IEA Bioenergy
Technology Collaboration Programme

Drop-in Aviation and Marine fuels by upgrading of products from Direct Thermochemical Liquefaction

Properties & certification

IEA Bioenergy: Task 34

March 2026

Drop-in Aviation (SAF) and Marine fuels (SMF) by upgrading of products from Direct Thermochemical Liquefaction (DTL)

Properties & certification

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LIST OF ABBREVIATIONS

ASTM	Amercian Society for Testing & Materials
CPK	Cyclic Paraffinic Kerosene
CPO	Catalytic Pyrolysis Oil
FBP	Final Boiling Point
FP	Fast Pyrolysis
FPBO	Fast Pyrolysis Bio-Oil
HDN	HydroDeNitrogenation
HDO	HydroDeOxygenation
HDS	HydroDeSulphurisation
HHV	Higher Heating Value
HPO	Hydrotreated Pyrolysis Oil
HTL	HydroThermal Liquefaction
IBP	Initial Boiling Point
IH2	Integrated HydroPyrolysis
ISO	International Organization for Standardization
LHV	Lower Heating Value
JFTOT	Jet Fuel Thermal Oxidation Test
MGO	Marine Gas Oil
SAF	Sustainable/Synthetic Aviation Fuel
SAK	Sustainable/Syntehtic Aromatic Kerosene
SMF	Sustainable Marine Fuel
TAN	Total Acid Number
ULSFO	Ultra Low Sulphur Fuel Oil
VLSFO	Very Low Sulphur Fuel Oil

SUMMARY

IEA Bioenergy Task 34 concerns Direct Thermochemical Liquefaction (“DTL”) and the use of their products. The objective of this report is to provide an overview of the physical-chemical properties and composition of upgraded products from Fast pyrolysis (‘FPBO’) and HTL (‘biocrude’), and their application as liquid, drop-in, advanced biofuel fuel in aviation and shipping.

Firstly, both processes and resulting products are described separately. Under fast pyrolysis three different approaches are considered being non catalytic fast pyrolysis, catalytic pyrolysis (catalytic vapor phase treatment), and Integrated HydroPyrolysis (catalyst in the primary conversion process). Under HTL a distinction between sub- and supercritical process is made. Other DTL technologies like solvolysis have not been considered because no detailed data is publicly available on the properties of the final fuels.

Both FP and HTL apply a hydrotreatment process to obtain drop-in, advanced biofuels. The quality of the fuels can be steered to a certain extent by the severity of hydrotreatment. Three main products are obtained after distillation being naphtha, jet and marine. The properties and application of the naphtha fraction is not further evaluated in this report.

The jet fraction from FP is characterized by a high cyclo-alkane content (>70%), a relative high density close to the maximum value (840 kg/m3) and a high energy density (~36 MJ/L). The jet fraction from HTL also shows a relative high density, but its composition resembles more a typical conventional jetfuel, and n- and iso-alkane content is higher than in FP derived jet.

Both FP and HTL derived jetfuels do not comply with any of the existing ASTM-D7566 annexes (process and/or jet specifications). Furthermore, the fuels obtained via both processes are also rather different with respect to composition and resulting fuel properties. Therefore, it is expected that each route requires its own Annex.

Marine fuels can be obtained via FP and HTL by co-production with jetfuel or stand-alone upgrading. Basically, all qualities (both distillates and residual) listed in ISO-8217 can be produced by hydrotreatment of FP bio-oil or HTL biocrude. In case of co-production the residue after recovery of the jetfuel is considered as marine fuel. Because the jetfuel production requires high severity hydrotreatment also the marine fuel will be of high quality. Stand-alone production of marine fuel can target multiple fuel qualities by controlling the hydrotreatment severity.

Index

List of Tables

List of Figures

INTRODUCTION

IEA Bioenergy Task 34 concerns Direct Thermochemical Liquefaction (“DTL”). The overall objective of the Task is to improve the implementation and success of direct thermochemical liquefaction of biomass for fuels and chemicals. An overview of the technologies and characteristics is given elsewhere[1].

Recently, a report was published on the direct use DTL liquids as fuels without further upgrading[2]. However, to enable the use of DTL liquids as liquid, drop-in, advanced biofuel in the aviation and shipping sector severe chemical upgrading is required. The objective of this report is to provide an overview of the physical-chemical properties and composition of upgraded products from Fast pyrolysis (‘FPBO’) and HTL (‘biocrude’) processes based on data from literature and complemented with data from the authors. A comparison will be made with specifications from standards and critical fuel properties will be identified. Standards will include ASTM D1655/D4054 and D7566 for jetfuels and the ISO-8217 standard for distillate and residual marine fuels.

Finally, the properties of DTL based drop-in fuels will be compared. An evaluation of the ASTM certification process for DTL derived jetfuels will be made, and an assessment will be included whether a joint standardisation approach could be envisaged, or separate annexes should be prepared (for FP and HTL). A comparison to other fuels described in the Annexes of ASTM D7566 will also be included. A similar exercise will be performed for the marine fuels in relation to the ISO-8217 specifications.

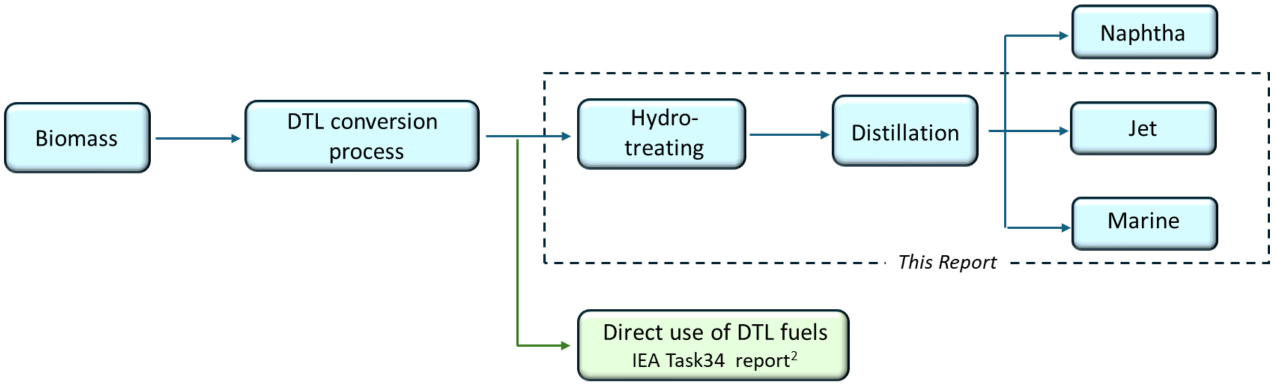

Fig. 1: Outline study and relation to previous report on direct use of DTL fuels

DROP-IN FUELS VIA FAST PYROLYSIS

Fast pyrolysis is a process in which organic materials are rapidly heated to 450 - 600 °C in absence of air. Under these conditions, organic vapours, permanent gases and charcoal are produced. The vapours are then quickly condensed to pyrolysis oil. Catalytic fast pyrolysis is the case when a catalyst is applied in the pyrolysis process or in the vapour phase. Integrated HydroPyrolysis (IH2) can also be considered here as a fast pyrolysis route to drop-in, advanced biofuels. In all cases, a downstream hydrotreating process is required to obtain the desired drop-in biofuels. These three fast pyrolysis approaches will be considered in more detail as also data is available on upgraded products from these processess. The scope of this report excludes slow pyrolysis and plastic pyrolysis.

Production Process(es)

Fast Pyrolysis & upgrading

The value chain starts with the production of FPBO followed by the hydrotreatment of the FPBO to the drop-in fuels. Fast pyrolysis of lignocellulosic biomass is being implemented commercially by a.o. Ensyn and BTG Bioliquids, and production plants have been implemented in Canada, the Netherlands, Sweden and Finland. Crude pyrolysis oil is acidic, contains water and is not miscible with traditional fossil fuels. Severe upgrading is needed to obtain a drop-in transportation fuel (e.g. such as the 2-step hydrotreatment process developed by BTG). In a first step, the FPBO is stabilized by converting the most reactive groups by adding a hydrogen atom to the carbonyl groups (aldehydes, ketones and carbohydrates). As a result, the reduction in oxygen content is limited but it enables further upgrading in a more standard hydrotreating process. Eventually, a Hydrotreated Pyrolysis Oil (HPO) is obtained which is virtually oxygen free and fully miscible with fossil fuels[3].

Catalytic Fast Pyrolysis

In the fast pyrolysis process a catalyst might be applied and this approach was investigated e.g. by the National Lab of the Rockies (NRL), previously National Renewable Energy Laboratory (NREL)[4]. A fluidized bed pyrolyser was applied and the vapor phase was catalytically upgraded at 500 °C using different types of catalyst. The resulting oil is already lower in oxygen content than fast pyrolysis oil. To obtain drop-in fuels it was further hydrotreated over a sulfided $NiMo/Al_2O_3$ catalyst, and then fractionated into SAF, marine fuels and others.

Integrated HydroPyrolysis (IH2)

In the IH2 process[5] biomass is pyrolyzed/depolymerized in a catalytic fluidized bed at elevated pressure (~30 bar) and in a hydrogen atmosphere. Further downstream hydrotreatment results in the desired fuel which is distilled into the drop-in gasoline, kerosene and diesel. The process was developed at GTI (Chicago) and further scaled-up by Shell. A large demonstration plant was constructed and operated at the Shell Research Center in Bangalore (India).

The three processes mentioned above all produce a wide boiling range fuel and requires further distillation into final products. Typically, three fractions are considered being naphtha/gasoline, jet and a diesel/marine fraction. Typical distribution is given in Table 1.

Table 1: Indicative fractionation yields form different pyrolysis processes

	HPO[9]	CFP[4]	IH2[6]
Naphtha/gasoline	15%	35%	58%
Jet	50%	51%	31%
Diesel/Marine	35%	14%	11%

Other developments & approaches

Many fast pyrolysis based developments targeting SAF and drop-in marine fuels are on-going around the world, but often no or limited information is available on chemical-physical properties of the final products and therefore not further described here. An example is Alder Renewables[7] who does the upgrading of a fraction of fast pyrolysis oil to e.g. SAF. Recently, a UOP press release indicated the successful development of a biocrude hydrotreatment process to produce SAF[8] .

Properties of the pyrolysis oil derived SAF

The SAF fraction is obtained by distillation, and typical range applied is 140 – 270 °C. In Table 2 some selected properties are given for the SAF fraction obtained from the three pyrolysis approaches. The fuel density and energy density is relatively high compared to fossil Jet A1, but rather similar for the three cases. The cold flow properties are very good and the freezing point is well below the Jet A1 specification of -47 °C. The FPB of the samples from catalytic pyrolysis is lower than for the other two processes, but it is a setpoint of distillation process. However, increasing the FPB will also have an impact on the properties, and it may result in a density above the maximum of 840 kg/m^3. Both CPO and CPK-O contain a higher amount of lighter compounds compared to HPO, which is in line with the distillation yields (see Table 1).

Table 2: Properties of the pyrolysis oil derived SAF fractions

	Fast Pyrolysis[9]		Catalytic Fast Pyrolysis[4]		IH2[5]
Properties	HPO-1	HPO-2	CPO-1	CPO-2	CPK-0
Density (15 °C)	829	836	833	834	832
Hydrogen [wt%), meas.	13,7	13,5	13,8	13,6	14,1
Hydrogen [wt%], calc ASTM D3343	13,68	13,41	13,70	13,72	13,85
Freeze Point [°C]	-64	-65	<-70	<-70	-61
Flash Point [°C]	39,0	47,0	46,6	49,6	40,0
Net Heat of Combustion [MJ/kg]	43,3	43,2	43,0	43,0	43,1
Energy density [MJ/L]	35.9	36.1	35.8	35.9	35.9
Viscosity (cSt, T =-20°C)	4,9	5,6	nd	nd	4,6
T10 [°C]	166	176	170	174	161
T50 [°C]	204	208	189	191	190
T90 [°C]	246	248	232	224	249
FBP [°C]	267	267	257	249	271
T50-T10 [°C]	38	32	19	17	29
T90-T10 [°C]	80	72	62	49	88

HPO: Jet derived from fast pyrolysis, CPO: Jet derived from Catalytic Fast Pyrolysis, CPK-0: jet derived from IH2 process

Composition

The compositions of the SAF samples have been determined by GCxGC FID. A division in the main groups n-paraffins, iso-paraffins, cyclo-paraffins/olefins and aromatics is obtained; results are shown in Fig. 2 and Fig. 3. Actually, the method is not able to properly distinguish between cyclo-paraffins and olefins. However, supporting evidence exist that hardly any olefins are present in the fuels (e.g. low Bromine index). The compositions of the fuels are quite comparable with low contents of n- and iso-alkanes, high content of cyclo-paraffins and variable amounts of aromatics. In the hydrotreatment process aromatic compounds are saturated yielding additional cyclo-paraffins. By adapting the hydrotreatment conditions, the aromatic content can be controlled to a certain extent. Reducing the aromatic content will impact fuel properties like e.g. increasing Cetane number and heating value and decreasing density.

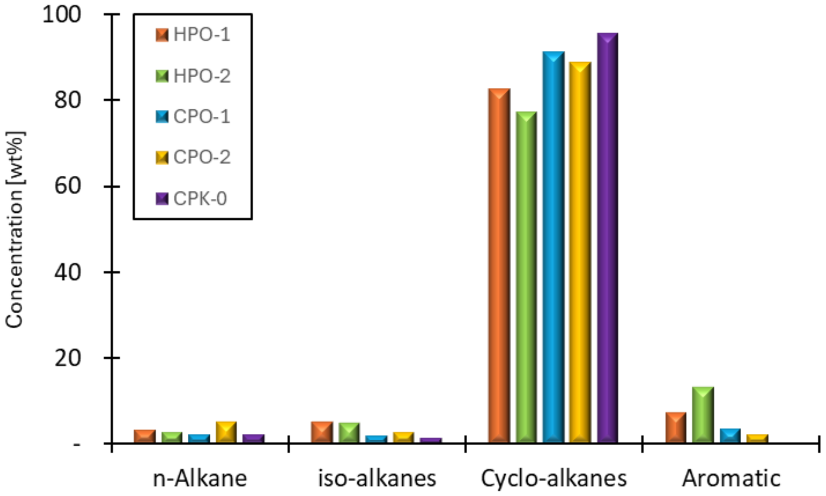

Fig. 2: Composition of pyrolysis oil derived SAF samples. (GCxGX FID); references as in Table 2.

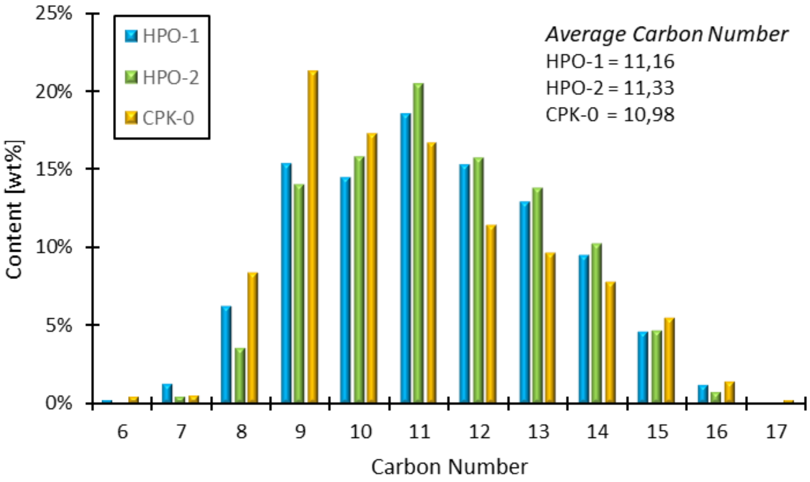

Fig. 3: Carbon number distribution of pyrolysis oil derived SAF samples; references as in Table 2.

In Fig. 3 the carbon number distribution is shown for the jet fraction from HPO and IH[2]. (No data was available for the jet fraction from CFP). The HPO derived jet shows a slightly higher average carbon number, but values are quite typical for jetfuels.

More detailed data are available on the jet fuel properties[5,9]. Several tests have been performed on e.g. thermal stability (JFTOT), existent gum, smoke number, copper strip corrosion and naphthalene content and all comply with specifications/requirements in the relevant ASTM standards. The Cetane Number is typically at the low end and is sensitive to the hydrotreatment severity. HPO-Jet is always low -almost independent from severity- in n- and iso-alkanes and these components typically result in high Cetane Numbers. Aromatic components result in low Cetane Numbers and its content is strongly impacted by hydrotreatment severity. Cetane Numbers is the range from 35 – 45 have been measured.

Jetfuel combustion

Public information on the testing of pyrolysis oil derived jetfuel in full scale engines is not readily available. Combustion trials with HPO-Jet in a small-scale research turbine have been performed by the Technical University Delft[9,10]. Primarily, the approach was to compare the performance of the turbine fuelled with a fossil Jet-A1 as reference and blends containing 10 and 20 wt% HPO-jet, respectively. The turbine speed was varied between 60,000 and 80,000 rpm. Overall conclusion was that differences between the different fuels were rather small without a clear trend.

Properties of the pyrolysis oil derived SMF

Marine biofuels can be obtained from the upgraded fuels by distillation. To obtain a minimum flashpoint of 60 °C at least the light fraction needs to be removed (roughly components with a boiling point below ~ 170 °C). Then two different approaches may be considered:

i) Maximising the marine fuel excluding the co-production of SAF. Required hydrotreatment severity might be lower than needed for SAF. For the purpose of this document the fuel is referred to as “HPO-M**A**”.

ii) First separate the SAF fraction and consider the remaining as the marine fuel. The quality is set by the hydrotreatment severity required for the production of SAF, and the minimum flashpoint of 60 °C will not be an issue. The fuel is referred to as “HPO-M**B**”.

Ad i) NREL (Chen et al[11]) studied the mild treatment of CFP to produce sustainable marine fuel. The aim was to produce a marine fuel complying with ISO 8217, miscible with VLSFO at low hydrotreatment severity. The results are promising and a clear impact on e.g. density and composition were shown as function of the hydrotreatment severity. However, the list of properties published is rather limited and therefore not further considered here. In the IH2 process also a marine/diesel fraction is co-produced, but public data on its properties were not found.

In Table 3 the properties of HPO-MA and HPO-MB are presented. HPO-MA can be obtained from low severity hydrotreatment (HPO-MA sample 2) or high severity treatment (HPO-MA sample 1). The latter one has also a sufficient quality to extract the SAF fraction. HPO-MB is the residue after separating the SAF fraction (see Table 2, sample HPO-1/2). HPO-MA has a targeted flashpoint of just above 60 °C, whereas the flashpoint of HPO-MB is typically in the range of 140 to 150 °C. The difference between both can also be easily recognized in the significant difference in IBP. The flashpoint of 60 °C for HPO-MA is achieved by evaporating low boiling components (the lights called Naphtha) with a boiling point below ~170 °C. A clear difference can be observed between HPO-MA and HPO-MB. HPO-MA has a lower initial boiling point, a lower viscosity and a lower oxidation stability. The difference in hydrotreatment severity for sample HPO-MA-1 and HPO-MA-2 can be recognized by its density and Cetane Number.

Table 3: Properties of pyrolysis oil derived, drop-in SMF[12]

		HPO - MA		HPO - MB	
Property	**Unit**	**1**	**2**	**1**	**2**
Density (T = 15 °C)	kg/m^3	859	897	898	902
Viscosity (40 °C)	cSt	3.6	3,8	14.0	13,4
Viscosity (50°C)	cSt	2.9	3,1	9.7	9,6
Acidity	mg KOH/g	<0.1	<0.2	<0.1	<0.1
Flashpoint	°C	75	65	> 100	> 140
IBP	°C	195,8		289.5	
FBP	°C	416.3		451.6	
Cloudpoint	°C		-		-27
Pourpoint	°C		-36		-27
MCRT	wt%	0	0	0	0
Net Heat of combustion (meas.)	MJ/kg	42.7		42.4	42.6
Specific Energy (calc ISO 8217-24)	MJ/kg	42,9	42,5	42.5	42.4
Oxygen	wt%	< 0.5	<0.5	< 0.5	<0.5
Hydrogen	wt%	13,5	12.0	12,9	12.9
Ignition Temperature	°C	215 - 245		215 - 230	
Nitrogen	ppm	<0.5		< 2	
Sulfur content	ppm	<5		<5	
Water	ppm	< 30	<30	< 30	< 30
Chlorine	mg/kg	< 1		< 1	
DCN/ICN	-	49.1	34.3	50.4	49.5
CCAI (calculated ISO 8217-24)	-	812	848	816	820
HFRR lubricity	µm		370		230
CFPP	°C		-35		17
Oxidation stability (PetroOxy)	min	97	120	669	421

Composition

The composition of the fuels in Table 3 have not been determined in detail. It is expected that similar to the jet fraction the fuel is rich in cyclo-paraffins, modest amounts of aromatics, and n- and isoparaffins. The lower hydrotreatment severity of HPO-MA-2 will likely result in higher aromatics content and consequently a lower Cetane Number. NREL[11] produced a fuel via catalytic fast pyrolysis followed by hydrotreatment. The fuel was distilled and the diesel fraction with a boiling point between 145 and 330 °C was recovered. Limited data is given on the physical properties of the diesel fraction, but its composition was determined by GC-TOFMS-FID. This fraction is rich in cyclo-paraffins and very low amounts of aromatic hydrocarbons resulting in a Cetane Number of 45.

SMF Combustion

The Technical University Eindhoven (TU/e)[13,14,15,16] carried out tests with hydrotreated pyrolysis oil (quality comparable to HPO-MA-2) in a combustion Research Unit (CRU) as well as in a diesel engine (DAF MX-13). In the CRU the HPO fuel was tested as such and in blends; engine tests were performed with blends containing up to 50% HPO fuel. CRU experiments showed that 100% HPO-MA-2 is hard to achieve, but by adding 25% HVO similar behavior is obtained as for EN590 diesel. The addition of HVO improved the ignition behavior (acts as ignition improver). Engine tests with up to 50% of HPO-MA-2 in MGO were successful; higher blending rates were not performed due to a lack of sufficient fuel.

Oak Ridge National Laboratory evaluated a partially upgraded FPBO in a research engine[32]. Stabilized Pyrolysis Oil (SPO) was purchased and further hydrotreated to obtain a fuel with a residual oxygen content of 3.2wt%. The product can be seen as a mild version of HPO-MA with a higher density (983 kg/m^3) and slightly lower LHV. A relatively low Cetane Number and high CCAI (>870) is to be expected and might be outside the IMO specifications for marine fuels. Subsequently, a blend of VLSFO with 10% upgraded FPBO is prepared and used in the engine test. Very positively, the combustion behavior in the engine was only marginally affected adding 10wt% of upgraded FPBO.

Engine tests with the other HPO fuel qualities are not yet available but based on the physical-chemical properties (e.g. Cetane number, viscosity and ignition temperature) of these fuels it is expected that operation will be easier and even operation on pure HPO fuel can be considered.

Other

The focus of this report is on drop-in aviation and marine fuel, but some other products might be considered as well. In all pyrolysis based processes a light fraction (“Naphtha”) needs to be removed to increase the flashpoint to a minimum value of 38°C (SAF) or 60°C (Marine). In case of IH^2 this fraction has even the largest share and via fast pyrolysis it is the smallest frcation. However, in all cases this product is very rich in ccyclo-paraffins (in particular methyl-, ethyl- and propyl cyclo hexane) and considered to be a valuable product like gasoline blending component or as renewable feedstock for steam crackers.

Road diesel is also not specifically addressed in this report, but could be considered as alternative for SAF and SMF, or combining road diesel and a heavy fraction for marine application. The aromatic content in the diesel fraction via IH2 and CFP is expected to lower than for upgrading FPBO which might be an advantage for road diesel. In all cases a rather severe hydrotreatment is needed to obtain a fuel with an acceptable Cetane Number (complying with diesel specifications like EN 590).

DROP-IN FUELS VIA HTL

Hydrothermal liquefaction (HTL) converts wet biomass slurries (e.g. algae, sewage sludge, wet agricultural residues) into a crude bio-oil ("biocrude") by reaction in hot compressed water, typically at 300–350 °C and 10–25 MPa for a few minutes. A key advantage of HTL is the ability to process high-moisture feedstocks directly, eliminating the energy-intensive drying step required by pyrolysis. Although, it should be noted that efficient energy recovery is a key challenge of the HTL process since heating a wet stream from room temperature to 350 C also requires substantial energy input. The subcritical water medium promotes depolymerization of biomass into a water-insoluble, hydrocarbon-rich biocrude (with higher heating value ~30–40 MJ/kg) along with an aqueous phase, gas, and solid residue. Reported biocrude yields vary widely with feedstock: for example, microalgae, or wet wastes such as food waste or sewage sludge can yield up to 50 wt% biocrude under optimum conditions, versus ~30 wt% for woody biomass.

Production Process(es)

Subcritical HTL

Subcritical hydrothermal liquefaction (HTL) refers to operation in liquid water below the critical point, typically about 280–350 °C and 10–25 MPa, where pressure is maintained high enough to prevent boiling. Under these conditions, water's dielectric constant decreases while its ionic product increases relative to ambient conditions, changing its solvent behavior and enhancing acid/base-catalyzed reactions. As a result, water becomes an effective reactive medium that promotes hydrolysis, dehydration, and decarboxylation of wet biomass, converting it into a biocrude phase without prior drying. Most wet-waste feedstocks, including sewage sludge, manure, food waste, and algae, are processed in this regime using tubular with residence times on the order of minutes. Organizations advancing subcritical HTL include PNNL, Genifuel, Circlia Nordic, Aarhus University, and Aalborg University, using bench- and pilot-scale systems to develop and demonstrate the technology. PNNL and Aarhus University have both published several reports of production campaigns using their continuous plants. Circlia Nordic offers standard modular units capable of processing 25000 wet tons of waste a year, approximately 76 wet tons a day. Genifuel operates a trailer-based demonstration continuous HTL plant, involved in many projects in the USA.

Supercritical HTL

Supercritical HTL operates above water's critical point (T > 374 °C, P > 22.1 MPa), where water exists as a single supercritical phase. In this regime, water exhibits gas-like diffusivity while becoming much less polar than liquid water. These properties favor rapid mass transfer and make radical reactions more prominent, enabling fast deoxygenation and cracking of lignocellulosic biomass and residues into a lower-oxygen biocrude. Leading commercial concepts in this area include Steeper Energy's Hydrofaction® process and Licella's Cat-HTR™ technology. Hydrofaction® uses homogeneous catalytic supercritical water to convert woody residues into a refinery-ready biocrude; Steeper has operated a continuous bench-scale unit for thousands of hours and licensed the technology to Silva Green Fuel, which completed an approximately 5,000 L/d industrial-scale demonstration plant in Norway in 2022. Licella's Cat-HTR™ platform similarly uses near- and supercritical water to process biomass feedstocks, including forestry residues and wood residuals, into a bio-intermediate for upgrading to advanced biofuels. Licella has scaled the Cat-HTR™ platform at Somersby, Australia, and its first commercial biomass-to-biofuels application is the Arbios facility in Prince George, Canada. Collectively, these supercritical HTL technologies are at the advanced pilot to commercial-demonstration stage and, in the bioenergy context, are focused on converting forest residues and other biomass streams into biocrudes or bio-intermediates that can be further upgraded to advanced biofuels. Plastic-focused applications of related supercritical hydrothermal processing technologies are better treated separately.

Upgrading to finished fuels

A representative upgrading sequence for aviation/marine drop-ins includes (a) feed conditioning (desalting/ filtration) and/or guard beds for solids capture and demetallation/dehalogenation to protect hydrotreating catalysts; (b) hydrotreating (HDO/HDN/HDS) for severe removal of O, N, and S to reduce TAN, and stabilize the oil (typically over sulfided NiMo/CoMo supported on alumina); (c) hydrocracking/isomerization to tune boiling range (kerosene/diesel) and cold flow while converting heavy resid to distillates; and (d) fractionation. Recent PNNL sludge-derived HTL results show jet-cut Tier α/β properties within conventional ranges, with nitrogen typically orders of magnitude above petroleum jet—necessitating deep HDN (NiMo/Al_2O_3). Following hydrotreating and distillation, indicative HTL fractionation yields are shown in Table 4.

Table 4: Indicative fractionation yields from different HTL process with various feedstocks

	Subcritical HTL of algae[17] or wet wastes[18,19,20]	Subcritical HTL[21,22] of wood	Supercritical HTL[23] of wood
Naphtha/gasoline	10-15%	15-20%	~10%
Jet	20-30%	20-30%	~20%
Heavier than Jet (Marine)	60-65%	55-65%	~70%

Nitrogen in HTL-derived products

Nitrogen is the principal heteroatom differentiator for HTL-derived intermediate fuels, especially for protein-rich feedstocks (e.g. algae, sewage sludge, manure and food waste). Carbohydrate-protein interactions during HTL boost HTL biocrude production through the production of N-containing heteroaromatics, and those are problematic molecules for hydrotreating[242526]. Even after deep deoxygenation, nitrogen in HTL-derived jet cuts can remain orders of magnitude higher than current specs from other approved SAF fuels (2ppm N), but can be managed through upgrading and the certification case.

Whole-oil analyses indicate that residual nitrogen is concentrated in refractory heterocyclic species (pyrrolic and pyridinic structures), including pyrroles/pyrrolidines, indoles, pyridines, pyrimidines and imidazoles, while more labile classes such as pyrazines and long-chain amides are largely removed during hydrotreating.

From a fuel-quality standpoint, deep HDN is often required to reach aviation-typical nitrogen levels (often ≤10 mg/kg). While the finished-fuel specification in ASTM D7566 does not include a nitrogen limit, approved synthetic blending component annexes generally specify nitrogen ≤2 mg/kg (ppm), so an HTL annex will likely need an explicit nitrogen limit. Because nitrogen removal can interact with thermal stability, confirmation of JFTOT performance under severe conditions remains important.

Key design levers for nitrogen control include: (i) feed pretreatment and conditioning (desalting/filtration, demetallation/dehalogenation and removal of solids); (ii) catalyst selection and operating severity for HDN (e.g. sulfided NiMo/CoMo, potentially in dedicated deep-HDN stages and/or with guard beds); and (iii) fractionation and blend strategy to bound nitrogen in the jet cut.

In contrast, upgraded fast-pyrolysis-derived drop-in fuels typically contain very low nitrogen (see Table 3), so nitrogen is primarily an HTL (wet-waste/algae) issue.

Properties of the HTL derived SAF

Upgraded HTL jet cuts include iso-/n-paraffins, cycloparaffins and aromatics with very low oxygen and sulfur after hydrotreating; for protein-rich feedstocks, nitrogen can remain the key residual heteroatom (see the subsection "Nitrogen in HTL-derived products"). The SAF fraction from HTL-derived products is likewise obtained by distillation, with the jet cut typically defined in a ~150–250°C window for both subcritical and supercritical routes. HTL-derived jet fractions often contain cycloparaffins which can help with density. The amount of aromatics is dependent on both feedstock and the hydrotreating severity, with deep hydrotreating minimizing aromatics. Table presents selected properties of SAF fractions derived from subcritical HTL of wet wastes and algae and from supercritical HTL of woody biomass, based on representative examples from literature. The densities of the HTL-based SAF cuts tend to fall toward the upper half of the Jet A1 range and are often slightly higher than fossil jet, reflecting the relatively high cyclo-paraffin content, but the different HTL routes give broadly similar densities when a comparable distillation window is used. Cold flow properties are generally favourable and freeze points at or below the Jet A1 specification of –47 ˚C can be obtained, provided that the distillation end point is not extended too far into the diesel range. For some of the HTL cases the final boiling point of the jet cut can be set lower (i.e. a narrower cut) to ensure adequate freeze-point margin and to keep density below the maximum of 840 kg/m3; relaxing the final boiling point to increase yield will tend to increase density and move the fuel closer to the specification limit. Subcritical HTL of algae and sewage sludge typically gives somewhat heavier jet cuts than wood-based HTL, whereas supercritical HTL of wood produces a slightly lighter jet fraction; this is in line with the distribution of naphtha/jet/diesel fractions observed for these processes (see Table 5).

Table 5: Properties of the upgraded biocrude derived SAF fractions

	Subcritical HTL		Supercritical HTL
Properties	PNNL - Wet Waste[27]	PNNL - Algae[28]	Hydrofaction[23] - Wood
Density (15 ˚C)	815	790	814-863
Hydrogen (wt%)			14.5-13.6
Freeze Point [˚C]	-49	-43	
Flash Point [˚C]	51	50	44.5-82
HHV [MJ/kg]			45.1-45.0
LHV [MJ/kg]	43.1	43.5	
Viscosity (-20˚C) [cSt]	4	4	nd

Composition

The composition of the HTL-derived SAF has been reported based on GC×GC–MS Tier α hydrocarbon-type analysis for jet fuel derived from subcritical HTL. The carbon-number and hydrocarbon family distributions are shown in Fig. 4 and Fig. 5, where the candidate fuel is broken into molecules classes (aromatics, n-alkanes, iso-alkanes, monocycloalkanes and dicycloalkanes) and compared to the average Jet A carbon-number envelope for a wet waste (Fig. 4) and for an algae feedstock (Fig. 5). The average carbon number of the HTL SAF ($\bar{C} \approx 11$) is close to that of conventional jet fuel ($\bar{C} \approx 11.4$), and the distribution lies completely within the conventional range. The mixture is dominated by cycloalkanes, with roughly one-third monocycloalkanes and ~15 % dicycloalkanes, while n-alkanes and iso-alkanes together contribute only about one-third of the fuel and aromatics make up ~20 % by mass. This is consistent with extensive saturation of aromatic and oxygenated precursors during hydrotreating, yielding additional cycloalkanes and only residual aromatics; by tightening or relaxing the hydrotreating severity, the aromatic fraction (and therefore density, energy density, and cetane/DCN) can be adjusted within the typical jet-fuel experience window. Whole-oil analyses indicate that remaining heteroatom-containing species are largely confined to trace nitrogenates (see the subsection “Nitrogen in HTL-derived products”).

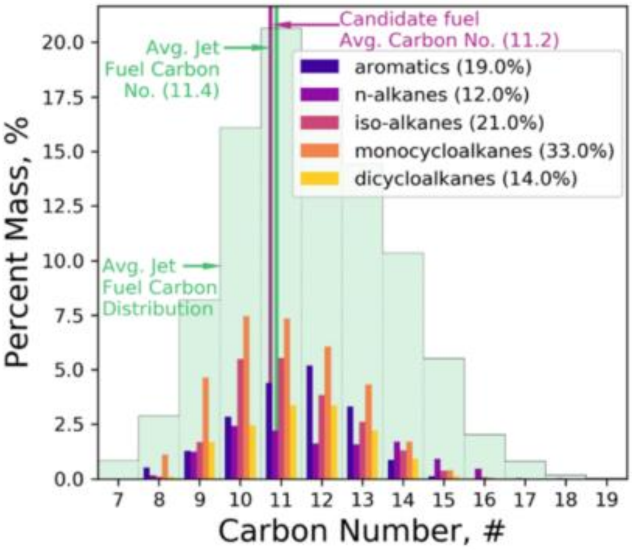

Fig. 4: The carbon-number and hydrocarbon family distributions as determined by GC×GC-MS for jet fractions derived from upgrading of HTL biocrude derived from of wet waste. [29]

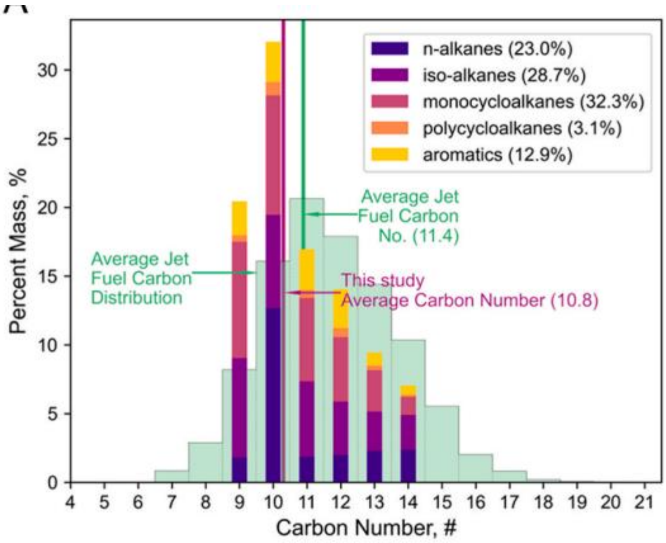

Fig. 5: The carbon-number and hydrocarbon family distributions as determined by GC×GC-MS for jet fractions derived from upgrading of HTL biocrude derived from algae. [30]

Properties of the HTL derived SMF

For HTL oils there are essentially two processing pathways for marine applications. In the first, the HTL biocrude is hydrotreated in a configuration designed to co-produce SAF, meaning the whole slate is subjected to deep hydrotreating (and often some hydrocracking/isomerization) to meet jet fuel requirements; the marine cut then comes from the heavier distillation fractions of this highly upgraded, fully deoxygenated product and will resemble a very clean, paraffinic low-sulfur marine fuel. In the second pathway, the biocrude is sent to a dedicated light hydroprocessing step targeted only at marine fuel production. Here the severity of hydrotreating becomes the key design knob: a light “polishing” hydrotreat can remove the most problematic oxygen, nitrogen and acids while retaining more aromatic and polar material, leading to a heavier, more aromatic marine fuel with higher density and possibly better miscibility with residual fossil streams, whereas a deeper hydrotreat in the same dedicated unit would move the product toward a more paraffinic, higher-cetane distillate with quite different cold-flow, stability and blending behavior.

Hydrotreating plus mild hydrocracking of HTL biocrude yields a diesel-range blendstock with high paraffin content and elevated cetane; scale-relevant hydrotreating studies show “high-cetane diesel fuel” outcomes from HTL streams, consistent with paraffinic distillates. Cold-flow may require isomerization or blending. For marine distillates (DMA/DMZ/DMB), ISO 8217 specifies limits on kinematic viscosity (40 °C), density (15 °C), sulfur, cetane index, CFPP/pour point, acid number, ash, metal contaminants, and other parameters; the 2024 edition introduces updates for bio content and clarifies several limits. In general, upgraded HTL distillate can be formulated to meet DMA/DMZ properties (sulfur, viscosity, density, water, acidity), with attention to blend-compatibility, oxidation stability, and cold flow.

Heavier HTL fractions in residual marine service (RMG/RMK) encounter the classic asphaltene stability problem: paraffinic/low-polarity blendstocks can destabilize asphaltene colloids, raising TSP/TSA above ISO limits. Any HTL-to-VLSFO blending should be governed by compatibility testing. Further, the extend of hydrotreating will limit the marine fuel properties. Table 6 below reports marine fuel properties as a function of the extent of hydrotreating of washed HTL biocrudes derived from food wastes, with HT1 having the longest residence time in the reactor (as measured by 'weight hourly space velocity' (WHSV) and HT3 having the shortest residence time in the reactor.

Table 6: Properties of drop-in Marine Fuel (SMF) from a mild upgrading of HTL biocrude[31]

Property	HT1[a]	HT2 [a]	HT3 [a]	ISO-F-RMA/RMG
WHSV of primary catalyst bed (h^{-1})	1.25	1.5	1.75	NA
Viscosity at 50C (cSt)	2.9	3.4	4.3	<10/700
Density at 15C (kg m^{-3})	815	828	838	<920/991
H2S (%)	<2	<2	<2	<2
Total Acid Number (mg KOH/g)	0	0	2.6	<2.5
Sediment (%)	None	None	None	<0.1
Water (wt%)	0.2	0.75	0.4	<0.3/0.5
Ash (weight%)	<0.1	<0.1	<0.1	<0.04/0.1
Vanadium (ppm)	<6	<6	<6	<50/350
Sodium (ppm)	<6	<6	20	<50/100
Al + Si (ppm)	61	50	50	<25/60
Oxygen (weight% dry)	0.27	0.19	0.63	-

[a]Hydrotreating Conditions: Guard bed, 300C; primary catalyst bed 400C

Combustion

Oak Ridge National Laboratory evaluated a partially upgraded HTL marine fuel blend stock produced from food-processing wastes by PNNL, blended at 10 wt% into a commercial very-low-sulfur fuel oil (VLSFO) to form "HTL10." Engine tests were carried out in a single-cylinder, low-speed, 2-stroke crosshead research engine representative of large marine main engines, at three operating points: low (≈14 % load), medium (≈51 % load) and high (100 % load) brake mean effective pressure[32]. No recalibration was done between fuels; injection timing and quantity were controlled automatically to hold the same load while firing neat VLSFO and HTL10. Combustion pressure and heat-release profiles showed that HTL10 behaved very similarly to VLSFO across all loads: two-stage ignition at low and medium load and single, smoother burn at high load, with only minor differences in ignition delay and premixed burn. At medium and high load, HTL10 delivered slightly higher brake thermal efficiency and slightly lower brake-specific fuel consumption than VLSFO, consistent with the presence of more reactive, lower-molecular-weight n-alkanes such as dodecane in the bio-intermediate fraction.

Exhaust emissions were broadly comparable between HTL10 and baseline VLSFO. HTL10 tended to run slightly leaner than VLSFO at medium and high load, with similar excess-air (lambda) and exhaust O_2 levels overall. Hydrocarbon emissions showed large scatter, but HTL10 generally produced higher brake-specific HC than VLSFO at all loads, for reasons the authors note are not yet clear. Particulate emissions (BSPM) showed no consistent trend with fuel at this low blend level: HTL10 gave the lowest BSPM at low load, slightly higher BSPM than VLSFO at medium load, and slightly lower BSPM at high load. NO_x emissions for HTL10 were similar to VLSFO at medium and high load; an apparent NO_x reduction at low load was attributed to variability rather than a true fuel effect. CO_2 emissions tracked the small BSFC improvements, with modest CO_2 reductions for HTL10 at medium and high load. Overall, the research engine operated smoothly on HTL10 with no operability issues, indicating that a 10 wt% HTL bio-intermediate in VLSFO is compatible with large 2-stroke marine engines and can provide slight efficiency gains without worsening regulated emissions.

COMPARISON OF DTL DROP-IN FUELS TO CONVENTIONAL FUELS & STANDARDS

This report concerns the production of drop-in aviation and marine fuels via DTL technologies. To justify these fuels as drop-in its properties should be the same or fully compatible with existing standards for these fuels. In this chapter a comparison is made between fuels derived via fast pyrolysis and HTL, and subsequently compared to the standards for aviation (ASTM D7566-25) and marine (ISO 8217-24).

DTL fuel comparison – pyrolysis vs HTL

A fundamental distinction is related to the biomass feedstock. Fast pyrolysis is typically framed around dry lignocellulosic feedstocks, while HTL is inherently suited to wet, high-nitrogen feedstocks such as sewage sludge, manures, food waste, agricultural residues and algae. That feedstock variability shows up downstream in fuel composition: compared with woody-HTL, upgraded wet-waste HTL fuels derived from sludge/algae can yield distillates with higher n-/iso-paraffins and lower density, giving a hydrocarbon-type profile that can look more like petroleum-jet. HTL biocrude's principal heteroatom (nitrogen) is linked to the feedstock. Further, the remaining nitrogenates are often refractory heterocycles that demand deep HDN to reach aviation-typical impurity expectations. This becomes a certification and operability issue because, while fossil jet has no explicit nitrogen spec in ASTM D7566, existing synthetic blending component annexes commonly impose very low nitrogen limits (e.g., 2 ppm)—meaning that HTL-derived drop-in fuels from nitrogen-rich wet wastes may face a higher HDN burden (hydrogen demand, catalyst choice/guarding, and stability) than wood-derived HTL or deeply hydrotreated pyrolysis-derived streams.

Fuels derived from DTL process (fast pyrolysis and HTL) share a number of common features at the finished-product level: in both cases, severe hydrotreating of the primary DTL liquid yields a wide-boiling hydrocarbon stream that is distilled into naphtha/gasoline, jet and diesel/marine fractions. The properties of the different products can be controlled to some extent by selecting the proper boiling range (as long as all the fuel specs are met), the most obvious one being the flashpoint.

A clear difference in the yields of specific fractions are observed for both HTL and FP, depending on the processing conditions and/or feedstock. Further, similar to petrochemical upgrading of crude oils, the SAF/marine split is dependent on if the upgrading strategy. Specifically, a SAF focused facility will require deeper hydroprocessing and can utilize cracking to increase the SAF cut, depending on the infrastructure available (e.g. hydrocracker). In the indicative HTL fractionation yields compiled in Table 4, supercritical HTL of algae or wet wastes produces roughly ~25% jet-range SAF and ~50% diesel/marine, whereas subcritical HTL of wood is shown as SAF-leaning at ~50% jet with only ~15% diesel/marine. By contrast, when the focus in on marine fuels, a mild hydroprocessing approach can be utilized to achieve cuts as high as 90%+. Using a catalyst in the FP process reduces the SMF yield and increases the gasoline/naphtha fraction. In practice, the reported "jet yield" is also sensitive to the chosen jet cut window—extending the final boiling point can increase SAF yield (within reason as all specs still must be met), but may push density and freeze point closer to specification limits.

After upgrading, pyrolysis-derived fuel (HPO) is strongly cyclo-paraffinic with low n-/iso-paraffin content and very low heteroatoms, while HTL-derived fuel shows a broader fuel composition mixture, including cyclo-paraffinic molecules, as well as aromatic, and n-/iso-paraffin character but with nitrogen as the key residual heteroatom (when processing wet wastes, but not with HTL biocrudes from woody feedstocks). The exact composition and properties of the fuels depend on the severity of the hydrotreatment. Increasing severity will typically result in a reduction of aromatic content and a decrease in density, but simultaneously in an increase in Cetane Number as well as boosting lights and reducing bottom residues.

For woody biomass, a consistent compositional difference emerges between upgraded fast-pyrolysis liquids and upgraded HTL biocrudes. After deep hydrotreating, pyrolysis-derived jet/diesel fractions tend to be strongly cyclo-paraffinic with relatively low n- and iso-paraffin content. That cyclo-paraffin richness generally pushes density toward the high end of the Jet A/Jet A-1 window, whereas wood-based HTL products more often produce a fuel mixture including n- and iso-paraffin fractions, which typically translates to lower density and higher ignition quality which is more relevant for the diesel/marine fractions. With jet fuel derived from HTL of woody biomass, lower hydrotreating severity increases aromaticity and lowers cetane numbers.

ASTM certification for aviation fuel

A practical certification path is the ASTM D4054 Tier 1–4 roadmap. Tier α/β prescreening (not part of the ASTM process) can de-risk with composition-based predictions, followed by engagement with the FAA Clearinghouse and OEMs for formal qualification and, ultimately, an ASTM D7566 annex specific to the jetfuel candidate. Tier α uses low-volume analytical methods (e.g., GC×GC with supporting NMR/IR) to quantify hydrocarbon families and infer/predict key properties (distillation/volatility distribution, density/LHV, ignition quality and smoke/sooting tendency), while Tier β adds small-volume *measured* property screening (e.g., density/viscosity/freeze/flash and targeted chemistry/impurity checks) to confirm the predicted trends and flag risks tied to contaminants or heteroatoms. ASTM approval requires larger volumes for Tiers 1–4 as needed. Tiers 1–2 cover specifications and fit-for-purpose rig/property tests on neat blendstock and blends; typical starting volumes total ~200–400 L, increasing for later tiers. Tiers 3–4 can include combustor/engine rig and full engine testing with OEM oversight. Early engagement with the FAA ASTM D4054 Clearinghouse is recommended because it serves as the coordinated entry point to the OEM review process—screening candidate readiness, helping define test plans, arranging/compiling test data into research reports, and managing iterative OEM feedback toward eventual incorporation into ASTM D7566. Recently, the European Clearinghouse was established with the aim to provide a similar service to European fuel producers.

ASTM D7566 is a standard specification for aviation turbine fuel "containing synthesized hydrocarbons". These hydrocarbons are often referred to as SAF, which might be somewhat misleading. The synthetic hydrocarbon fuel is blended with conventional Jet fuel in amounts up to 50%, and after blending the fuel should comply with the specifications of ASTM D7566. Each synthetic blending components is further specified in separate annexes. So far, eight different annexes have been included in the standard, an overview is given in Table 7.

Table 7: *Annexes included in ASTM D7566-25 for approved synthetic blending components.*

Annex No	Synthetic blending component	Max blend [%]	Density [kg/m3 at 15 °C]	Composition
1	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosine (SPK)	50%	730-770	Cyclo < 15% Aromatic < 0.5%
2	Synthesized paraffinic kerosine from hydroprocessed esters and fatty acids (HEFA)	50%	730-772	Cyclo < 15% Aromatic < 0.5%
3	Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP)	10%	765-780	Farnasane>97%
4	Fischer-Tropsch synthesized paraffinic kerosine plus aromatics (SPK/A)	50%	755-800	Cyclo < 15%
5	Alcohol-to-Jet synthetic paraffinic kerosene (ATJ-SPK)	50%	730-770	Cyclo < 15% Aromatic < 0.5%
6	Catalytic Hydrothermolysis Jet from fatty acid esters and fatty acids (CHJ)	50%	775-840	Cyclo: Report
7	Synthesized paraffinic kerosine from hydroprocessed hydrocarbons, esters and fatty acids (HC-HEFA-SPK)	10%	730-800	Cyclo < 50% Aromatic < 0.5%
8	Alcohol-to-jet paraffinic kerosene with aromatics (ATJ-SKA)	50%	775-840	Cyclo < 40%

The synthetic blending component from Fast Pyrolyis – called SAF in the previous chapters- are characterized by a relative high density (830 – 840 kg/m^3) and a high cyclo-paraffin content (75 – 95%). The only annex allowing such combination is Annex 6, but the feedstock (fatty acid esters and fatty acids) is very different from the feedstocks considered for Fast Pyrolysis. It means a separate Annex will be required for "*FP derived synthetic blending components*". It has been demonstrated that SAF produced via fast pyrolysis and IH2 can meet all the physical/chemical properties listed in ASTM - D7566.

For HTL, fuel quality is strongly feedstock dependent, and nitrogen management becomes especially important for nitrogen-rich feedstocks such as algae and wet wastes (e.g., sewage sludge, food waste, manure), where reducing residual nitrogen is likely necessary to limit fuel thermal-stability risk. While no nitrogen specification exists for fossil-derived jet fuel in ASTM D7566, the synthetic blending annexes impose a stringent nitrogen limit (2 ppm), effectively pushing HTL pathways toward deep HDN on the jet cut. A practical concern is that when a higher-sulfur conventional jet is blended with a higher-nitrogen HTL SAF (or one carrying more polar N-species), there is potential for worsened thermal-oxidative stability and deposit formation driven by trace heteroatomic species[33]. This interaction is best treated as an empirical question and screened with JFTOT (ASTM D3241) and possible subsequent thermal stability testing on the intended blend ratios (and, ideally, across representative Jet A sulfur "bookends"), since D3241 directly rates a fuel's tendency to form deposits under thermal stressing via heater-tube deposits and downstream filter pressure drop. Nonetheless, achieving < 2ppm in the final fuel is possible with a polishing hydro processing step.

Also for HTL a separate annex will be required and an obvious question is whether a joint annex can be considered for the "DTL derived synthetic blending components". The fuel obtained after blending the DTL components with fossil jet should comply with the fuel specifications listed in Table 1 of ASTM D7566. Some relevant properties of the blended fuels as well as typical values for DTL derived jet fuels are listed in Table 8 .

Table 8: Selected properties for Aviation turbine fuel containing synthesized hydrocarbon (according to ASTM D7566-25) compared to DTL derived Synthesized hydrocarbons ("SAF").

Property	Unit	**ASTM-D7566-25**	**DTL**	
			Typical range FP	Typical range Subcritical HTL
Density (T = 15 °C)	kg/m^3	775 - 840	825 - 840	790-820
Viscosity (-20 °C)	cSt	<8.0	4 -5	~4
Viscosity (-40°C)	cSt	<12.0	9 – 12	9-11
Acidity	mg KOH/g	<0.1	<0.01	<0.01
Flashpoint	°C	>38	> 40	~50
Freeze point	°C	<-40 Jet A <-47 Jet A1	< -60	<-40
Aromatics	vol%	8 - 25	< 15	10-20
N- and iso paraffins	vol%	30 - 60	7 – 10	20 - 55
Cyclo-paraffins	vol%	20 – 40	75 - 85	35 - 55
Net Heat of combustion	MJ/kg	42.8	42.8 - 43.2	43.1-43.5
DCN/ICN	-	>35 (ASTM D4054)	35 - 45	

From a certification standpoint there is essentially no realistic pathway to a joint SAF annex that covers both HTL- and pyrolysis-derived fuels. Under ASTM D4054/D7566, each annex is tied to a specific conversion process (see Table 7) with a tightly defined chemistry, property envelope, and impurity set. HTL and biomass pyrolysis differ fundamentally in intermediate fuel quality (oxygen and nitrogen levels, heteroatom speciation, metals, stability) and in upgrading strategies, and even after deep hydrotreating their finished kerosenes are expected to carry different constraints and variability. In practice, HTL- and pyrolysis-derived SAF would each need to qualify through D4054 on their own merits and, if successful, would be expected to receive separate D7566 annexes rather than a shared one. Further, it is quite possible that HTL may need separate annexes for different feedstock classes (wood vs wet wastes).

A Fast Track approach is unlikely for both HTL and FP fuels due to the relative high density; maximum acceptable value for Fast Track is 800 kg/m^3. The advantage of Fast Track is the simplified procedure, but max blending rate is limited to 10%.

ISO specifications for Marine fuels (SMF)

Different qualities of marine fuels are specified in ISO-8217-24. A first distinguish can be made between Distillate fuels (DM) and Residual fuels (RM). New categories have been included in the specification referred to as "Biobased liquid fuels including Fatty Acid methyl Ester(s) (FAME)", denoted as RF fuels, but this category is not considered relevant for the DTL liquids as it will not contain FAME in any significant amount (i.e < 0.5 wt%). In Table 9 a summary of the most relevant properties is given for the a few qualities (for both DM and RM fuels there are some intermediate qualities defined). Basically, the marine fuel quality is set by its density and viscosity.

Table 9: Selected properties for different marine qualities according to ISO 8217 - 24

		DM -Distillate Marine Fuel			RM - Residual Marine Fuel	
Property	Unit	DMX	DMA	DMB	RMA 20	RMK 500
Density (T = 15 °C)	kg/m^3	-	<890	<900	<955	<1,010
Viscosity (40 °C)	cSt	1.4 - 5.5	2 - 6	2 - 11		
Viscosity (50°C)	cSt				2 - 20	150 - 500
Acidity	mg KOH/g		<0.5	<0.5	<2.5	<2.5
Flashpoint	°C	>43	>60	>60	>60	>60
Sulphur		Statuary requirements, VLSFO < 0.5 wt%; ULSFO < 0.1 wt% S				
Ox. Stability	h		>8	>8		
(PetroOxy method)	min		>60	>60		
MCRT	wt%			<0.3	<10	<20
Cetane Number	-	>45	>40	>35		
CCAI (calculated)	-				<860	<870
Cloudpoint	°C	<-16				
Pourpoint	°C		<-6 / 0	<6 / 0	<6	<30

Within ISO 8217, DTL-derived marine fuels can in principle be positioned either as distillate grades (DMX/DMA/DMB) or as residual grades (RMA–RMK), depending on how far the biocrude has been hydrotreated and fractionated. The standard defines viscosity and density windows for each grade (e.g. 2-11 cSt at 40 °C and $\rho < 890$–$900\ kg\ m^{-3}$ for DMA/DMB; 2–20 cSt at 50 °C and $\rho < 955$–$1010\ kg\ m^{-3}$ for light and heavy residual grades), together with limits on flash point (≥60 °C for all but DMX), total acid number, micro-carbon residue, water, ash and key metals (V, Na, Al+Si), and requires compliance with statutory low-sulfur caps (VLSFO/ULSFO).

Marine fuels produced via fast pyrolysis can meet the specifications listed in ISO-8217, and -depending on hydrotreatment severity and distillation- covers all the distillate qualities (DMX, DMA, DMB, DMZ) and the light residual (RMA). The sulphur content is always low and will meet the specifications for ULSFO (< 1,000 ppm). Further reducing the hydrotreatment severity will result in worsening the ignition properties but likely also in an increase in Acid Number (TAN) to values above the maximum of 2.5 mg KOH/g. This is probably less an issue when blended with conventional marine fuels.

Bench-scale upgrading of HTL oils shows that diesel/marine cuts produced under progressive hydrotreating severities fall comfortably inside the ISO 8217 distillate envelope on viscosity (≈3–4 cSt at 50 °C), density (≈815–840 $kg\ m^{-3}$), sulfur, TAN, ash and metals, with water near or below the 0.3–0.5 wt% limits—indicating that fully upgraded HTL marine fractions can be formulated as DMA/DMZ/DMB-type ULSFO products.

For residual applications, direct blending of raw or partially upgraded HTL biocrude into RMG-type fuels has also been demonstrated: a 10 wt% blend of sewage-sludge HTL biocrude in ISO-F-RMG 380 met ISO 8217:2017 limits for TAN, sulfur and metal contaminants, with only a slight exceedance in ash. Overall, ISO 8217 does not preclude HTL-based SMF—either as neat distillates or as blend components in VLSFO—but it makes ash, inorganics (V, Na, Al+Si), water and, critically, compatibility/asphaltene stability the gating parameters that must be managed through hydrotreating severity, feed pretreatment and conservative blending practice. The hydrotreating severity is really a question of how mild of a hydrotreating touch can be used (if any is required). Compatibility and asphaltene stability are critical when considering HTL streams in VLSFO blends. For marine residual applications, compatibility and sediment stability when blending with asphaltenic fuels is a concern. Spot blend tests are an excellent first screen for compatibility.

For marine fuel applications, whether large-scale engine testing is needed to obtain OEM acceptance depends on how far the candidate fuel sits outside established marine fuel norms. If the proposed fuel (or blend) is a true drop-in that meets an existing ISO 8217 grade and falls within an engine maker's published acceptance guidance, OEM "approval" is often handled through fuel analysis, spec compliance and operational guidance, rather than a full-scale engine campaign for each new supplier (e.g., MAN's two-stroke guidance explicitly accepts common biofuels such as FAME/HVO and blends with ISO-8217-compliant fossil fuel under defined operating guidelines)[34]. By contrast, for novel blendstocks/streams not covered by ISO 8217 or where composition is atypical, additional assessment should be considering, including potential trials/tests. In the CIMAC report, the category "*Products derived from lignocellulosic biomass*" is listed as an example which needs consultation and possibly consensus of the OEM and Class"[35]. In practice, when the fuel/system is truly new, OEM sign-off commonly does hinge on large-scale testing milestones—including extended campaigns, type-approval tests, and/or sea trials to confirm performance, durability, deposits/wear, and safety controls under representative load profiles[36].

CONCLUSIONS

The fast pyrolysis (FP) and Hydrothermal liquefaction (HTL) processes both yield liquids which can be upgraded to drop-in, advanced biofuels. In both cases, hydrotreatment is a common upgrading strategy choice. In case of FP a 2-step hydrotreating process is applied or a catalyst is already used in the FP primary process. A single stage hydrotreatment is normally sufficient for the upgrading of HTL biocrude. The severity of hydrotreatment determines the final quality of the fuels. Eventually, the upgraded liquid is fractionated by distillation and typically, three products are then obtained being naphtha, jet and marine fuel.

The jet fraction from FP is characterized by a high cyclo-alkane content (>70%), a relative high density close to the maximum value (840 kg/m3) and a high energy density (~36 MJ/L). The Cetane Number of FP derived jet is in the lower range; low severity hydrotreatment of FP liquids will result in Cetane numbers below the minimum (<35). The jet fraction from HTL also shows a relative high density, but its composition resembles more a typical conventional jet-fuel, and n- and iso-alkane content is higher than for FP. Remaining nitrogen levels in the HTL derived jet might be challenging, in particular when treating feedstocks like sludge and algae.

Both FP and HTL derived jetfuels do not comply with any of the existing ASTM-D7566 annexes (process and/or jet specifications). Furthermore, the fuels obtained via both processes are also rather different with respect to composition and resulting fuel properties. Therefore, it is expected that a joint ASTM certification process is not feasible, and each route (FP and HTL) will require a separate annex in ASTM-D7566.

Marine fuels can be obtained via FP and HTL and different approaches can be considered. One approach is to combine the production of marine fuels with jet-fuel. After recovery of the jet-fuel the residue is considered as marine fuel. Because the jet-fuel production requires high severity hydrotreatment also the marine fuel will be of high quality. When stand-alone production of marine fuel is targeted also lower severity hydrotreatment can be considered and different product qualities are obtained. Basically, all qualities (both distillates and residual) listed in ISO-8217 can be produced by hydrotreatment of FP bio-oil or HTL biocrude.

REFERENCES

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[1] Direct Thermochemical Liquefaction - Characteristics, processes and technologies, Axel Funke and Nicolaus Dahmen (KIT), IEA Bioenergy: Task 34, July 2020.

[2] Direct use of Direct Thermochemical Liquefaction liquids as fuels, Aaron Tay, François-Xavier Collard (SCION), Daniele Castello, Kamaldeep Sharma (Aalborg University), IEA Bioenergy: Task 34, June 2025

[3] Sustainable Aviation and Marine Fuel from fast pyrolysis bio-oil, L. van de Beld, 32nd European Biomass Conference & Exhibition, 2024, Marseille.

[4] Cycloalkane-rich sustainable aviation fuel production via hydrotreating lignocellulosic biomass-derived catalytic fast pyrolysis oils, Chen et al, Sustainable Energy Fuels, 2024, 8, 5504-5513.

[5] Sustainable Aviation Fuels - Shell's Activities, University of Toronto Institute for Aerospace Studies, Griffin Valentich, May 19, 2021.

[6] Biozin-Conversion of waste and residue Biomass from Norwegian forestry and sawmills to advanced low carbon fuels for zero emission transport industry, Innovation Fund Factsheet, https://climate.ec.europa.eu/document/download/905576ff-00d1-4563-8095-33301b2f9a88_en?filename=if_pf_2022_biozin_en.pdf

[7] https://www.alderrenewables.com/our-technology

[8] https://biomassmagazine.com/articles/honeywell-introduces-new-technology-to-produce-low-cost-high-quality-renewable-fuels-from-biomass

[9] Sustainable Aviation Fuel from Fast Pyrolysis Bio-Oil, L. van de Beld, International Conference on Sustainable Aviation Research – Dublin - July 2025

[10] Combustion Characterisation of SAF derived from Hydrotreated Pyrolysis Oil, Rishikesh Sampat, Arvind Gangoli Rao, Royal Aeronautical Society journal, to be published (2026).

[11] Sustainable marine fuel production through mild hydrotreating of catalytic fast pyrolysis bio-oil, Xiaolin Chen, Martha A. Arellano-Trevino, Kellene A. Orton, Abhijit Dutta, Calvin Mukarakate, Kristiina Iisa, Eric C.D. Tan, Fuel 398 (2025), https://doi.org/10.1016/j.fuel.2025.135455.

[12] Unpublished Data from BTG Biomass Technology Group BV, 2025

[13] Hydrotreated pyrolysis oil for marine application: fuel production and combustion performance, Bert van de Beld, Hans Heeres, Bart Somers, Jinlin Han, Felipe Ferrari, PyNe 52, IEA Bioenergy Task 34, December 2022

[14] Ignition and combustion characteristics of hydrotreated pyrolysis oil in a combustion research unit, Jinlin Han, Yu Wang, L.M.T. Somers, Bert van de Beld, Fuel 316 (2022), https://doi.org/10.1016/j.fuel.2022.123419

[15] Combustion and emission characteristics of hydrotreated pyrolysis oil on a heavy-duty engine, Jinlin Han, L.M.T. Somers, Bert van de Beld, Fuel 351 (2023), https://doi.org/10.1016/j.fuel.2023.128888

[16] Experimental investigation performance and emission of hydrotreated pyrolysis oil in a heavy-duty engine with EGR, Jinlin Han, L.M.T. Somers, Bert van de Beld, Fuel Processing Technology 255 (2024) 108061

[17] Hydrothermal liquefaction of wastewater-grown algae to produce synthetic aviation fuel: A combined experimental study and techno-economic assessment, Kumar et al., *Energy Conversion and Management: X*, 2025, 27, 101096.

[18] Sustainable aviation fuel from hydrothermal liquefaction of wet wastes, Cronin et al., *Energies*, 2022, 15(4), 1306.

[19] From food waste to sustainable aviation fuel: cobalt molybdenum catalysis of pretreated hydrothermal liquefaction biocrude, Summers et al., *Nature Communications*, 2025, 16, 9570.

[20] https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-33622.pdf

[21] Catalytic hydrotreatment of bio-crude produced from the hydrothermal liquefaction of aspen wood: a catalyst screening and parameter optimization study, Yu et al., *Sustainable Energy & Fuels*, 2017, 1, 832.

[22] Catalytic upgrading of hydrothermal liquefaction biocrudes: Different challenges for different feedstocks, Castello et al., *Renewable Energy*, 2019, 141, 420–430.

[23] https://steeperenergy.com/wp-content/uploads/2021/11/Hydrofaction%E2%84%A2-Renewable-Crude-Oil-Upgrading-Pathways.pdf

[24] Upgrading of hydrothermal liquefaction biocrudes from mono- and co-liquefaction of cow manure and wheat straw through hydrotreating and distillation, Souza dos Passos et al., Chemical Engineering Journal, 2023, 452(4), 139636.

[25] Synergies during hydrothermal liquefaction of cow manure and wheat straw, Souza dos Passos et al., Journal of Environmental Chemical Engineering, 2022, 10(5), 108181.

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[26] Origin of carbon in the bio-oil from hydrothermal liquefaction of protein and glucose via isotopic labeling, Lu et al., Fuel, 2022, 308, 121941.

[27] Sustainable aviation fuel from hydrothermal liquefaction of wet wastes, Cronin et al., *Energies*, 2022, 15(4), 1306.

[28] Hydrothermal liquefaction of wastewater-grown algae to produce synthetic aviation fuel: A combined experimental study and techno-economic assessment, Kumar et al., *Energy Conversion and Management: X*, 2025, 27, 101096.

[29] Sustainable aviation fuel from hydrothermal liquefaction of wet wastes, Cronin et al., *Energies*, 2022, 15(4), 1306.

[30] Hydrothermal liquefaction of wastewater-grown algae to produce synthetic aviation fuel: A combined experimental study and techno-economic assessment, Kumar et al., *Energy Conversion and Management: X*, 2025, 27, 101096.

[31] Desalting biocrude for improved downstream processing toward marine fuel application, Kilgore et al., *Sustainable Energy & Fuels*, 2023, 7, 2670–2679.

[32] Rheology and engine performance of very low sulfur fuel oil blended with 10% fast pyrolysis and hydrothermal liquefaction oil in a 2-stroke crosshead engine, Kass et al., *Fuel* 407 (2026) 137221.

[33] Contribution of sulfur compounds to deposit formation in jet fuels at 140 °C using a quartz crystal microbalance technique, Rawson et al., *Fuel*, 2018, 231, 1–7.

[34] https://www.man-es.com/docs/default-source/service-letters/sl2023-741.pdf

[35] https://www.cimac.com/cms/upload/workinggroups/WG7/CIMAC_Guideline_Marine-fuels_containing_FAME_04-2024.pdf

[36] https://www.turbomachinerymag.com/view/man-energy-solutions-dual-fuel-methanol-genset-passes-type-approval-test

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