Sustainable Aviation Fuel Feedstock and Pathways

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ASCENT
AVIATION SUSTAINABILITY CENTER

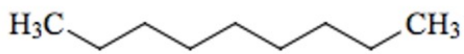
Outline

- Conventional jet fuel
- Sustainable aviation fuel (SAF)
- Feedstock and Conversion Technologies
- Example minimum selling price and abatement cost (US values)

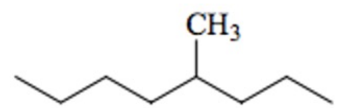
Jet Fuel Composition[1]

Gasoline: C4-C12
Jet: C8-C16
Diesel: C9-C23

Paraffins (70-85%)



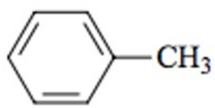
Normal Paraffins

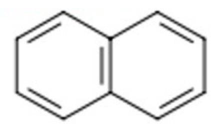


Iso-Paraffins

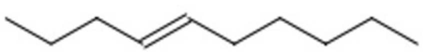
Cyclo-Paraffins

Aromatics (<25%)

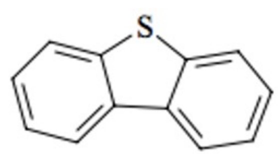


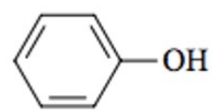


Olefins (<5%)



Sulfur, Nitrogen, Oxygen Containing Compounds





Jet fuel must meet detailed specifications for safety [2-3]

Fuel	Jet A	Jet A-1	TS-1	Jet B
Specification	ASTM D 1655	DEF STAN 91-91	GOST 10227	CGSB-3.22
Acidity, mg KOH/g	0.10	0.015	0.7 (mg KOH/100ml)	0.10
Aromatics, % vol, max	25	25.0	22 (% mass)	25.0
Sulfur, mass%	0.30	0.30	0.25	0.40
Sulfur, mercaptan, mass%	0.003	0.003	0.005	0.003
Distillation, °C:				
Initial boiling point	—	Report	150	Report
10% recovered, max	205	205	165	Report
50% recovered, max	Report	Report	195	min 125; max 190
90% recovered, max	Report	Report	230	Report
End point	300	300	250	270
Vapor pressure, kPa, max	—	—	—	21
Flash point, °C, min	38	38	28	—
Density, 15°C, kg/m³	775–840	775–840	min 774@20°C	750–801
Freezing Point, °C, max	–40	–47.0	–50 (Chilling point)	–51
Viscosity, –20°C, mm²/sec, max	8	8.0	8.0 @ –40°C	—
Net Heat of combustion, MJ/kg, min	42.8	42.8	42.9	42.8
Smoke point, mm, min	18	19.0	25	20
Naphthalenes, vol%, max	3.0	3.00	—	3.0
Copper corrosion, 2 hr @ 100°C, max rating	No. 1	No. 1	Pass (3 hr @ 100°C)	No. 1
Thermal stability				
Filter pressure drop, mm Hg, max	25	25	—	25
Visual tube rating, max	<3	<3	—	<3
Static test 4 hr @ 150°C, mg/100 ml, max	—	—	18	—
Existent gum, mg/100 ml, max	7	7	5	—

- Aircraft and engines are certified for fuel specified in a standard, such as Jet A/A-1 (ASTM D1655).
- If a fuel is not "equivalent" to Jet A/A-1, the fuel requires:
  - its own fuel specification,
  - separate handling,
  - and the aircraft and the engine require certification for that fuel
- ASTM D7566: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons

Sustainable Aviation Fuel (SAF)

CORSIA defines SAF as renewable or waste-derived aviation fuels that meet specific sustainability criteria [4]

Drop-in = fuels are fleetwide and infrastructure compatible

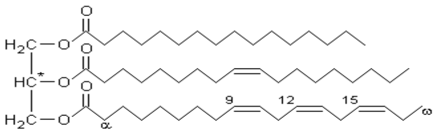
CORSIA Sustainability Criteria [5]

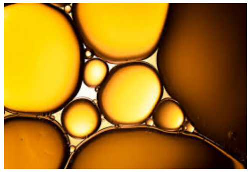
Sustainability Themes	
1. Greenhouse Gases (GHG)	Carbon reduction themes
2. Carbon stock	
3. GHG reduction permanence	Environmental, social, and economic themes
4. Water	
5. Soil	
6. Air	
7. Conservation	
8. Waste and Chemicals	
9. Seismic and Vibrational Impacts (only for LCAF)	
10. Human and labour rights	
11. Land use rights and land use	
12. Water use rights	
13. Local and social development	
14. Food security	

Feedstock

- **Lipids**

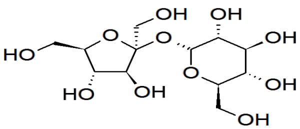
Triglycerides



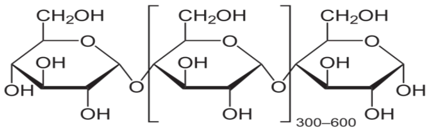


- **Sugar and Starch**

Sucrose

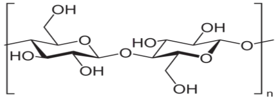


Starch

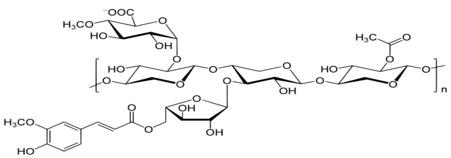


- **Lignocellulosic**

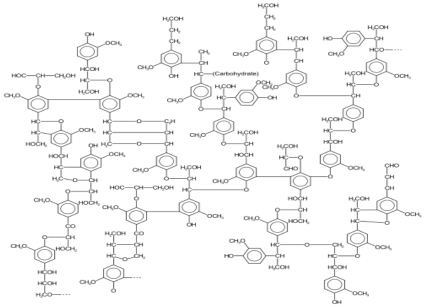
Cellulose



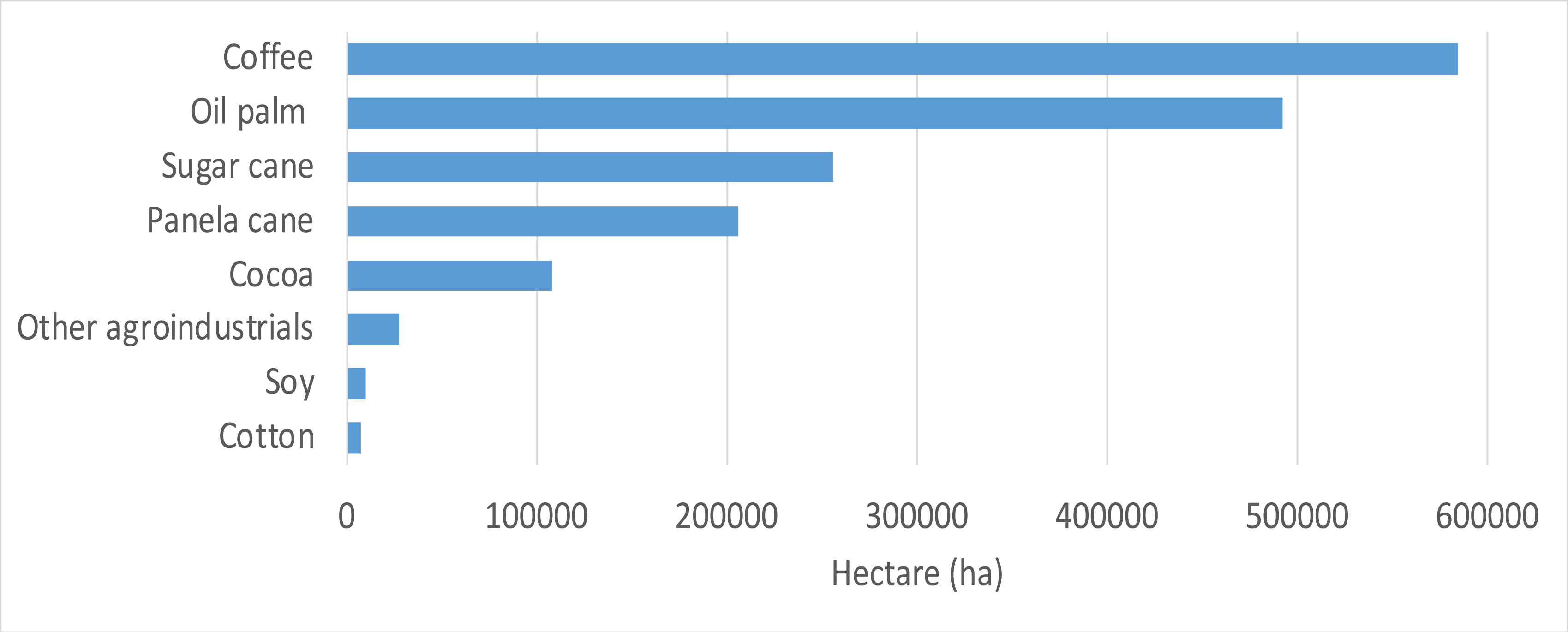
Hemicellulose (Xylan)



Lignin



Colombian agroindustry crops (in productive age or harvested area)



Source: DANE, Encuesta Nacional Agropecuaria. 2020

Potential Feedstock

Inventories and/or studies are required

Main Harvest

Crop
Palm oil*
Sugar cane

Residues

Harvest	Residues
Coffee	Pulp
	Husk
	Stem
Palm oil	Empty fruit bunch
	Fiber
	Palm shell
	POME
Sugar cane	Leaves-top
	Bagasse
Cacao	Pod shell
	Bean shell
Rice	Straw
	Husk
Corn	Stover
	Cob
	Husk

Wastes

Source
Landfills
Animal fat

Energy Crops

To be developed
Miscanthus
Poplar
Energy canes*
Switchgrass
Eucalyptus*
Willow*

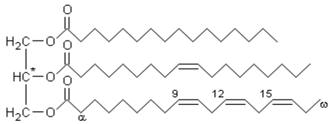
*iLUC calculation is required

Conversion technology

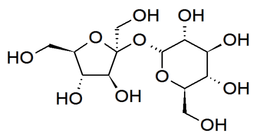
- **Oleochemical:** convert fatty acids using physicochemical methods.
- **Biochemical:** conversion transforms carbohydrate-rich feedstock into an intermediate product using microorganisms.
- **Thermochemical:** deconstructs macro-molecules of solid biomass using high temperatures and oxygen deficiency.
- **Electrochemical:** uses hydrogen and a concentrated source of CO_2, methane, methanol, or short carbon chain molecules. Also known as power-to-liquid or e-fuels, requires renewable electricity for electrolytic production of hydrogen and a renewable/waste carbon source.

Conversion technology

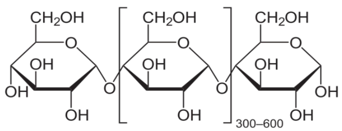
Triglycerides



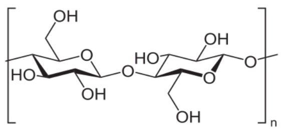
Sucrose



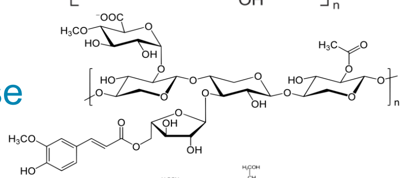
Starch



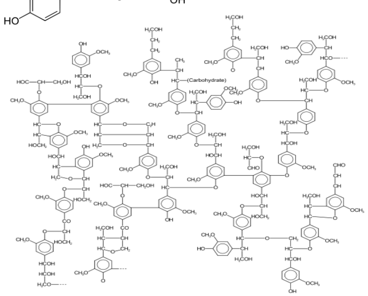
Cellulose



Hemicellulose



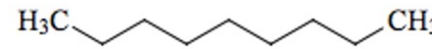
Lignin



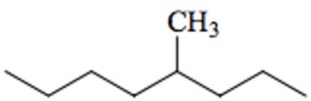
Cracking / Hydrolysis
(Molecular weight reduction)

Hydro-deoxygenation
(Oxygen removal)

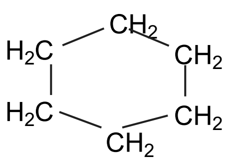
Paraffin



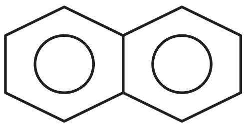
Iso-paraffins



Naphthenes

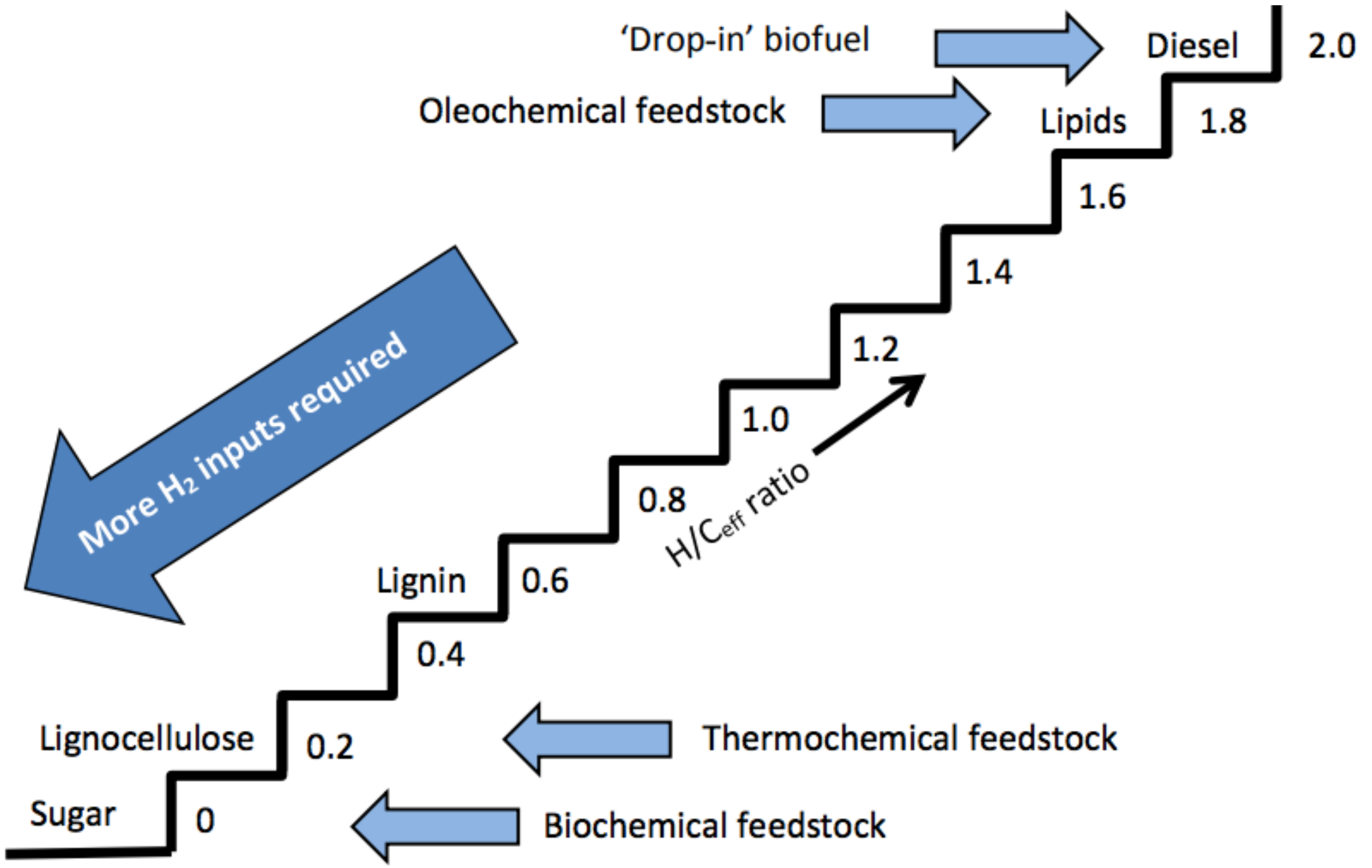


Aromatics



Hydrogen to Carbon Staircase [6]

$$H_{eff}/C = \frac{n(H) - 2n(O)}{n(C)}$$ where *n*=number of atoms of each element



Approved Conversion Pathways (1/2) [7-8]

ASTM D7566	Conversion process	Process Feedstock	Process feedstock sources	Max blend ratio
A1	Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Syngas (CO and H2)	Biomass such as municipal solid waste (MSW), agricultural and forestry residues, wood and energy crops; Industrial off-gases; Non-renewable feedstocks such as coal and natural gas.	50%
A2	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	Fatty acids and fatty acid esters	Bio-oils, animal fat, recycled oils: chicken fat, white grease, tallow, yellow grease, brown grease, purpose-grown plant oils, algal oils, and microbial oils.	50%
A3	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	Sugars	Sugars from direct (cane, sweet sorghum, sugar beets, tubers, field corn) and indirect sources (C5 and C6 sugars hydrolyzed from cellulose)	10%
A4	Fisher-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)	Syngas	Same as A1, with the addition of some aromatics derived from non-petroleum sources	50%
A5	Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Ethanol and isobutanol	C2-C5 alcohols derived from direct and indirect sources of sugar (see A3), or those produced from the microbial conversion of syngas	50%
A6	Catalytic hydrothermolysis jet fuel (CHJ)	Fatty acids and fatty acid esters	Same as A2	50%
A7	Synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids (HC-HEFA-SPK)	Algal oils	Specifically, bio-derived hydrocarbons, fatty acid esters, and free fatty acids. Recognized sources at present only include the tri-terpenes produced by the Botryococcus braunii species of algae.	10%
A8	ATJ derivative starting with the mixed alcohols (ATJ-SKA)		C_2 to C_5 alcohols	TBD

Approved Conversion Pathways (2/2) [7-8]

ASTM Reference	Conversion process	Process Feedstock	Process feedstock sources	Max blend ratio
D1655 A1	Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery	Fat, oils, greases	Fats, oils, and greases (FOG) co-processed with petroleum	5%
	Co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery	Syngas (CO and H2)	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%
	Co-hydroprocessing of biomass	non-petroleum sources such as coal, natural gas, biomass, fatty acid esters and fatty acids	Gasification, Fischer-Tropsch synthesis, and hydroprocessing	5%

Conversion processes under evaluation [8-9]

- Synthesized aromatic kerosene
- Integrated hydropyrolysis and hydroconversion of lignocellulosic materials
- ATJ derivative utilizing biochemical production of isobutane
- Single reactor HEFA
- Pyrolysis of non-recyclable plastics
- Co-processing of pyrolysis oil from used tires

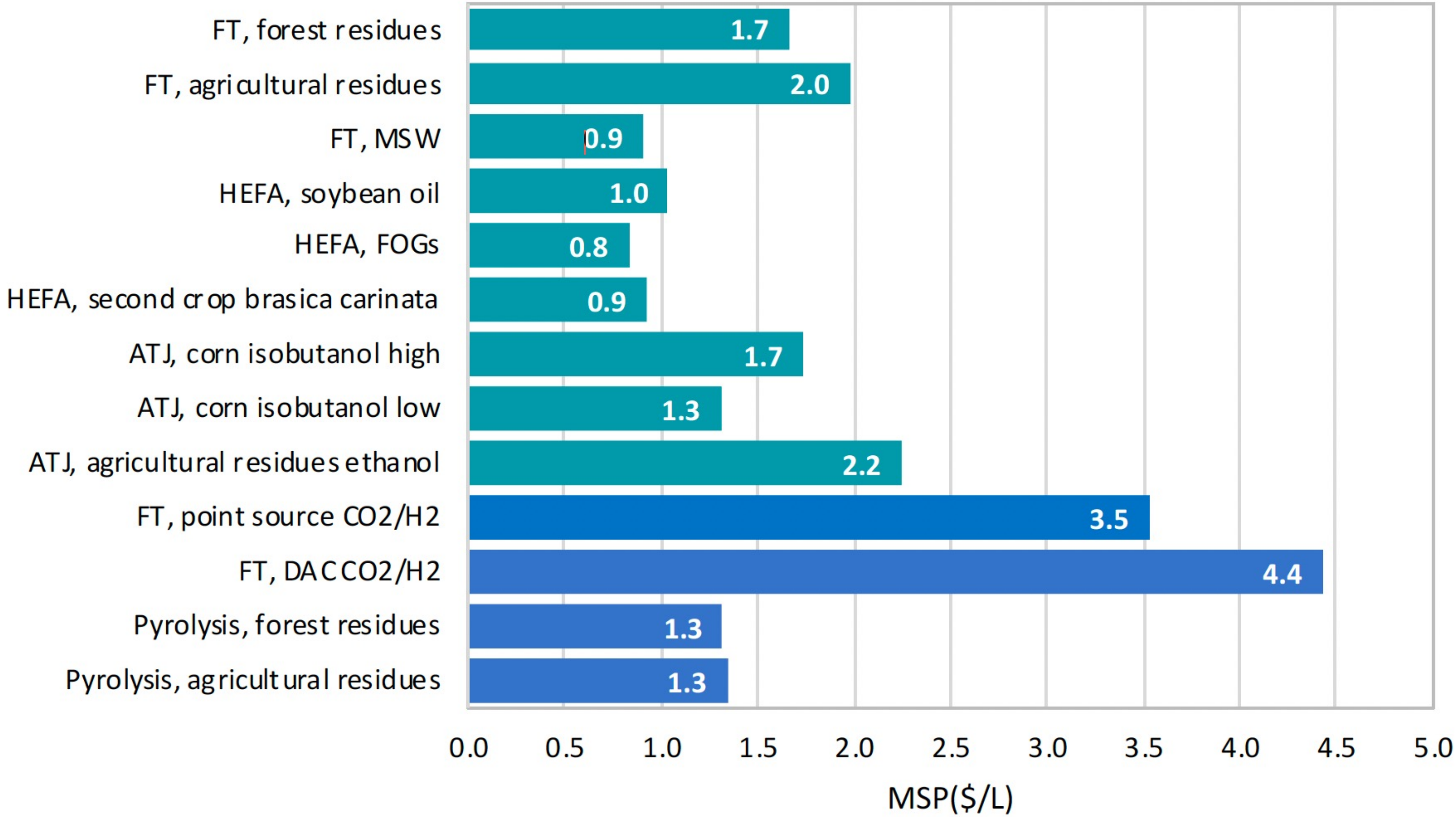
Commercial or near commercial pathways

	HEFA	ATJ	GFT
Feedstock cost	High	Medium	Low
Yield	High	Low*/High**	Low
Conversion cost	Low	Medium	High

*Second-generation alcohols
**First-generation alcohols

$$\text{Minimum Fuel Selling Price} = \frac{\textit{Feedstock Price} + \textit{Conversion Cost}}{\textit{Product Yield}} \quad [10]$$

MSP, n^{th} plants* [11]



*MSP estimated based on U.S. financial assumptions, CAPEX and OPEX
DAC= Direct Air Capture

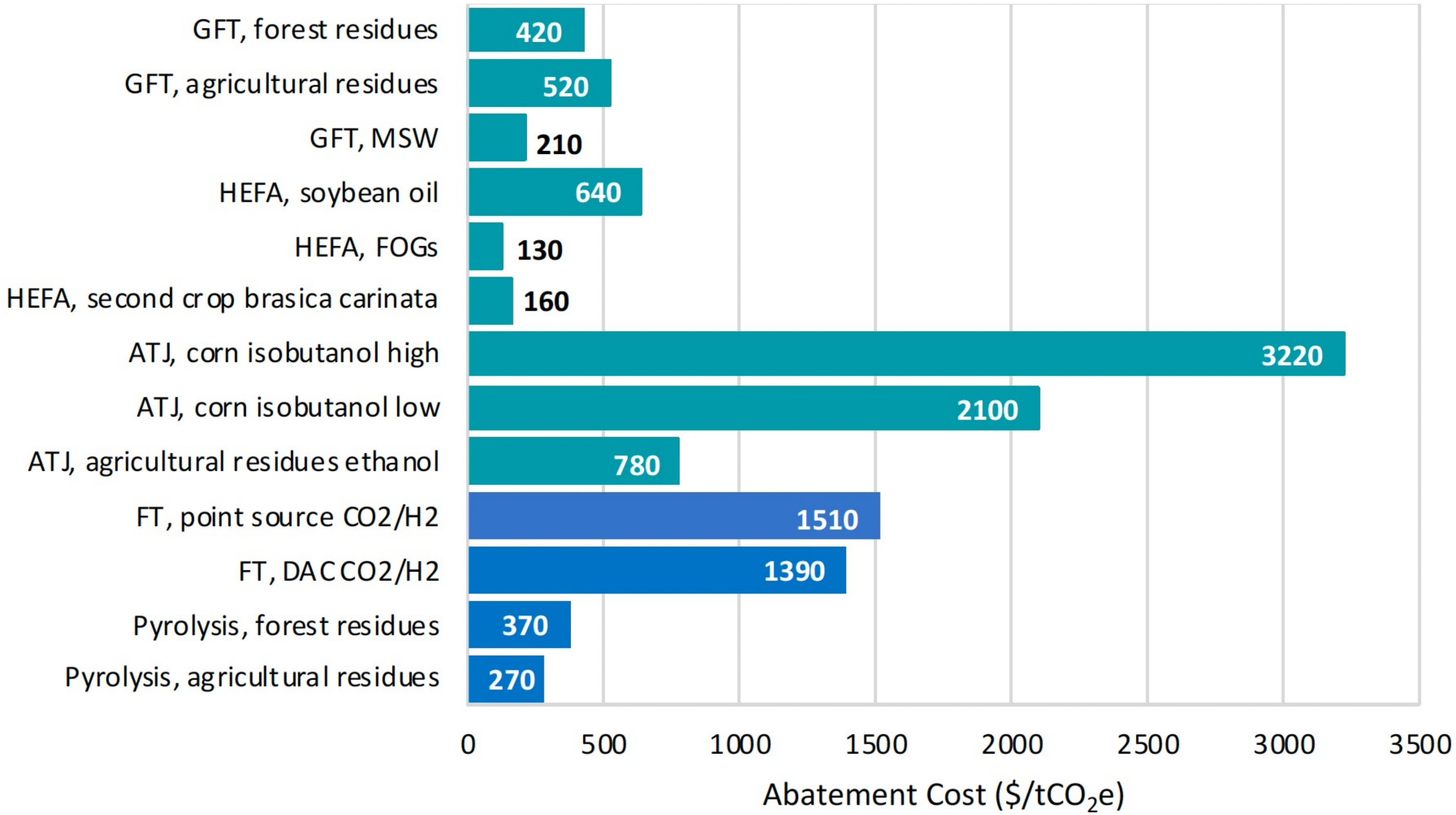
CO_2 Abatement cost, n^{th} plants

$$Abatement\ Cost\left(\frac{\$}{tCO_2e}\right) = \frac{SAF\ MSP - petroluem\ jet\ price}{SAF\ LS_f - petroleum\ jet\ LS_f}$$

- MSP = minimum selling price
- SAF and conventional processes are \$/MJ
- LS_f is the emissions tCO2e/MJ
- Petroleum jet process assumed to be \$0.5/L[1]= \$0.015/MJ

[1] 2017 – 2019 US EIA average

CO_2 Abatement cost, n^th plants*[11]



*Abatement cost estimated based on U.S. financial assumptions, CAPEX and OPEX
FT, MSW assumes 16% non-biogenic carbon

QUESTIONS

References

[1] Rahmes et al. 2009. Sustainable Bio-Derived Synthetic Paraffinic Kerosene (BioSPK)Jet Fuel Flights and Engine Tests Program Results. 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO). Hilton Head, SC.

[2] Chevron Corporation. 2007. Aviation Fuels: Technical Review. Chevron Products Company. https://www.chevron.com/-/media/chevron/operations/documents/aviation-tech-review.pdf

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[4] ICAO. 2018. Annex 16 to the Convention on International Civil Aviation , Volume IV.

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