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BIOMASS TO LIQUIDS (BTL) VIA FISCHER - TROPSCH A BRIEF REVIEW

Biomass to liquids (BtL) via Fischer-Tropsch – a brief review

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Cover image: Gasification and FT demo plant under construction in Vienna at BEST – Bioenergy and Sustainable Technologies (former BIOENERGY 2020+ GmbH).

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LIST OF ABBREVIATIONS

ASF	Anderson-Schulz-Flory
BBL	Barrel
BPD	Barrels Per Day
BtL	Biomass to Liquid
CtL	Coal to liquid
DAC	Direct Air Capture
DFB	Dual Fluidized Bed
FEED	Front End Engineering Design
FT	Fischer-Tropsch
FTP	Fischer-Tropsch Products
FTS	Fischer-Tropsch Synthesis
GHG	Greenhouse Gas
GtL	Gas to liquid
HTFT	High Temperature Fischer Tropsch
IRR	Internal Rate of Return
kTPY	kilo Tonnes Per Year
LCA	Life Cycle Analysis
LTFT	Low Temperature Fischer Tropsch
MSW	Municipal Solid Waste
MTFT	Medium Temperature Fischer Tropsch
NPV	Net Present Value
PtL	Power to Liquid
SAF	Sustainable Aviation Fuel
TEA	Techno-Economic Analysis
WGS	Water Gas Shift
WWT	Wastewater Treatment

ABSTRACT

A brief review of Fischer-Tropsch synthesis (FTS) is presented. FTS, a technique known for about a century, is a mature technology that converts synthesis gas (CO and H_2) into liquid crude readily upgradable to standard transportation fuels. The synthesis gas may be produced from a variety of carbonaceous feedstocks, such as coal, natural gas, biomass, residues or even carbon dioxide. The sustainability of a FT value chain depends on the feedstock used to derive the synthesis gas. This review summarizes recent experimental, commercial/demo/pilot and techno-economic publications of FT technology based on feedstocks that qualify REDII Annex IX A and with a product focus on sectors deemed more difficult to decarbonize in the short-term, such as long-distance transport, aviation and shipping.

Keywords Fischer-Tropsch, biomass, demo, pilot, BtL, PtL, economic assessment.

BACKGROUND

To combat climate change, net emissions of greenhouse gases by human activities, the emissions from fossil resources, must be reduced severely from the current levels. This entails transitioning away from a fossil-based economy to a sustainable economy, including not only energy services and industrial production but also change of land use and agricultural strategies. Some sectors are relatively straightforward to transform with partly electrification, such as industrial heating and cooling, passenger vehicles and the rail system. Long distance trucks, aviation and shipping are however difficult to electrify or decarbonize with the current state of the art. Therefore, transforming these sectors necessarily requires substitution fuels derived from renewable sources, such as lignocellulosic residues and various waste feedstocks. Electricity can contribute to the production of renewable fuels via electrolysis in the so-called power-to-liquid (PtL) configurations.

TECHNOLOGY

Fischer-Tropsch Synthesis (FTS) is a catalytic process for converting CO and H_2 into organic compounds, primarily hydrocarbons of different chain lengths. Production of aliphatic hydrocarbons via FTS was discovered by German scientists, Franz Fischer and Hans Tropsch, in 1920s[1,2]. In the area of technical processes for producing hydrocarbon fuels from various resources, FTS is a relatively developed and commercially mature technology to produce liquid fuels[3]. The main products of the FTS are linear paraffins and α-olefins with small fractions of oxygenated products. The major chemical reactions in the FTS are summarized in Table 1, and detailed reaction mechanisms and kinetics over different catalysts are reported in[2,4–11]. The formation of the desired products, alkanes and alkenes, proceeds according to the exothermic reactions, (1) and (2) in Table 1, over metal catalysts. The water gas shift (WGS) reaction (3) also takes place over most metal catalysts balancing the CO:H2 ratio. Side reactions such as those producing alcohols (4) and carbon deposits (5) and (7) may occur in the FTS reactor. Oxidation and/or reduction of the catalyst metals may also occur (6). The conversion process is often catalyzed by metals such as cobalt, iron and ruthenium[12–20]. Cobalt (200–250℃) and iron (250–350℃) are used for commercial production[21] at pressure of 10–65 bar.

The polymerization of n-paraffins and their kinetics are independent of the products formed, as such product selectivities can be predicted theoretically using statistical distributions derived from chain growth probability and carbon number. Anderson-Schulz-Flory (ASF) distribution is the widely accepted approach to predict selectivities which relates the weight fraction (Wn) of hydrocarbons formed to the corresponding carbon number (n) and chain growth probability factor (α) according to equation 122. Figure 1 presents Fischer-Tropsch product (FTP) selectivities according to the ASF distribution. The chain growth probability factor (α) is in turn a function of product propagation rate (rp) and termination rate (rt) constants, equation 2[2,22]. The α-parameter is dependent on the reaction conditions 2 and catalyst characteristics[2,22].

$$W_n/n = (1-\alpha)^2\,\alpha^{n-1} \qquad (1)$$

$$\alpha = r_p/(r_p + r_t) \qquad (2)$$

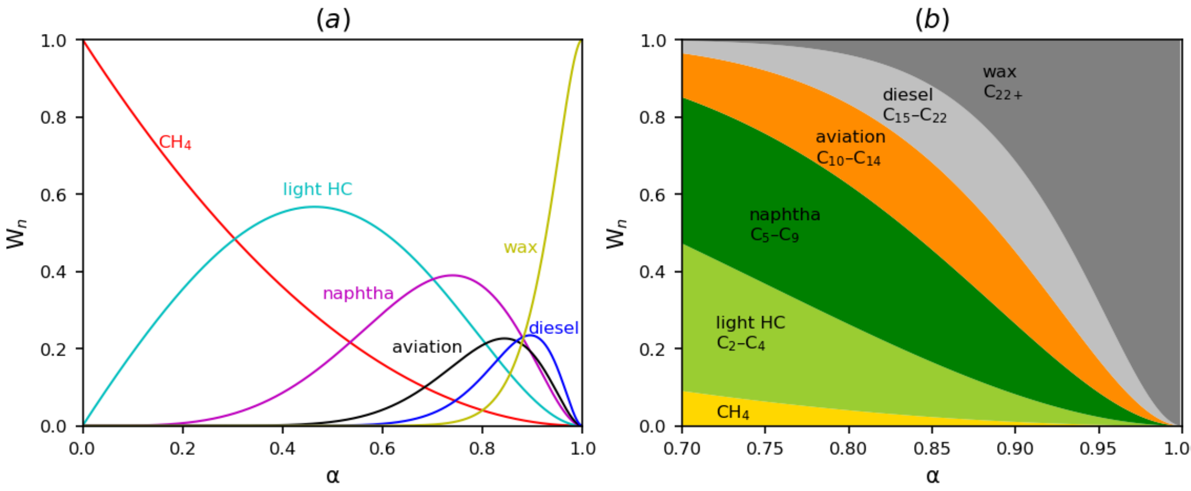


Figure 1. ASF distribution–FTP selectivities as function of growth probability factor (α) according to equation 1

According to AFS distribution Figure 1a, the maximum theoretically obtainable production of naphtha, diesel and aviation range hydrocarbons are about 39%, 23.4% and 22.5%, respectively, achieved at α factors of 0.75, 0.90 and 0.84, respectively. To increase productivity, the best strategy is to operate the system under high α values to produce high chain products, Figure 1b, and transform the corresponding wax fractions into desired product ranges by hydrocracking[22]. In practice, the selection of reaction temperature has a strong effect on the performance of the FTS with higher temperatures favoring the deposition of carbon and leading to increased degree of branching and the amount of secondary products formed[23]. In addition, higher reaction temperatures result in smaller α values, which favor lighter hydrocarbons, Figure 1. Thus, commercial FTS reactors have three distinct temperature ranges, high temperature FT (HTFT) 300–350℃, medium temperature FT (MTFT) 250–300℃ and low temperature FT (LTFT) 220–250℃. HTFT often runs on Fe catalysts and favors production of olefins and naphtha, whereas LTFT runs on Fe or Co and favors diesel and wax fractions[24].

Table 1. Major reactions in an FTS reactor[2].

Major reactions		
Paraffins (alkane)	$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$	(1)
Olefins (alkene)	$2nH_2 + nCO \rightarrow C_nH_{2n} + nH_2O$	(2)
WGS reaction	$nCO + H_2O \leftrightarrow CO_2 + H_2$	(3)
Side reactions		
Alcohols	$2nH_2 + nCO \rightarrow C_nH_{2n+2}O + (n-1)H_2O$	(4)
Boudouard reaction	$2CO \rightarrow C + CO_2$	(5)
Catalyst (Metals) oxidation/reduction	$M_xO_y + yH_2 \leftrightarrow yH_2O + xM$ $M_xO_y + yCO \leftrightarrow yCO_2 + xM$	(6)
Bulk carbide formation	$yC + xM \leftrightarrow M_xC_y$	(7)

In general, low-molecular weight and gaseous products are of low commercial value and undesirable in FTS processes. ASF distribution tends to underestimate the selectivity of methane and overestimates that of ethene/ethane fractions[21]. Besides, actual FTP distribution may deviate from the AFS distribution depending on catalyst type and characteristics[2]. Furthermore, given the exothermic nature of the FTS, rapid removal of heat is a major focus in the design of reactors. As a result, three different reactor types are available for use in different applications[23]— a) fixed-bed reactors for LTFT synthesis aiming at high average molecular weight product, b) fluidized-bed reactors for HTFT synthesis aiming at low molecular weight olefinic hydrocarbons and c) modern LTFT slurry phase reactors to produce hydrocarbon wax, offering improved temperature control and high per-pass conversion.

The focus of this review is on recent and planned developments and techno-economic assessments about BtL processes via FTS. Particular attention is given to relevant experimental (lab or bench scale), pilot/demonstration, pre-FEED (front end engineering design) feasibility studies and commercial developments. Publications on techno economic and environmental performance of BtL process including PtL aspects are summarized.

Gasification and FT demo plant under construction in Vienna at BEST – Bioenergy and Sustainable Technologies (former BIOENERGY 2020+ GmbH).

EXPERIMENTAL PERSPECTIVE

Vast experimental literature about FTS is available, but only those that fitted to the narrow screening implemented in this review are presented here. The screening specifically looked at the feedstock which must be renewable according to RED II Annex IX Part A, the description of gasification technique and operating conditions, the description of FTS reactor and/or catalyst performance, FTP yield including some form of product characterization (selectivity or carbon number). Table 2 summarizes experimental[25–30] aspects of BtL development.

Gruber et al.[26] performed multiple BtL experiments to produce C_1 to C_{60+} liquid hydrocarbons via a demo-scale dual fluidized bed (DFB) biomass gasification and laboratory scale FTS (20 liters slurry bubble column reactor, SBCR) using 2.5 kg commercial-grade Co/Al_2O_3 catalyst. The FTS feed was automated to adjust for optimal H_2/CO ratio via addition of H_2, preferably derived from renewable electricity driven electrolysis[31], which was run at 20 bar and 230℃. Depending on the catalyst type and space velocity, CO conversions of 12–52%, α-values of 0.87–0.93 and C_{5+} hydrocarbons yield of 0.04–0.11 g/(h g-cat.) were reported.

Hanaoka et al.[28] performed bench scale BtL experiments to produce 16 liters/d (~0.1 BPD) liquid hydrocarbons via oxygen-enriched air/CO_2 biomass gasification (downdraft fixed-bed reactor) and FTS (slurry bed reactor) loaded Ru/Mn/Al_2O_3 catalyst. The FTS reactor was fed syngas with H_2/CO ratio of 2 and was run at 40 bar and 290–320℃ resulting in CO and H_2 conversions of 73.5% and 83.9% and α-value of 0.82. Under these conditions, the selectivity and yield of C_{5+} hydrocarbons were 81.4% and 1.793 kg/(kg-cat. h), respectively.

Hanaoka et al.[29] used a bench scale FTS setup described in[28] to investigate BtL performance for aviation range hydrocarbons production under different catalysts and operating conditions of a hydrocracking reactor. The CO conversion and average C_{5+} hydrocarbons yield of the FTS over Co-Mn-Zr/SiO_2 catalyst were 67.7% and 52.7%, respectively. The corresponding productivity was 14.4 liters/d with an FTP distribution on carbon basis C_5 C_8 1.1%, C_9-C_{15} 10.5%, C_{16} 69.1% and C_{17+} 19.3%. Hydrocracking of the FTP over Pt(0.1)/940HOA catalyst resulted in a maximum C9-C15 hydrocarbons selectivity value of 21.5% at 250℃ and 15 bar.

Hanaoka et al.[27] used an experimental setup described in[28] to demonstrate production of liquid hydrocarbons via oxygen-enriched air (60 vol. % oxygen) gasification of woody biomass. The slurry bed FTS reactor loaded Co/SiO_2 catalyst was operated under different operational pressure (20–40 bar) and temperature ranges (240–340℃). The selectivity of C_{5+} was in the range 73–87.5%, α parameter 0.84 and the corresponding productivity liquid hydrocarbon 1.1–7.8 liters/d. Respective CO and H_2 conversions in the range 36–49% and 76–88% were observed.

Gardezi et al[25] performed bench-scale experiments to produce 0.15 liters/d C_{5+} at yield rate 1.6 g/(g-cat h) and selectivity 74.4%. The FTS process was run on eggshell Co/SiO_2 catalyst at 20 bar and 230℃.

Kim et al.[30] conducted long-term bench-scale BTL investigations producing 6 liters/d (0.037 bpd) liquid hydrocarbons using steam-blown bubbling fluidized bed gasifier (20 MW_{th}) and Fe-based catalyst loaded fixed bed bench-scale FTS reactor. The FTS was operated at 310℃ and 13.5 bar for 500 hours at a syngas feeding rate 3 Nm^3/h. The respective CO and H2 conversions which varied over time were in the range 88–96% and 52–58%. The overall C_{5+} selectivity was over 50%.

Table 2. Overview of studies on the development of BtL processes—experimental.

Parameter	Unit	Development of BtL processes—experimental					
Reference	-	[26]	[28]	[29]	[27]	[25]	[30]
Feedstock	-	woodchips	woodchips			Pine chips	wood pellets
Feedstock mass flow	kg/h		32		40		
Gasifier type	-	DFB	downdraft fixed bed			Indirectly heated entrained flow	bubbling fluidized bed
Gasification medium	-	steam	O_2-enriched air/CO_2	O_2-enriched air/CO_2	O_2-enriched air	steam	steam

FTSR configuration	-	slurry bubble column reactor	slurry bed	slurry bed	slurry bed	cylindrical tube	fixed bed
FTS classification		LTFT	MTFT, HTFT	MTFT	MTFT, HTFT	LTFT	HTFT
Temperature	℃	230	290–320	260–280	280–340	230	310
Pressure	bar	20	40	30	40	20	13.5
FTSR catalyst	-	Co/Al_2O_3	$Ru/Mn/Al_2O_3$	$Co\text{-}Mn\text{-}Zr/SiO_2$		Co/SiO_2	Fe-based
H_2/CO	-	1.8–2.24	2			2	>2
Feed	Nm^3/h	4.5–5.6	4.3	4.8		0.042	3
Space velocity	$Nl/h\text{-}g_{catalyst}$	1.8–3.1				2	
C_{5+} selectivity	%		81.4	52.7	78–87.5	74.4	50
C_{5+} yield	$g/h\text{-}g_{catalyst}$	0.04–0.11	1.793	0.94^{a}	$1.01–2.03^{a}$	1.6	
α-value	-	0.87–0.93	0.82		0.84		
CO conversion	%	12–52	73.5	67.7		60	92

^{a}recalculated based on reported parameters

DEVELOPMENT AND STATUS OF BTL PLANTS VIA FTS

In several places in the world, development projects are underway to produce sustainable liquid fuels from biomass. As mentioned in the introduction, the scalability of FTS is proven at commercial level for converting coal (Sasol plant in South Africa, 170 000 bpd combined capacity[11]) and natural gas (Pearl GTL in Qatar, 140 000 bpd)[21]. There are a few smaller commercial installations for natural gas-based FTS[4,21]. Table 3 presents efforts made towards the development of BTL process in the EU and around the globe – commercial, demonstration/pilot or pre-FEED feasibility studies.

Current and announced commercial SAF oriented FT installations indicate nearly 300 million liters of FT liquid production by 2025[32].

In the beginning of 2021, Fulcrum bioenergy and Essar Oil UK announced Fulcrum NorthPoint project[43] which aims for annual SAF production of 100 million liters at Essar Oil site in Stanlow, UK. Fulcrum NorthPoint will see estimated budget £600 million with planned production start-up date in 2025.

Altalto, a partnership project by British Airways, Shell and Velocys, aims for the development of first commercial production of biojet from MSW at a capacity of 60 million liters/year of combined FTS liquid[33].

BioTfueL project[34], driven by a group of companies from France (Axens, CEA, IFP Energies Nouvelles, Avril, ThyssenKrupp Industrial Solutions, Total), aims for the production of 60 t/y[35] FT liquids from lignocellulosic material, such as agricultural by-products, forest waste and energy crops.

Glamour, a project driven by a consortium of two universities and three large research institutes and funded by EU Horizon 2020 research and innovation programme, aims at developing biojet production from bio-glycerol[36].

COMSYN, an EU-funded international project with partners from Finland, Germany, Czech Republic and Italy, aims to demonstrate compact production of liquid fuels at low cost[37].

ICO2CHEM is a PtL concept project run by partners from Finland, Germany and Italy and is funded by EU Horizon 2020. Within the ICO2CHEM project[38], a containerized chemical pilot plant is synthesizing liquid fuels using CO2 from biogas upgrading and H_2 from electrolysis.

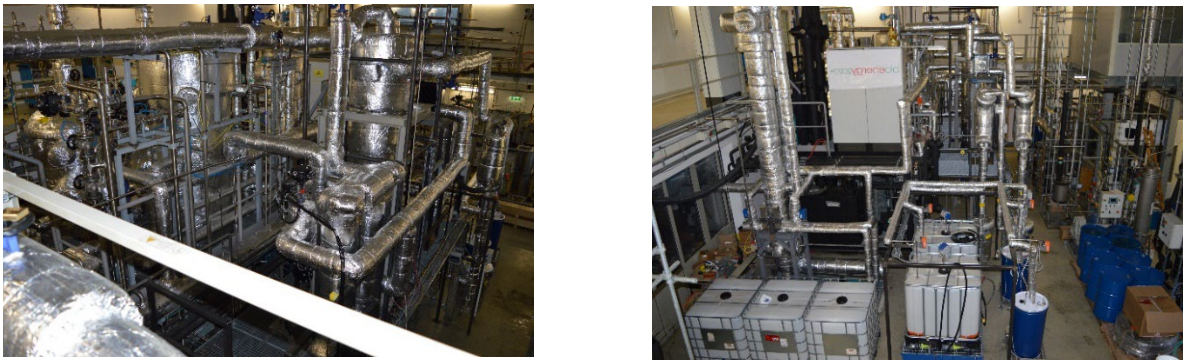
Several projects have been developed outside the EU and the major ones are discussed here. AgBioEn[39], Australia's ground-breaking bioenergy facility, with an estimated cost two billion Australian dollars began construction in the beginning of 2020. The facility involves pyrolysis and FTS to produce diesel and jet fuel as well as renewable electricity, fertilizer and food-grade CO_2.

The Lakeview project[40], developed by Red Rock biofuels, converts 166 kTPY of dry waste woody biomass into 1 100 bpd FT liquid with expected production start-up in spring 2021. Bayou fuels project[41], under development by Velocys in Mississippi, aims at producing 95 million liters of FT liquid from woody biomass.

Sierra biofuels plant[42], developed by Fulcrum bioenergy, converts 350 kTPY MSW into 175 kTPY of feedstock for the biorefinery which produces about 42 million liters of liquid fuels.

At the end of 2021, Fulcrum bioenergy[43] has announced its completion for interim financing to fund development of similar biofuel plant in Indiana, USA. There are a few pre-FEED feasibility studies[44–46] that involved the key actors required towards the development of commercial facilities for the production of second generation biofuels. FFS project[44], a consortium involving research institutions, academia, local municipality, local energy companies, forest owners, airline and airport, investigated site-specific and integrated production of sustainable aviation fuel (SAF) from bark and forest residues in Småland, Sweden. The highlights of the FFS study, which was funded by the Swedish Energy Agency, were communicated to the public and a video link of the event is available[47]. Another project tasked with validation and demonstration of forest-based jet fuel[45], involving all the relevant actors including technology developers, investigated site-specific production of SAF from black liquor in Piteå, Sweden. An existing demonstration facility for DME production via entrained flow gasification of black liquor[48] motivates demonstration of biojet production onsite.

Northwest advanced biofuels (NWABF) announced a feasibility study to produce SAF from forest residues in Washington State, USA. The investigation was strengthened by Delta Air Lines[46] that signed the largest of its kind offtake contract agreement to purchase SAF produced by NWABF.



Pilot facility for the production of 1 barrel per day of Fischer-Tropsch raw product at BEST – Bioenergy and Sustainable Technologies (former BIOENERGY 2020+ GmbH), Austria.

TECHNO-ECONOMIC PERSPECTIVE

To facilitate the development and deployment of BtL plants, preliminarily assessments about the technical viability of the production chain and their economic feasibility must indicate good odds for positive outcome. In this regard, most research activities promoting BtL often shade light on the techno-economic potential of the subject process. Several researchers have studied process performance[49–54] and techno-economic performance of integrated[55–60] or standalone[12,61–71] configurations to produce FT liquid hydrocarbons from biomass. Table 4 summarizes recent publications about process and economic performance of BtL plants via FTS. The commonly used indicators for process performance (efficiency – yield or energy) and economic performance (production cost, NPV or IRR) are presented along with indicators for plant size, conversion technology (primary conversion and FTS), configuration and assessment type. Annual average currency exchange rates were applied if the published economic indicators are not in Euro.

Bressanin et al.[60] performed techno-economic assessment (TEA) and environmental assessment of integrating eucalyptus gasification based FTS at a sugarcane biorefinery producing bioethanol based on cornstalk or energy cane. The TEA resulted in unfavorable NPVs with IRR values in the range 6.2–9.4% which are lower than the minimum acceptable return rate. The environmental benefits showed 85–95% reduction in greenhouse gases (GHG) emissions.
Li et al.[61] performed life cycle assessment (LCA) based on environmental and economic performances of producing jet fuel from cornstalk using DFB gasification and LTFT technologies. Depending on the process configuration, jet fuel production cost 124–141 €/MWh (before allocation) and 52–64 €/MWh (after allocation) were reported.

Tagomori et al.[64] performed TEA and georeferenced analysis of forest residues for producing FT diesel using high temperature entrained flow gasification. The production cost of FT diesel with and without CCS was estimated 125–130 €/MWh.
Sahir et al.[12] compared minimum fuel selling price (MFSP) for FT products based on co-feeding of biosyngas (0–100%) and natural gas. Depending on biosyngas share and process configuration (whether a hydrocracker was implemented or not), MFSP 65–92 €/MWh with hydrocracker and 58–95 €/MWh without hydrocracker were estimated. High ends of the ranges correspond to 100% biosyngas. Co-feeding natural gas and economy-of-scale improved the economic performance, e.g. compared to a study[63] based on cornstover feedstock (2000 t/d) that resulted in a production cost 90–112 €/MWh.
Herz et al.[62] compared TEA performance of biogas-based FT waxes using autothermal (ATR) and steam reformer (SR). Conversion efficiencies of 54% and 62% and breakeven periods of 9 years and 6.5 years were estimated for the ATR and SR configurations, respectively.
Production cost and environmental performance of integrated[56–58,72] and standalone[56–58,65,67,69,70,72–75] configurations for FT crude production were evaluated. Depending on the process configuration, conversion technology, feedstock cost, plant capacity, product type (crude or upgraded), coproducts incentive and other economic assumptions, production costs of 42–140 €/MWh FT liquid were reported.

A few studies have looked at the potential for converting CO_2 into liquid fuel in the so-called power-to-liquid (PtL) configuration[76–78]. When a PtL process is run on biogenic CO2 (that otherwise would have been released to the atmosphere) and renewable electricity, the product fuel qualifies as renewable. Generally, PtL processes are costlier than BtL[78] and further developments about direct hydrogenation of

CO_2[79–87] are required to make PtL mature and cost competitive. Hannula and Reiner[88] compared production cost of BtL to PtL pathway assuming a liquid fuel production capacity of 150 MW. The PtL case covered multiple options based on a wide range of electricity sources and real situations of several EU countries. Depending on the carbon intensity of the electricity source, electricity price and investment cost (low and high scenarios), the estimated breakeven fossil oil prices required to match the corresponding biofuel production costs were 146–188 €/MWh (solar PV), 214–233 (solar thermal), 93–111 (onshore wind), 169–189 (offshore wind), 220–231 (nuclear), 159–170 (geothermal) 245–256 (EU-28 average), 312–323 (Germany), 197–208 (France), 152–163 (Sweden) and 181–192 (Norway). The estimated production cost range for the corresponding BtL plant, which assumed LHV conversion efficiency 40%, was 58–74 €/MWh. Table 5 presents a few noteworthy PtL plants installed[89–91] or planned and under construction[92,93] in Europe based on CO_2 conversion via RWGS or co-electrolysis.

DISCUSSION AND OUTLOOK

The FTS is a well-established technique for gas-to-liquid (GtL) and coal-to-liquid (CtL) processes. GtL processes utilize Co- or Fe- based catalysts, whereas the CtL units operated by SASOL use Fe-based catalyst. Thus, it is not straight forward which catalyst and reactor configuration lead to the best performance for BtL. In order to shed some light in this direction, this review indicates on catalyst, reactor configuration and yield when presenting the summary of experimental and TEA publications, presented in Tables 2 and 4.

The TEA summary showed a wide range in production costs for FT crude, 42–140 €/MWh. This indicates that economic assumptions, process configuration, feedstock cost and economy-of-scale effects influence the production costs. Thus, site-specific assessment is inevitable when prospecting potential BtL development[44,45].

Most of the publications focus on standalone plant configuration which often miss out potential income from excess heat and other synergies. Integrated process design in the form of industrial symbiosis can facilitate deployment of BtL plants by providing additional revenue from waste/excess heat, excess electricity and existing infrastructure such as feedstock handling and WWT.

The suitability of biosyngas for traditionally used catalysts has been tested in many investigations with varying degrees of success[13–20,94]. Fe and Co-based catalysts dominate the field providing the best compromise between performance and economy[95].

BtL via FTS is the most promising technique to provide renewable alternatives to sectors difficult to decarbonize otherwise, such as long-distance trucking, aviation and marine transport. Commercial developments recently announced or currently under construction are implementing this route. FTS, as one of the few ASTM approved options for aviation, will remain central to BtL developments in the short-term.

Table 3. Development of BtL processes—Commercial, demonstration/pilot plants and feasibility assessments.

Organization	Project	Year/ Target	Conversion	FTS	Finance/ Status	Scale-TRL	Feedstock
Essar Oil (UK), Fulcrum Bioenergy (Stanlow, UK)	Fulcrum NorthPoint	2025	TRI steam reformer	JM/BP FT technology	Estimated budget £600 million	Annual SAF production 100 million liters	Municipal solid waste
British Airways/Shell/Velocys (Immingham, UK)	Altalto	Q2 2021	TRI steam reformer, POX-Arvos Schmidtsche-Schack with Linde's oxygen burner	Velocys technology, Haldor Topsoe upgrading	planning permission granted (June 2020)	60 million liters/y (SPK jet fuel, diesel and naphtha) (commercial)	Municipal solid waste 500 ktonnes, 70% reduction GHG compared to ordinary jet fuel, 90% reduction in particulate matter from engine exhausts
UK (University of Manchester, Argent Energy), Netherlands (TU/e, TNO innovation for life), CSIC (Spain), vito (Belgium), Italy (CiaoTech, Siirtec Nigi), Germany (INERATEC, C&CS)	GLAMOUR	2020-2024	ATR/gasification		EU Horizon 2020	Aviation & Marine fuels (demo)	Bio-based glycerol
Finland (VTT, AF-CONSULT OY), Germany (INERATEC, GKN, DLR EV), UniCRE AS (Czech), AMEC SRL (Italy)	COMSYN	2017-2021	DFB, steam-blown, 100 kg/h feedstock, 700–820℃, 1–3 bar	INERATEC (MOBSU)	EU Horizon 2020	Gasifier (demo), FTS (lab or pilot)	Bark
Finland (VTT), Germany (INERATEC, Infraserv Höchst, ALTANA, Provadis Hochschule), Italy (Politecnico di Torino)	ICO2CHEM	2017-2021	Industrial CO_2, RWGS	INERATEC microchannel reactor	EU Horizon 2020	Biogas (demo), FTS (pilot), electrolysis (pilot)	Industrial CO_2, electricity

Axens, CEA, IFP Energies Nouvelles, Avril, ThyssenKrupp Industrial Solutions, Total (Dunkirk, France)	BioTfueL	2021				60 t/y FTP (diesel and jet fuel) (demo)	straw, forest waste, dedicated energy crops
Solena Fuels, Green Sky (UK)		2015	Solena plasma gasifier	Velocys microchannel reactor, Co catalyst	discontinued	1157 bpd jet fuel (demo/commercial)	Municipal solid waste
SYNDIESE (France)		2015	Entrained flow, oxygen-blown			Commercial, 530 bbd liquid fuel, 205 t/ day feedstock	forest and agriculture residue
CUTEC (Germany)		2010	CFB, 400 kW$_{th}$, steam/oxygen-blown	Fixed bed, Co catalyst,		0.150 liters/d (lab)	straw
Gussing, Austria	Velocys	2010	DFB, steam blown, 8MWth	Velocys microchannel reactor, Oxford catalyst		Gasifier (demo) 150 t/d dry, 1 bpd FTP FTS (pilot)	woodchips
	RENEW	2007	DFB, steam blown, 8MWth	Slurry bed, Co catalyst		C5+ selectivity >90%, no loss of catalyst, FTS (lab)	woodchips
	TUV	2005	DFB, steam blown, 8MWth	Tubular slurry, Co or Fe catalyst, CO conversion 90%		2.5–5 kg/d, FTS (lab)	woodchips
Choren (Freiberg, Germany)	Beta	2009	Carbon V, entrained flow reactor (3 stage), 45 MW$_{th}$	Fixed bed, Co catalyst	discontinued	43 t/d FTP FTS (demo)	
ECN (Netherlands)		2003	CFB, oxygen-blown	Fixed bed, Co catalyst, C5+ selectivity 90%		Pilot/Lab	willow

Fulcrum Bioenergy (Indiana, USA)	Fulcrum 2	2023	TRI steam reformer	JM/BP FT technology			Municipal solid waste
Toyo Engineering, Japan	biomass to jet, commercial			Velocys microchannel			biomass
AgBioEn (Katunga, Australia)	Australia's ground-breaking Biomass Energy Facility	2020	Pyrolysis		under construction	Demo/commercial	Agricultural byproduct
In negotiation (Mississippi, USA)	Bayou Fuels	Q4 2021		Velocys technology, Haldor Topsoe upgrading	pre-FEED and federal permitting completed	95 million liters/y FTP (SPK jet fuel, diesel and naphtha) (demo/commercial)	Woody biomass, forest residue
Red Rock biofuels (Oregon, USA)		2017	TRI steam reformer	Velocys, Co catalyst		460 t/d biomass feed, 1100 bpd FTP (demo/commercial)	Forest and sawmill waste
Sierra Biofuels (Nevada, USA)	Fulkrum bioenergy	2016	TRI steam reformer	Velocys, Co catalyst		400 t/d MSW, 657 bpd FTP (demo/commercial)	Municipal solid waste
SYNDIESE (USA)		2015	Entrained flow, oxygen-blown			530 bbd liquid fuel, 205 t/d feedstock (demo/commercial)	forest and agriculture residue
Clearfuels, Rentech (Colorado, USA)		2011	Entrained flow, High Efficiency Hydrothermal Reformer (HEHTR)	Slurry bed, Fe catalyst	closed in 2013	1600 liters/d FTP (diesel and jet fuel) (pilot)	Waste wood and bagasse
TRI (USA)			BFB, steam-blown	Fixed bed, Co catalyst, CO conversion 70%		80 liters/d FTP (pilot)	Black liquor

RISE, Södra, SkyNRG, Luleå University, Växjö municipality, Växjö Energi, Småland Airport, KLM, Fores (Småland, Sweden)	Flying on forest residues in Småland (FFS)	2019-2020	Dual fluidized bed, steam oxidized		Swedish Energy Agency	Feasibility	Forest residue, bark
RISE, INERATEC, SkyNRG, Luleå University, SAS AB, BRA Sverige AB, Fly Green Fund, ARVOS GmbH, Smurfit Kappa, Sveaskog, SVEBIO (Piteå, Sweden)	Validation & demonstration of forest-based jet fuel-step 1	2018-2019	Entrained flow, oxygen blown	INERATEC	Swedish Energy Agency	Feasibility	Black liquor
NWABF, Delta (Washington state, USA)	NWABF	2019				Feasibility	forest residue, wood slash

Table 4. Technoeconomic assessments of integrated (Int) and standalone (SA) BtL FTS configurations.

Ref.	Int/SA	Host facility	Feedstock	Conversion	FTSR	Capacity	Configuration	Assessment	Indicator
60	Int	Sugarcane biorefinery: cornstalk 4million t (wet) to ethanol	Eucalyptus	Gasification	multi-tubular fixed bed, 25 bar, 200–240℃, LTFT	Eucalyptus 0.8–0.86 million t (dry)	ASF distribution	Comparative assessment: Refinery cornstalk or energy cane with Eucalyptus, TEA	IRR 6.2–9.4%
61	SA		Corn stalks	Dual fluidized bed, steam oxidized, 750℃, 10bar	15 bar, 240℃, LTFT		standalone, steam generated used for: process heat or power generation	LCA, TEA	Production cost 124–141 €/MWh Jetfuel (before allocation), 52–64 €/MWh Jetfuel (after allocation)
50	SA		crashed bark	dual fluidized bed, steam- or steam/oxygen-blown	Once-through fixed bed, Co catalyst, α=0.93, 200℃, 20 bar, AFS distribution (except methane & ethane), C5+ selectivity 88.5%, LTFT	100 MW LHV feedstock	standalone, different feedstock drying configuration	Comparative assessment	47.7–54.6% FTP to feedstock, energy basis
49	SA		Torrefied biomass	Entrained flow, steam & oxygen blown, 1600℃, 40bar	FTS1 (stirred tank slurry), 15–25bar, 195–230℃, Re-Co/Al2O3 catalyst), LTFT FTS2 (plug flow	435 MW LHV feedstock (83.5 t/h)	standalone, FTS: three kinetic models	Mass & energy balance	FTP 46 t/h

					fixed bed, atmospheric, 250℃, Co/Al2O3 catalyst), LTFT FTS3 (CSTR, 220–240℃,5–15 bar, Co/MgO/SiO2 catalyst), LTFT				
64	SA		forest residue–eucalyptus & pine	entrained flow reactor, 40bar, 1427℃, oxygen blown	AFS distribution, α=0.9	Feedstock input 100 t/h	standalone, with and without CCS	Comparative assessment, geographically explicit deployment potential	Production cost 125–130 €/MWh FTP
12	SA		biomass, natural gas	Indirect steam-blown gasifier		50 million gallons of gasoline equivalent (192 MW, assuming continuous operation)	Biomass feed 0–100% with natural gas, ASF distribution, α=0.87		MFSP 58–95 €/MWh FTP
65	SA		Woodchips	CFB, steam & oxygen blown, 870℃, 28bar Entrained flow, steam & oxygen blown,	230℃, 25 bar, 80% CO conversion, α=0.85, Co-based catalyst, LTFT	207 MW FTP	standalone	TEA	Production cost 64 €/MWh (CFB) 66 €/MWh (entrained)

				1400℃, 28 bar					
73	SA		milling waste, bagasse	Fluidized bed, steam-blown; Fast pyrolysis	AFS distribution, α=0.9	100 t/h feedstock (main case)		comparative assessment FTS and fast pyrolysis	Production cost 40 €/MWh (fluidized bed) 44 €/MWh (fast pyrolysis)
66	SA		Bio oil aqueous phase with 35%wt organic concentration	supercritical water reforming, 240 bar, 800℃	LTFT, 50% CO conversion (single pass), α=0.9	Bio oil aqueous phase input 60 t/h	standalone with CCS	process performance assessment	Carbon efficiency 38.5%, 5.3MW electricity coproduction
62	SA		Biogas				ASF distribution, α=0.93, CO conversion 80%, Co catalyst	Comparative performance assessment, autothermal (ATR) vs. Reforming (SR)	Energy efficiency (excluding losses): ATR 54%, SR 62%, Economic performance: breakeven ATR 9 & SR 6.5 years
55	Int & SA	Oil refinery	wood fuel	Circulating fluidized bed, oxygen & steam blown, 850℃ 25bar	Slurry phase reactor, Co-catalyst, 210℃, 23 bar, 90% CO conversion, LTFT		standalone, integrated, CO_2 capture	ENPAC (future energy market scenario), GHG emissions estimates	Production cost 84–125 €/MWh FTP

51, 71	SA		rice straw	Downdraft, oxygen blown, 700℃	slurry phase, 20bar, 220℃, LTFT	393 MW HHV rice straw (80 t/h)		Comparative assessment, Pinch Analysis, Environmental analysis, FT tail gas recycle 0.1–0.9	Incremental NPV -3.1– -1444, assuming diesel price 72 €/MWh, electricity 72 €/MWh
59	Int	Sugar mill	bagasse, trash from field	Autothermal gasification, atmospheric & pressurized	fixed bed, 23.5 bar, 240℃ and slurry reactor, 40bar, 240℃, LTFT	66.4 t/h dry		Comparative assessment	IRR 16.9%
54	Int	Pulp and paper mill	wood fuel—milling torrefaction, pyrolysis	Entrained flow, oxygen-blown, 1350℃, 30bar	Slurry phase reactor, Co-catalyst, 210℃, 23 bar, 90% CO conversion, LTFT	128–157 MW FTP	Integrated, CO_2 capture	Pinch analysis, GHG emissions reduction	
74	SA		woody biomass	BFB, Andritz Carbona	LTFT, 80% CO conversion, α=0.85, AFS distribution	400 MW_{th} feedstock	standalone, FT tailgas recycle	Comparative assessment	106 €/MWh FT diesel
56,57	Int & SA	Scandinavian Kraft pulp and paper mill	wood fuel (35 €/MWhwf), electricity (70 €/MWhel)	CFB, oxygen & steam blown, 850℃ 25bar	Slurry phase reactor, Co-catalyst, 210℃, 23 bar, LTFT	36–180 MW FTP	standalone, integrated, lignin extraction	Pinch analysis, economics, GHG emissions reduction	Production cost 100–120 €/MWh FTP

58	Int & SA	Oil refinery	wood fuel (28–53 €/MWh), electricity (69–89 €/MWh)	CFB, oxygen-blown	Slurry phase reactor, Co-catalyst, 210℃, 23 bar, LTFT	259 MW FTP	standalone, integrated, CO_2 capture	Pinch analysis, economics, GHG emissions reduction	Production cost 69–107 €/MWh FT diesel 62–98 €/MWh FT gasoline
25	SA		Pine chips	Indirectly heated entrained flow reactor	Cylindrical tube, Co-catalyst, 230℃, 20 bar, 74.4% CO conversion, LTFT	390 MW LHV feedstock	standalone	Experimental, TEA	Breakeven cost of oil product 63 €/MWh
75	SA		Residual wood, straw	Entrained flow reactor		760 MW HHV syngas (103 t/h)	standalone	Comparative TEA, CO_2 tax assessment	Production cost 136 €/MWh FTP (diesel and gasoline)
52	SA		biosyngas from woodchips	Fluidized bed		10000 Nm (Functional unit, FU)	standalone, electricity coproduction	LCA analysis (ADP, GWP, ODP, POFP, LC, AP, EP)	
53	Int	Scandinavian mechanical pulp and paper mill, Sawmill	wood fuel	CFB, oxygen & steam blown, 850℃ 25bar	Slurry phase reactor, Co-catalyst, 210℃, 23 bar, 90% CO conversion, LTFT	115–148 MW FTP	Integrated	Pinch analysis, GHG emissions reduction	
67	SA			fluidized bed, 29.9 bar, oxygen blown		3900 bpd	standalone, with and without FT tailgas recycle	Comparative TEA, coproduct value	Production cost 42–140 €/MWh FTP

69	SA		woody biomass	directly or indirectly heated—Entrained flow reactor, circulating fluidized bed	FTS 340℃, 25 bar, H2/CO=2, CO conversion 80%, HTFT	20 MW and 400 MW biomass input	standalone, HT FT, with and without FT tail-gas recycle	Comparative TEA, Economy of scale	Production cost 53–90 €/MWh FTP
63	SA		Cornstover	entrained (1300℃), fluidized bed (870℃)		Cornstover 2000 t/d	ASF distribution, α=0.9	Comparative assessment	Product value 90–112 €/MWh FTP
70	SA		popular wood	CFB	fixed bed, slurry bed, 20–40bar, 180–250℃, LTFT	100 MW_{th} feedstock	standalone, FT and power, α=0.8–0.9, CO conversion 60–80%	comparative process assessment & TEA	Production cost 61 €/MWh FTP

Table 5. Overview of PtL plants in Europe[76].

Ref.	Organization	Project	Country	Year/target	Conversion	FTS	Production	CO_2 source
92,96	Nordic Blue Crude AS, Sunfire, Climeworks, EDL Anlagenbau	Nordic Blue Crude	Norway	2022	SOEC, RWGS		Commercial 8000 t/y FTP	DAC, Industrial
93	Rotterdam The Hague Airport, Climeworks, SkyNRG, EDL Anlagenbau, Schiphol, Sunfire, Ineratec, Urban Crossovers	The Hague Airport Demo-Plant	Netherlands	Announced May 2019	SOEC, Co-electrolysis	Microstructured channel reactor	Demo 1000 liters/d	DAC
91,96,97	KIT, Climeworks, Ineratec, Sunfire	PtL test facility	Germany	2019	SOEC, Co-electrolysis	Microstructured channel reactor	Pilot 10 liters/d	DAC
89,98–100	VTT, LUT	SOLETAIR	Finland	2017	PEM, RWGS	Microstructured channel reactor		DAC
90,99	Sunfire, EIFER, Fraunhofer, GETEC, HGM, FZ Julich, Kerafol, Lufthansa, Univ. Bayreuth, Univ. Stuttgart	Sunfire-fuel 1 plant	Germany	2014	SOEC, RWGS			DAC

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