced, tested and evaluated using scalable technologies from renewable methanol, Fischer-Tropsch hydrocarbons and pyrolysis oils. In addition, a classification is made against the background of the regulatory framework.

Renewable fuel components produced by the research partners are formulated into tailor-made fuels using a systematic approach. They are examined and evaluated for their conformity with current and potentially future standards and their technical applicability. The industrial partners are involved primarily in the practical development and scaling of the technology combinations necessary for the production of the fuels as well as in the testing, evaluation and further development of the fuels. The refinery concepts derived from this are evaluated with regard to technical, ecological and economic characteristics and their flexibility for future fuel requirements. Examples of possible paths to successful implementation are shown for selected refinery concepts.

Project partners cover all aspects of this value chain: ASG, BASF, CAC, DBRZ, DLR, EDL,

DEMONSTRATION ACTIVITIES

Nexxoil

The first Nexxoil pilot unit based on waste cooking fat/ vegetable oil is operational in Hamburg/ Germany and a first commercial unit is planned for 2024. This places Nexxoil at the forefront of industrial implementation of a solvolysis process.

Fraunhofer UMSICHT

The first TCR® industrial demonstration facility was constructed and put into operation within the EU H2020 project TO-SYN-FUEL. Over 500 metric tons sewage sludge were converted into approx. 50,000 litre bio-oi. The plant will continue to be operated by Fraunhofer Umsicht and is available for additional test campaigns.

COMMERCIAL APPLICATIONS

Currently, there are no commercial applications of DTL technologies and/ or processes in Germany.

United States

Major stakeholders in the United States around Direct Thermochemical Liquification (DTL) technologies are summarized in Table 2. All of **these** stakeholders have been actively researching and/ or promoting DTL technologies in 2023. There are scores of universities and small businesses who are active in the field at smaller scale, and they are also stakeholders even if they are not included individually.

Table 2: DTL Stakeholders in the United States

Company or Institution	Main Contact/ CEO	Key activities
RTI International	Dave Dayton	Pilot plant for catalytic fast pyrolysis, development of reactive catalytic fast pyrolysis
NREL	Bob Baldwin	Thermal and Catalytic Process Development Unit for catalytic and fast pyrolysis
PNNL	Michael Thorson	Hydrothermal Process Development Unit for HTL, and catalytic upgrading
Iowa State University	Robert Brown	Autothermal pyrolysis, free-fall, and auger reactor
Biogas Energy Ltd.	Brian Gannon	Ablative fast pyrolysis reactor from thermophil international
Genifuel	Jim Oyler	HTL demonstration unit and commercial plant with Metro Vancouver
Origin Materials	John Bissel	Plant for the conversion of woody feedstock into chloromethyl furfural.
Frontline BioEnergy	Jerod Smeenk	Autothermal pyrolysis (ATP) technology developed by Iowa State University researchers
New Hope Energy	Johnny Combs	Pyrolysis plant to covert HDPE, LDPE, Polystyrene, and Polypropylene into a pyrolysis oi
Alder Renewables	Derick Vardon	Demonstration plant to deploy their Advanced Pyrolysis Oil (APO™) technology with solvent fractionation

DTL WITHIN THE NATIONAL POLICY FRAMEWORK

The landscape of sustainable liquid transportation fuels in the United States continues to evolve, with continued support under the Renewable Fuels Standard (RFS) and the market for Renewable Identification Numbers (RINs). Here's an updated summary:

1. **Renewable Fuels Standard and RINs**: The RFS remains a key driver for the production of biofuels. High-value RINs continue to incentivize the production of second-generation biofuels, supporting technologies like cellulosic ethanol, direct thermochemical liquefaction (DTL), and gas-to-liquids processes.
2. **State Programs**: Programs like California's Low Carbon Fuel Standard (LCFS) persist in their role in promoting low-carbon fuels, complementing federal efforts.
3. **Sustainable Aviation Fuel (SAF) Goals**: Ambitious targets for SAF remain a major policy focus.

Efforts to replace all jet fuel with sustainable alternatives by 2050 and to produce three billion gallons of SAF by 2030 are key drivers. Policies and investments are increasingly geared towards meeting these objectives, with a notable emphasis on reducing aviation emissions by 20% by 2030.

4. **Commercial Activity and Investments**: The commercial activity in fast pyrolysis and hydrothermal liquefaction has seen modest activity. Projects have advanced. Also, investment is observed in the conversion of ethanol to SAF and in renewable diesel production.
5. **Renewable Diesel Production**: The trend of retrofitting existing refinery assets for renewable diesel production continues. As the demand for used cooking oils and tallow outpaces supply, there is upward pressure on feedstock prices. Given the increased demand for renewable fuels and the constraints in feedstock for renewable diesel, DTL technologies that rely on abundant sources present significant opportunities.

Commercial activity in fast pyrolysis or hydrothermal liquefaction is currently limited. There are several pilot and demonstration projects in addition to proposed commercial plants. This are also major projects focused on (a) ethanol to SAF or (b) renewable diesel (often retrofits). Renewable diesel requires preferably used cooking oil or tallow as a feedstock. Both small and large energy companies have retrofitted existing refinery assets to produce renewable diesel. Since DTL technologies rely on abundant, non-food biomass there is an opportunity to market liquid intermediates like bio-oil or biocrude to meet the current refinery capacity expansion for renewable fuels.

RESEARCH ACTIVITIES

RTI International

RTI continues to develop technology and capabilities for fast pyrolysis. They operate a fast pyrolysis pilot plant with a capacity of 1 tonne of biomass per day. In-situ catalytic fast pyrolysis (CFP) is supported by this plant, broadening the range of process conditions and configurations. RTI International has partnered with Topsoe for catalyst development for RCFP and bio-oil upgrading.

RTI International has 4 BETO funded projects. The first focuses on biocrude production and upgrading to renewable diesel. The second focuses on integrated reactive catalytic fast pyrolysis system for advanced hydrocarbon biofuels with scale up of in-situ RCFP process by 10 times. The third focuses on integrated separations to improve biocrude recovery for biofuel and bioproducts, where they aim to scale up separations into a 1TPD pilot plant and co-process biocrude with refinery intermediates. The fourth project focuses on a corn stover pyrolysis pathway for SAF, with a focus on biocrude production from catalytic corn stover pyrolysis in 1TPD pilot plant followed by hydrotreating and fractional distillation to recovery SAF.

RTI International has been developing an advanced biofuels technology that integrates catalytic biomass pyrolysis and hydroprocessing to produce infrastructure compatible biofuels and bioproducts. During the primary direct liquefaction step, catalysts are applied, and process conditions are optimized to maximize the yield and adjust the chemical composition of the liquid biocrude intermediate. Biocrude quality is typically described by the amount of oxygen contained in the organic liquid. The driver for removing oxygen during biomass pyrolysis is to produce biocrude that can be upgraded using conventional hydroprocessing technology, but biocrude is a complex mixture of hundreds of compounds with a wide boiling range and molecular weight distribution. New strategies are being evaluated for upgrading biocrude and recovering bioproducts that look beyond bulk oxygen content. They focus on the impact of feedstock variety and process conditions on biocrude yield in RTI's 1 ton/day catalytic biomass pyrolysis unit and biocrude fractionation to support upgrading strategy development in RTI's pilot-scale hydroprocessing unit.

US Department of Energy National Laboratories

Two US Department of Energy (DOE) national laboratories house DTL capabilities at the pilot or engineering scale. Known as Process Development Units (PDUs), these integrated systems provide data to bring the gap between applied research and commercialization.

The National Renewable Energy Laboratory (NREL) operates two laboratory fluidized-bed pyrolyzers (2 kg/h feed) with in-situ or ex-situ upgrading to catalytic fast pyrolysis (CFP) oil. For ex-situ vapor upgrading, fixed bed or fluidized bed reactors are available. A Davison Circulating Riser (DCR) is a circulating fluidized bed reactor that can be coupled to one of the laboratory pyrolyzers to catalytically upgrade vapors during a short catalyst contact time (~2s). For scaling up the pyrolysis/CFP process, NREL manages the Thermal and Catalytic Process Development Unit (TCPDU). This facility has a high-throughput fast pyrolysis reactor (18 kg/h). Efforts are under way to update the system configurations for commercial advantages. NREL maintains supporting capabilities in feedstock preparation, gas cleanup, catalyst development, material characterization, and process analytics. To convert CFP oils to final transportation fuels, fluid-catalytic cracking (FCC) and hydrotreating (HT) reactors are available at scales of 1 kg/hr and 50 g/hr, respectively.

Pacific Northwest National Laboratory (PNNL) manages the Hydrothermal Process Development Unit (PDU). The main reactor is the Modular HTL System (MHTLS), an engineering-scale system that includes process heat integration, continuous product separation, and feed slurry preparation. With a nominal throughput of 12 L/h of wet biomass slurry, the scale is optimized for obtaining useful data for scale up without staging and storing enormous quantities of wet and sometimes perishable biomass. PNNL has made several innovations in the HTL space, including alternative approaches to completely eliminate heat exchangers. PNNL proposes using steam flashing, in combination with autothermal HTL to produce an embodiment which eliminates heat exchangers, an area potentially prone to fouling.

Included with the Hydrothermal PDU is a continuous hydrotreater with a bed volume of 400 mL and a trailer-mounted system for catalytic hydrothermal gasification (CHG). Together, these reactors transform wet biomass slurries into fuel blendstocks, methane, and clean water.

Iowa State University

Since 2018, Iowa State University (ISU) has made significant advancements in pyrolysis research and commercialization, focusing on various technologies and collaborations. Two major facilities contain the reactors: the Biorenewables Research Laboratory (BRL) and the BioCentury Research Farm (BCRF). Several pyrolyzers are in operation at the 1-2 kg biomass/h scale, including an autothermal pyrolysis reactor, a free-fall reactor, and an auger reactor.

Autothermal Pyrolysis: ISU has developed an innovative autothermal pyrolysis process, which uses air as the fluidizing gas, allowing energy for pyrolysis through partial oxidation of pyrolysis products. This technology simplifies the reactor design and reduces capital costs. A major project in Redfield, Iowa, demonstrates this technology on a commercial scale, converting corn stover into sugars, phenolic oil, and biochar. This effort contributes to atmospheric carbon dioxide removal, recognized by the XPRIZE Carbon Removal Program.

Fast Pyrolysis Pilot Plants: ISU has several pilot units for fast pyrolysis, involving rapid heating of biomass in low-oxygen environments to produce bio-oil, biochar, and gases. The development unit at the BioCentury Research Farm processes up to 8 kg biomass/h. Current research focuses on improving bio-oil recovery and understanding the properties of pyrolysis products.

Frontline BioEnergy's Iowa Pyrolysis Project: In collaboration with Frontline BioEnergy and Stine Seed Farms, ISU has contributed to the Stine pyrolysis plant in Redfield, Iowa. This project aims to convert biomass into biochar and bio-oil using autothermal pyrolysis, showcasing the scalability of this process (discussed below).

DEMONSTRATION AND COMMERCALIZATION ACTIVITIES

Biogas Energy Ltd.

Biogas Energy Ltd. operates an ablative fast pyrolysis pilot plant at an existing organics recycling facility in Placer County, California. Waste wood will be the proposed feedstock, and upon successful demonstration the commercialization plan is to develop modular systems that can be deployed close to biomass resources

and to scale by numbering up in situations where greater capacity is required. Modular systems will be sized for a target of 12 dry tonne per day of biomass.

In March of 2021, the Ablative Fast Pyrolysis System was put into operation in Sacramento, California. The entire modular system has a throughput of 500 kg of biomass per hour and will produce 200.0000 Liter of bio-oil in the course of the project.

The concept of the AFP differs significantly in concept from other methods of fast pyrolysis:

- In ablative pyrolysis, heat is conducted from a hot reactor wall in order to melt biomass that is pressed against the wall. The pyrolysis front moves unidirectional through the biomass body. The remaining oil film provides lubrication and evaporates quickly to volatile components (bio-oil)
- The reaction rate is strongly influenced by the pressure, the relative velocity of the biomass with the heat exchange surface and the reactor temperature

Frontline BioEnergy

Frontline BioEnergy delivered the final module for Stine Seed Farm's pyrolysis plant in Redfield, Iowa (Partners: Stine Seed Company, Frontline Bioenergy and Iowa State University). This plant utilizes autothermal pyrolysis (ATP) technology to convert biomass into biochar, bio-oil, and thermal energy. The ATP process, developed by Iowa State University, enables the transformation of agricultural and forest residues into these products efficiently and without combustion. The plant, with a capacity of 50 tons per day, serves as a demonstration of the scalability and functionality of this technology. The biochar produced is used for soil improvement, while bio-oil can be processed into bio-asphalt or fuel, and thermal energy can be used for heating or electricity generation.

Genifuel

Genifuel has been advancing HTL technology through the advancement of a HTL demonstration unit known as the CHPDS (Containerized Hydrothermal Processing Demonstration System). The CHPDS has been deployed at several WRRFs for demonstrations across north America. In conjunction with Metro Vancouver, they are beginning fabrication in 2024 of a pilot facility to convert 10 tons of sludge per day into biocrude. Larger projects are in the planning and engineering states throughout the world.

Alder Renewables

Alder Fuels was renamed as Alder Renewables in 2023. Alder Renewables aims to convert sustainable solid biomass into transportation fuels by integrating existing fast pyrolysis technology with refinery infrastructure. Their core technology, the Alder Renewable Crude (ARC) process, fractionates pyrolysis oil, removes water, and increases energy density while reducing metals and organic “bad actors” that lead to polymerization in a hydrotreating catalyst bed. They have announced a partnership with Honeywell UOP to commercialize ARC and refinery integration. Alder Renewables was awarded a DOE project to scale Alder’s proprietary ARC technology to convert 0.5 tonnes of biomass per day and produce sustainable aviation fuel (SAF) with a negative carbon intensity from regen-ag Miscanthus.

New Hope Energy

In 2018, New Hope Energy laughed their Trinity Oaks Tyler facility, a pyrolysis plant to covert HDPE, LDPE, Polystyrene, and Polypropylene into pyrolysis oil. New Hope has formed numerous partnerships. Lummus Technology has announced an agreement with New Hope Technologies to license their waste plastics conversion technology. This agreement allows Lummus to offer New Hope's pyrolysis technology as part of its portfolio. Dow has established a multi-year agreement with New Hope Energy, in Tyler, Texas, to supply the Company with pyrolysis oil feedstocks derived from plastics recycled in North America. Final commissions for the plant was planned for late 2022. New Hope Energy converts used plastics into pyrolysis oil feedstock, which Dow will use to produce circular plastics.

S&B Engineers and Constructors has been selected as the contractor for New Hope Energy’s advanced plastics recycling unit, which will be a significant expansion of the Tyler plant. The multi-year master service agreement involves S&B providing engineering, procurement, and construction (EPC) services for a

plastics pyrolysis unit. The initial project under this agreement is an expansion in Tyler, Texas, adding 420 metric tons per day of capacity. This expansion will enable the Tyler plant to divert over 300 million pounds of plastic waste from landfills annually. The project, which began in late 2021, is expected to be completed and commissioned in early 2024. Upon completion, the expansion of the Trinity Oaks Tyler plant may be the largest pyrolysis facility in the world.

Origin Materials

Origin materials converts the carbon in wood residue, with an organic solvent under acid conditions and at high temperature, they generate chloromethyl furfural (CMF) and hydrothermal carbon (HTC). The CMF is extracted and the HTC is filtered out. The CMF is then converted to dimethyl furan and then to PET. Origin announced commencement of commercial scale production at their plant, *Origin 1*, in Sarnia, Ontario. The company has announced numerous partnerships and offtake agreements. Origin 2, a subsequent larger scale plant is currently being developed in Geismar, Louisiana

PHOTOS WITH CAPTIONS THAT CAN BE USED AS NEEDED

Fast pyrolysis Stine plant assembled at the project size. Frontline is engineering, procuring, and constructing a modular 50 ton per day pyrolysis demonstration plant in Redfield, Iowa. This plant will utilize auto-thermal pyrolysis which is more efficient and versatile than regular pyrolysis. The plant will produce bio-oil and biochar that have a variety of uses.

New Hope Energy’s facility to covert waste plastic to a pyrolysis oil

Fast pyrolysis pilot plant at RTI International in Research Triangle, North Carolina. The plant has a capacity of 1 tonne of dry biomass per day.

The Thermal and Catalytic PDU at NREL in Golden, Colorado.

PNNL's Modular HTL System in Richland, Washington.

Biogas Energy Ltd.’s ablative fast pyrolysis pilot plant modules at an organics recycling facility in Placer County, California. The technology and reactors were provided by thermophil international.

Further Information

IEA Bioenergy Website
www.ieabioenergy.com

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