Sustainable Aviation Fuel Progress Overview

American Institute of Aeronautics and Astronautics
Los Angeles - Las Vegas Section

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First flight from continuous commercial production of SAF, 10Mar'16
Fuel from World Energy - Paramount (HEFA-SPK 30/70 Blend).

27Feb'21

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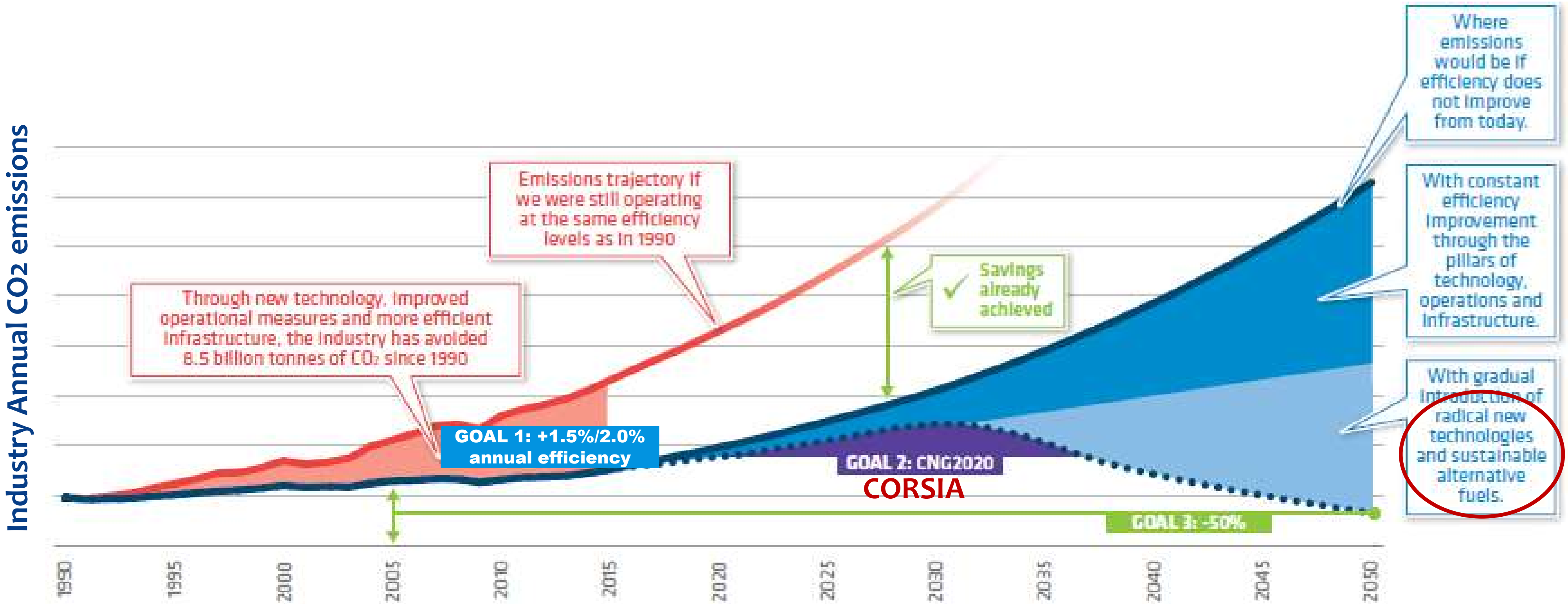
Commercial Aviation commitments on CO₂ reductions



 Courtesy of ATAG: www.atag.org/our-publications/latest-publications.html; Beginner's Guide to Sustainable Aviation Fuel; **Business Aviation made similar commitments**

Majority of CO_2 emissions come from medium- and long-range flights, and larger aircraft

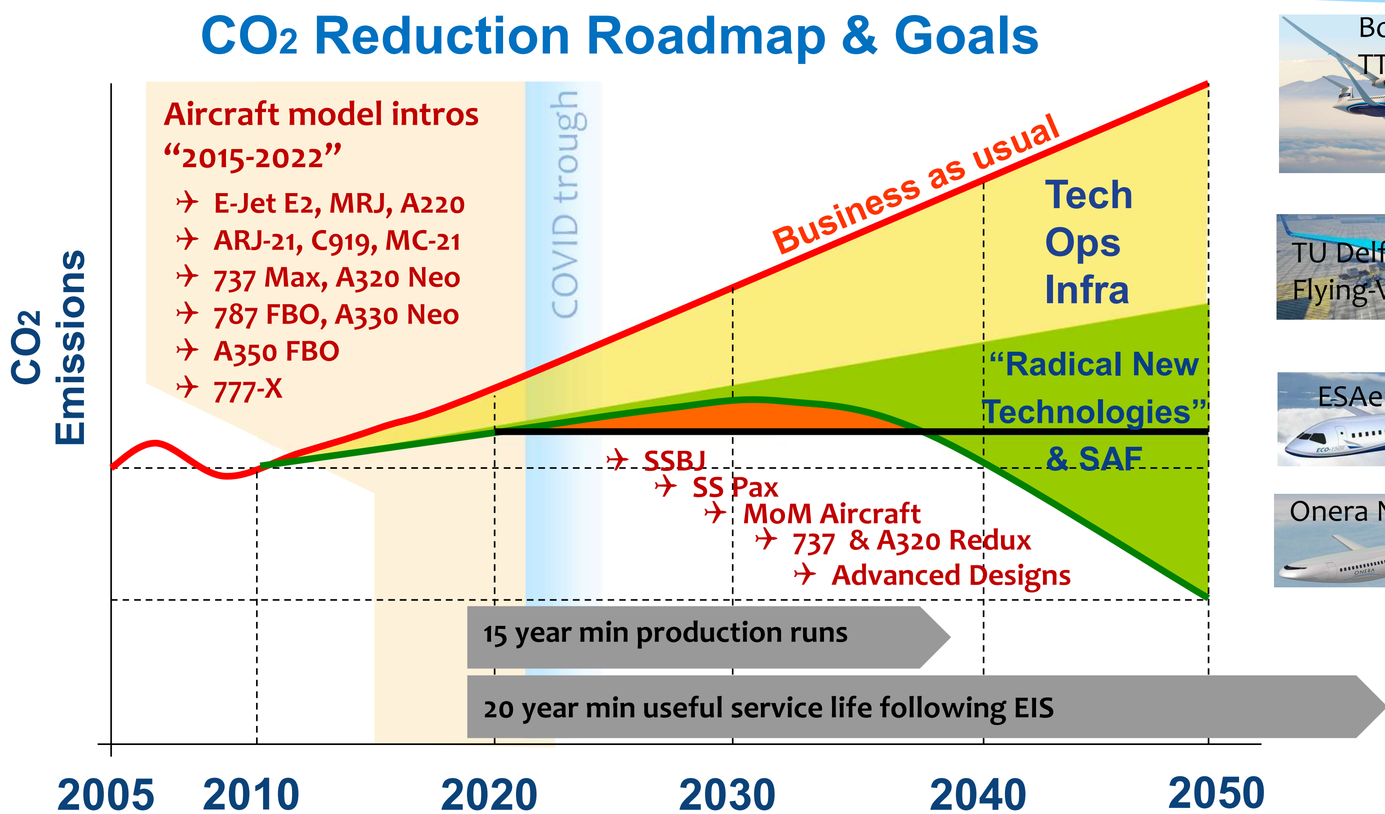
Global CO2 emissions from aviation – 2018, in % of total CO2 emitted

	Flight Range Category (km)						Total Share CO2 Emissions	Global Fleet
Aircraft Type	0-500	501-1000	1001-2000	2001-3000	3001-4500	>4500		
Commuter <19	<1%						<1%	4%
Regional 20-80	1.2%	1.2%	0.8%	0.1%			3%	13%
Short Range 81-165	1.6%	5.8%	10.1%	4.0%	2.0%		24%	53%
Med. Range 166-250	1.1%	4.9%	13.1%	8.4%	6.9%	8.5%	43%	18%
Long Range >250	0.1%	0.5%	1.6%	1.6%	1.9%	24.2%	30%	12%
Total	~4.5%	~12.4%	~25.6%	~14.1%	~10.7%	~32.7%		

Source: World Economic Forum – Mission Possible Platform, DiioMi

Jet fuel usage will continue …

Through several decades, with tomorrow's technology



E.g. 10 of 11 touted Advanced Designs include gas-turbines … burning jet fuel to produce thrust / onboard distributed power

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Key drivers that led to SAF strategy in 2008

Issues which must be addressed by energy switching concepts

Significant benefits, few challenges beyond comparative cost of the production itself

- **No equipment changes, no operational changes**
  - Aircraft certification basis remains
- **No distribution infrastructure changes**
  - Only primary challenge is blending terminals, of comparative low cost versus other needs
- **No airport energy / fueling infrastructure changes**
  - Continued use of most efficient architecture – fuel farm common storage, hydrant system delivery
- **No impact to surety of supply**
  - Distributed production and supply could actually improve energy security
- **No limitation to volume of potential supply** (reaffirmed by multiple source studies)
  - Sufficient & multiple sustainable feedstock sources and conversion methodologies
- **No limitation on potential producers**
  - From entrepreneurs, to existing refinery integration, to full refinery retrofit
- **No changes to execution of aviation paradigm**
  - Enables safe, effective, efficient system, leveraging 70 years of experience/learning

Additional drivers for consideration of SAF

- **Enables the carbon reduction to start TODAY**
  - 50-70% net GHG LCA available already, pursuits for achieving **and surpassing 100%** ongoing
- **Brings along other benefits – besides key benefits of jobs and rural development**
  - Reductions to criteria pollutants (SOx, PM, CO, ice nucleation), reduction of supply chain GHGs
  - Environmental services of the supply chain (erosion, water, nutrients, habitat, C-sequestration)
- **Promise of additional future SAF production approaches**
  - Oleaginous yeasts, algae (unlimited feedstock and CO_2 consumption), P-t-L, …
- **Allows advanced technology to enter the market at its own, justified pace**
  - After the new tech can substantiate OpCost improvements that justify fleet introduction

    …After the new tech achieves adequate TRL

    …After the certification basis is established

    …After a 5-8 year design and certification process
  - After challenges for different energy supply infrastructure have been addressed

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SAF (Sustainable Aviation Fuel)
a.k.a. aviation biofuel, biojet, alternative aviation fuel

Aviation Fuel: Maintains the certification basis of today's aircraft and jet (gas turbine) engines by delivering the properties of ASTM D1655 – Aviation Turbine Fuel – enables drop-in approach – no changes to infrastructure or equipment, obviating incremental billions of dollars of investment

Sustainable: Doing so while taking Social, Economic, and Environmental progress into account, especially addressing GHG reduction

How: Creating synthetic jet fuel with biochemical and thermochemical processes by starting with a different set of carbon molecules than petroleum … a synthetic comprised of molecules essentially identical to petroleum-based jet (in whole or in part)

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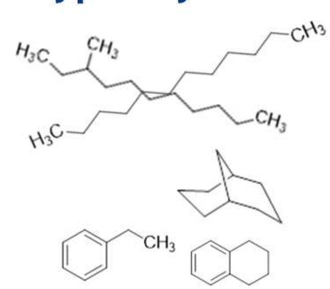
Okay, then let's start with – What is jet fuel?

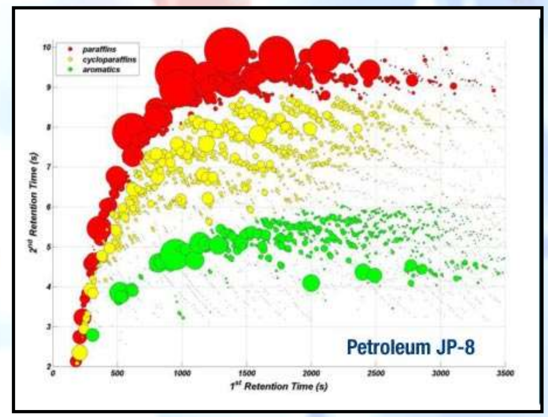
Definition around which aviation enterprise is optimized / certified

A middle distillate refinery stream is used for jet fuel

- Comprised of mixtures of aliphatic and aromatic hydrocarbons with carbon numbers predominantly in the range of C7-C17, which is typically a mixture of:
  - ~25% / 11% normal / branched paraffins
  - ~30% / 12% / 1% mono- / di- / tri-cycloparraffins
  - ~16 / 5% mono- / di-nuclear aromatics

    (25% max aromatics – air quality concern)





- A Gaussian distribution of hydrocarbons, represented as $C_{12}H_{23}$

There is no standard "formula" for jet fuel

- Composition that delivers the physical properties and performance-based requirements / characteristics of ASTM D1655 specification

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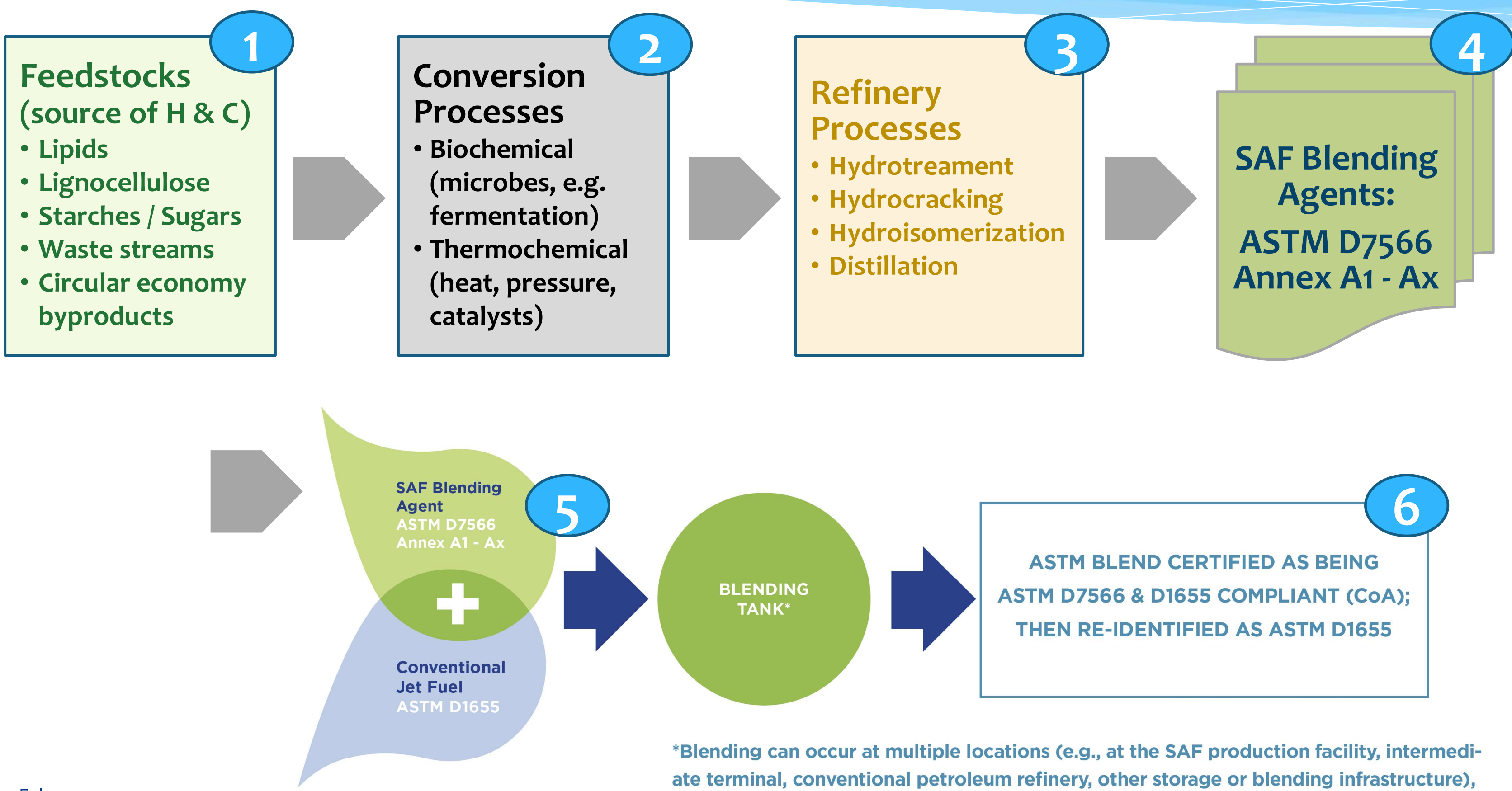
How is SAF made?



*Blending can occur at multiple locations (e.g., at the SAF production facility, intermediate terminal, conventional petroleum refinery, other storage or blending infrastructure), but must be followed by batch compliance testing and certification as identified in D7566 and D1655.

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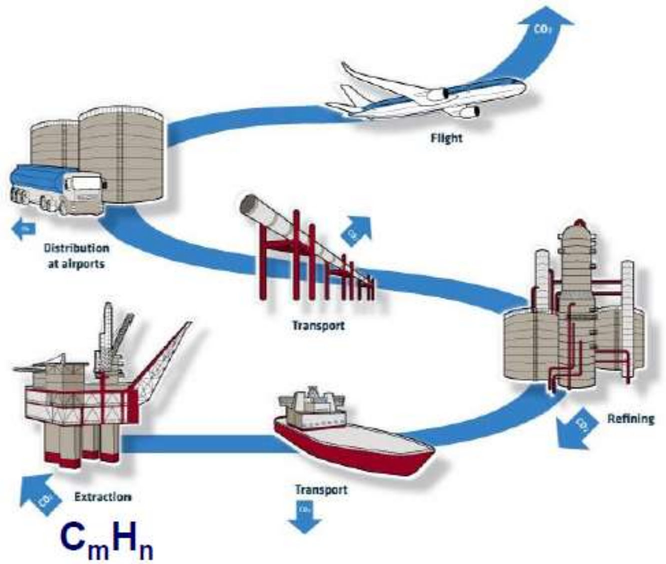
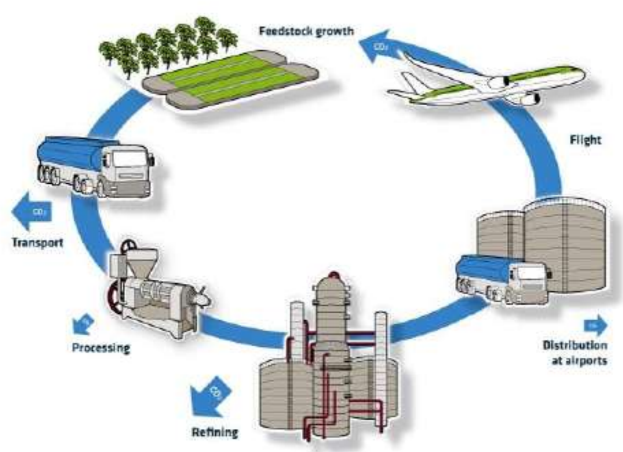
Achieving net Lifecycle GHG Reductions with SAF

Petroleum based Jet CO_2



Continuing to pull additional carbon from the ground and releasing it into the atmosphere as CO_2

Sustainable Aviation Fuel



Acquiring the majority of our carbon from the atmosphere, via biology or recycling, and turning it back into fuel

Result is a net reduction of additional GHG (CO_2) being introduced into our biosphere.

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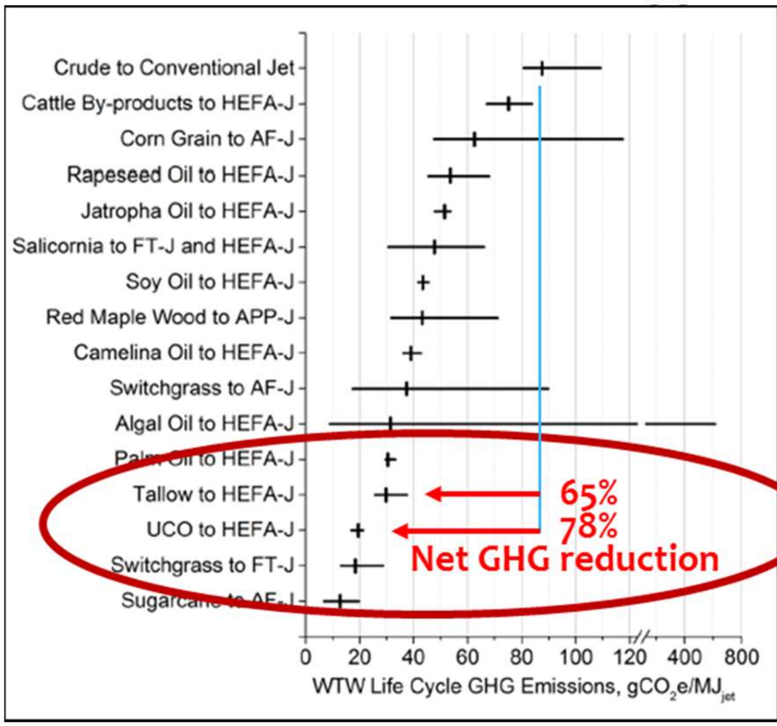
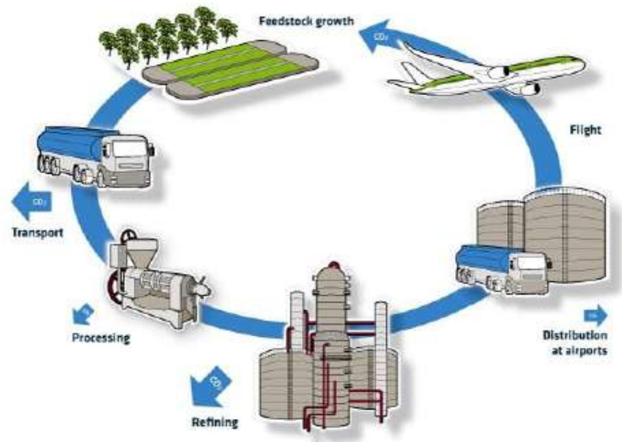
Achieving net Lifecycle GHG Reductions with SAF



Sustainable Aviation Fuel



Acquiring the majority of our carbon from the atmosphere, via biology or recycling, and turning it back into fuel

- **Policy rewards reductions >50%**
- **Many solutions in the 60-80% range**
- **Some solutions achieve >100% via carbon sequest'n or other emission reductions**

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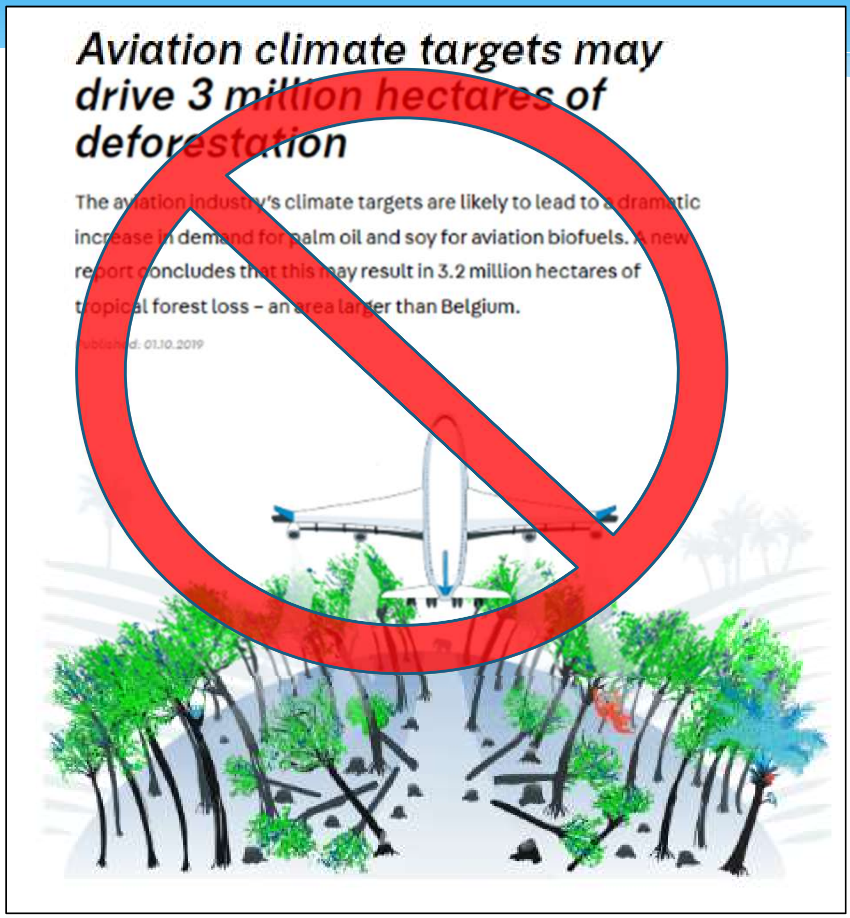
SAF Progress - technical

- SAF are becoming increasingly technically viable
  - Aviation now knows we can utilize numerous production pathways

    (7 approved, 6 in-process, >15 in pipeline)
  - Enabling use of all major sustainable feedstocks

    (lipids, sugars, lignocellulose, H & C sources)
  - Utilizing thermo-chemical and bio-chemical conversion processes to produce pure hydrocarbons, followed by standard refinery processes
  - Following blending, fuel is drop-in, indistinguishable from petro-jet
  - Some future pathways will produce blending components that will need less, or zero, blending
  - Expanding exploration of renewable crude co-processing with refineries
- Continuing streamlining of qualification and impacts – time, $, methods
- Challenge remaining is achieving production at reasonable cost

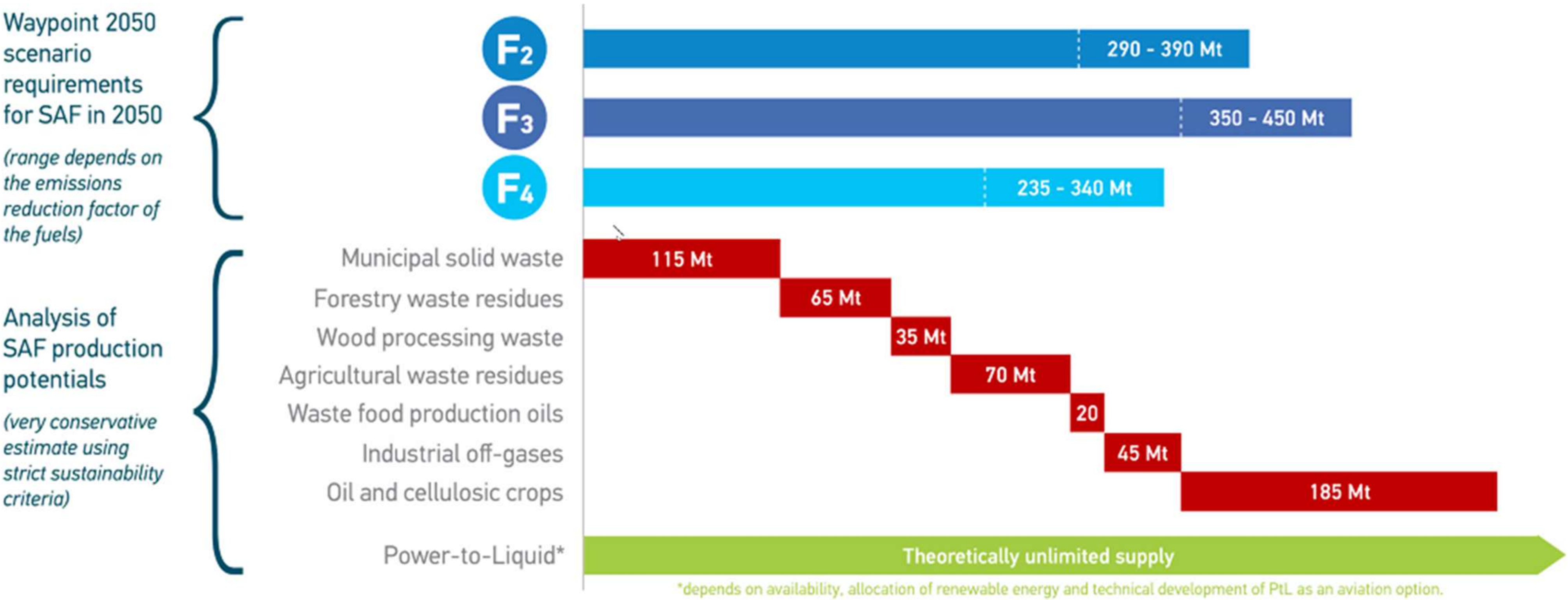
No single feedstock is targeted, nor sufficient



- Extrapolation of uniformed positions, sacrosanct beliefs and pet-peeves can lead to extraordinary theories and positions
- Aviation has embraced verifiable sustainability and standards, and has shunned some more controversial solutions

SAF production potential

Targets of opportunity that do not compete for food or land use change



Source: WEF Clean Skies for Tomorrow analysis with ATAG and IATA additions

www.aviationbenefits.org | 12

Aviation industry path to SAF evaluation and qualification – foundation of enabling specifications

* **ASTM D1655 - Standard Specification for Aviation Turbine Fuels**
  * **A1.1.2 …** Aviation turbine fuels with synthetic components produced in accordance with Specification D7566 meet the requirements of Specification D1655.
* **ASTM D4054 - Standard Practice for Qualification and Approval of New Aviation Turbine Fuels**
  * **1.1** This practice covers and provides a framework for the qualification and approval of new fuels and new fuel additives for use in commercial and military aviation gas turbine engines…
* **ASTM D7566 - Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons**
  * **1.2 …** Aviation turbine fuel manufactured, certified and released to all the requirements of this specification, meets the requirements of Specification D1655 and shall be regarded as Specification D1655 turbine fuel.

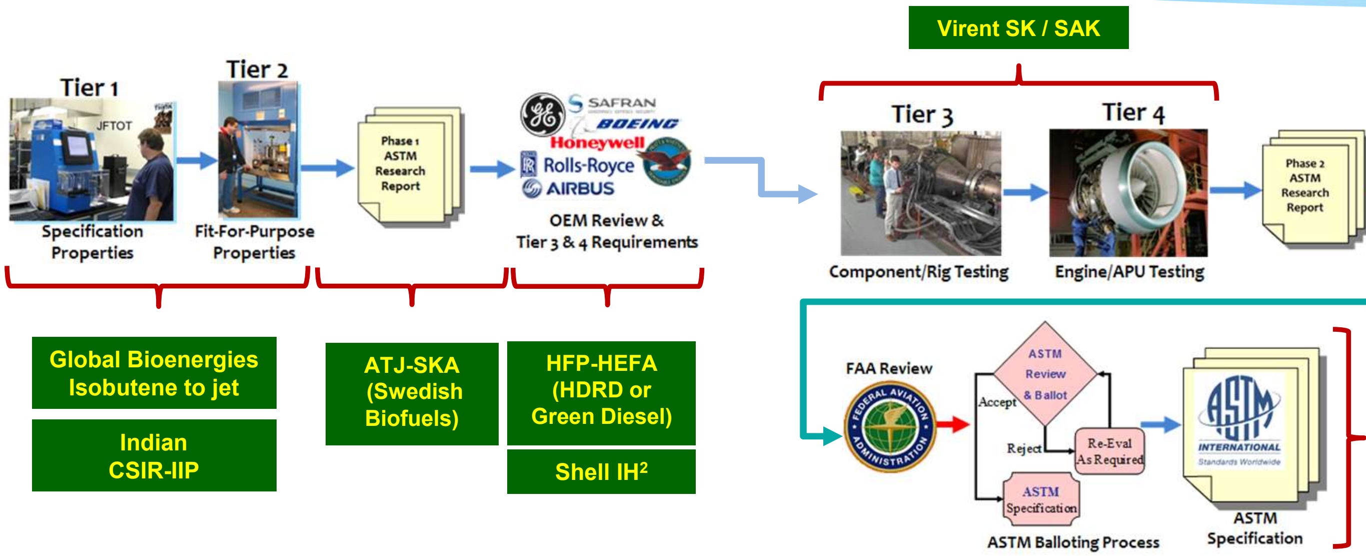
Progress on SAF production pathways

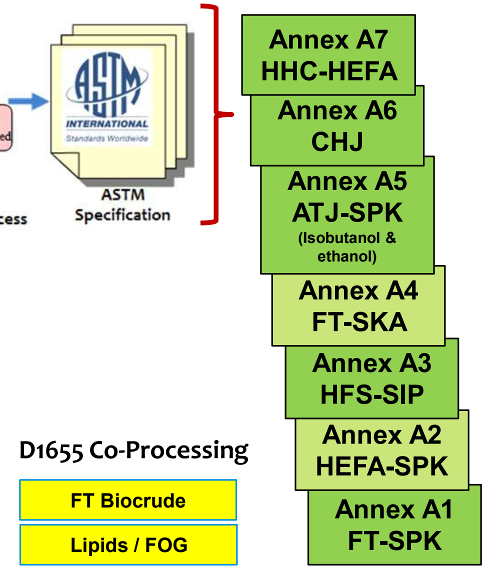
ASTM D7566 Annex	Technology Type	Process Feedstock	Process Feedstock Sources	Blend Requirement	Certification Date	Technology Developer*/ Licensor
A1	Fischer-Tropsch Synthetic Paraffinic Kerosene (**FT-SPK**)	Syngas (CO and H_2)	Gasified sources of carbon and hydrogen. Biomass such as municipal solid waste (MSW), agricultural and forest residues, wood and energy crops, as well as non-renewable feedstocks such as coal and natural gas.	Yes, 50% max	2009	****Sasol**, Shell, Velocys, Johson Mathey/BP, …
A2	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (**HEFA-SPK**)	Fatty Acids and Fatty Acid Esters	Various lipids that come from plant and animal fats, oils, and greases (FOGs): chicken fat, white grease, tallow, yellow grease, brown grease, purpose grown plant oils, algal oils, microbial oils.	Yes, 50% max	2011	**Honeywell UOP**, Neste, Haldor-Topsoe, UPM, …
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);	Yes, 10% max	2014	**Amyris**
A4	Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (**FT-SPK/A**)	Syngas	Same as A1	Yes, 50% max	2015	**Sasol**
A5	Alcohol to Jet Synthetic Paraffinic Kerosene (**ATJ-SPK**)	C2-C5 alcohols, (limited to ethanol and iso-butanol at present)	C2-C5 alcohols derived from direct and indirect sources of sugar (see A3), or those produced from microbial conversion of syngas	Yes, 50% max	2016	**Gevo, Lanzatech,** (others pending including Swedish Biofuels, Byogy, ...)
A6	Catalytic Hydrothermolysis Synthesized Kerosene (**CH-SK, or CHJ**)	Fats, Oils, Greases	Same as A2	Yes, 50% max	2020	**Applied Research Associates** (ARA) / CLG
A7	Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (**HHC-SPK**, or **HC-HEFA**)	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.	Yes, 10% max	2020	**IHI Corporation**

* The entity who was primarily responsible for pushing the technology through aviation's D4054 qualification is shown in bold.

** There are 3 major systems associated with FT conversion: Gasification, Gas Clean-up, and Fischer-Tropsch Reactor. This column focuses on the FT reactor only. There are over a hundred gasification entities in the world, and several of the major oil companies own and utilize gas clean-up technology. Further, up to the current time, FT reactors were only produced at very large scale. The unique technology brought to the market by Velocys *et al.* is a scaled-down, micro-channel reactor appropriately sized for processing of modest quantities of syngas as might be associated with a biorefinery.

ASTM D4054 Status
Technologies applicable to SAF – see ASTM D7566





- 7 approved pathways (D7566 Annexes)
- 6 in-process (dark green boxes)
- >15 in pipeline (e.g. REVO, OMV Re-Oil, Forge, Vertimas …)
- 2 refinery co-processing concepts

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Promising emerging technologies

- Those that lower cost or increase value
  - Lower CapEx
  - Lower OpEx – enabling use of low-cost, plentiful, 24x7 type feedstocks
  - Integrated systems
  - Finding higher value for production slip streams or byproducts
  - Capturing value from other environmental services
  - Driving to ultra low CI scores to increase value from rewarding policy
- Steady stream of low TRL examples for the above
- In some other cases (e.g. electrofuels), difficult to envision near-term tangible progress, rather mid-term

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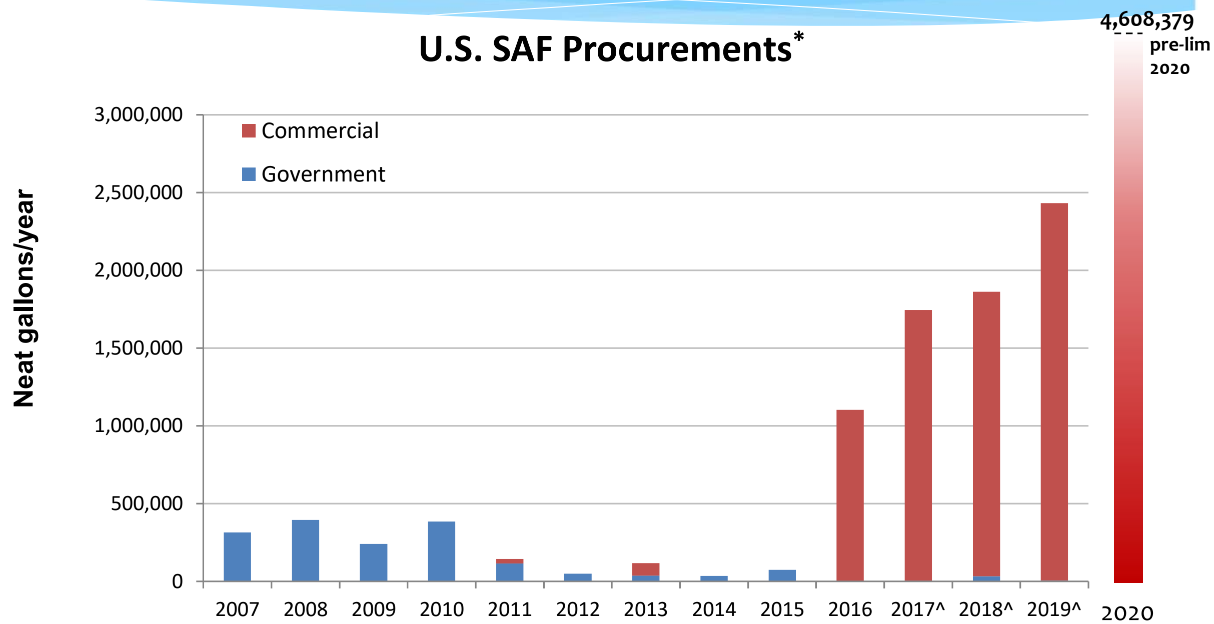
Where we stand on U.S. SAF consumption
Initiation under way, still early

- Four years of sustained commercial use
- Commercial & General Aviation engaged
- One+ facilities in operation
- Two facilities under construction, others in development
- Cost delta still a challenge, with renewable diesel favored policies
- In spite of that … we still have $6B in airline offtake commitments for >350M gpy … with more in development



Credit: FAA
*Reflects voluntarily reported data on use by U.S. airlines, U.S. government, manufacturers, other fuel users, and foreign carriers uplifting at U.S. airports.
^2017-2019 calculation includes reported EPA RFS2 RINs for jet fuel.

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Worldwide SAF production capacity forecast

Announced intentions – most supported by offtake agreements*

Year-end Production Capacity (M gpy)

2020
- World Energy – Paramount 25
- Neste – Porvoo 34
- Gevo – Silsbee, Demo quant's
- ~59+M

2021
- Fulcrum Bioenergy – #1, Sierra 7
- Red Rock Biofuels – Lakeview 6
- ~72+M

2022
- Neste – Singapore & Rotterdam 480
- SkyNRG Nordic – Delfzijl 33
- LanzaJet – Freedom Pines 10
- World Energy – Paramount 150
- ~746+M

2023
- Gevo – Luverne 10
- Go Sunshine (drive clean, save green) – New Orleans 29
- Fulcrum Bioenergy – #2, Gary, IN 21
- ReadiFuels – 2 locations 24
- ~830+M

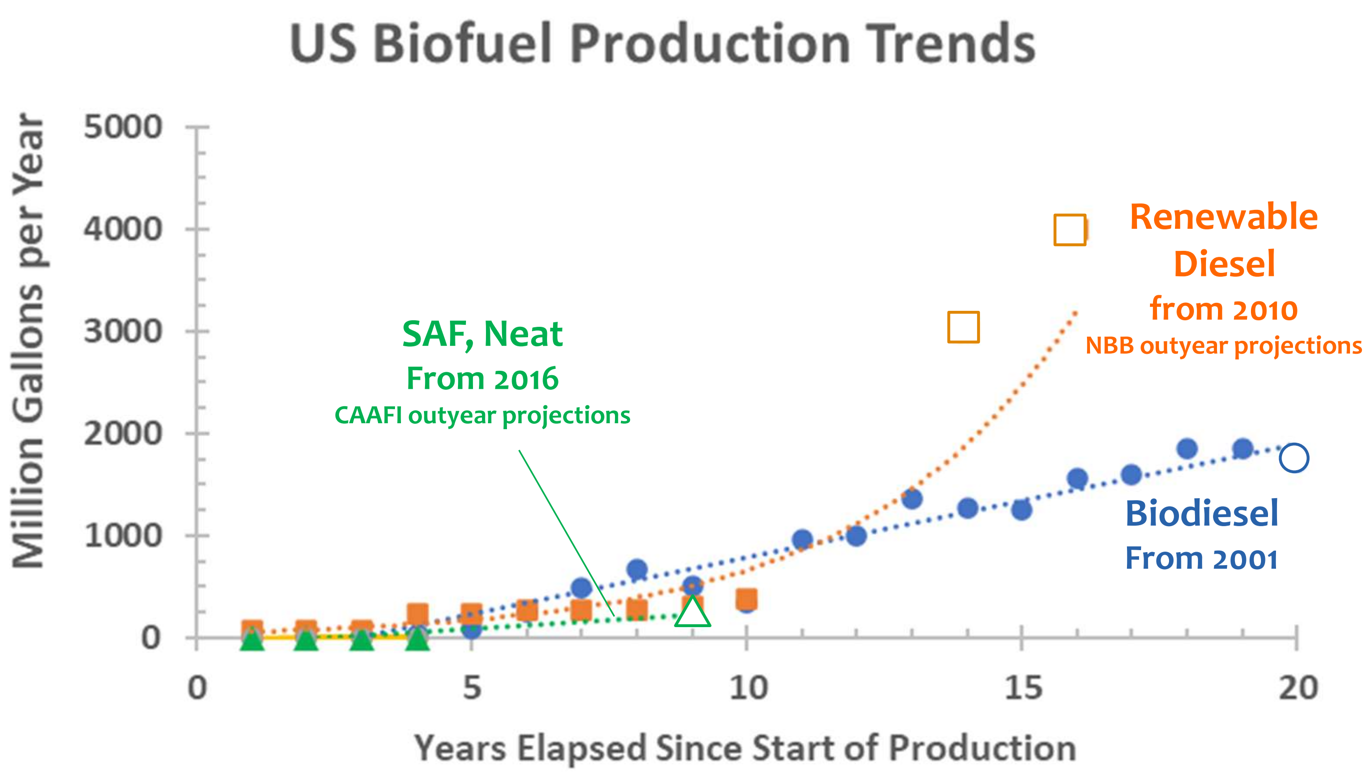
2024
- Phillips 66 – Rodeo 290?
- Total – Grandpuits 56
- Preem – Gothenburg ~70
- LanzaJet – 3 International locations 90
- ~990 – 1336 M

2025
- Velocys Altalto – Immingham, UK 16
- 1 B +

IATA reports as much as 1.9B gpy capacity (Waypoint 2050 analysis)

* Not comprehensive; CAAFI estimates (based on technology used & public reports) where production slates are not specified

Industry focus on enabling SAF affordability



* We know what impact policy had on the ramp-up of ethanol and bio-diesel / renewable diesel – it can be replicated for SAF

Summary – let's not lose site that:

- Aviation will continue to use jet fuel for decades
- 94+% of CO_2 comes from long-range and/or larger aircraft operations
  - Fuel / energy switching technologies are not applicable to these aircraft today
- Electrification/propulsion-switching TRL levels low beyond smallest applications
  - Power/Energy per unit mass and volume off by factor of 50 for larger aircraft
  - Limited experience with associated hardware
    - Motors, generators, inverters, higher-voltage conductors, switches, storage, control, thermal mgmt.,
- SAF can contribute to lower carbon aviation today, for any jet-powered flight
- SAF need H_2 for their manufacture, preferably low carbon H_2
- H_2 use for SAF sets stage for later expansion to other concepts, including mid-term PtL development
- You can build bridges to your technology development approaches by affirming the use of H_2 for SAF production which starts us on our aviation decarbonization journey

ASTM D7566 hydrogen needs

And use of low carbon hydrogen continues to lower SAF Carbon Index, increasing LCFS policy support value

ASTM D7566 Annex	Fuel Type	Descriptor (see D7566 Annexes A1-An, Paragraphs An.4, Material and Manufacture, for exact wording and requirements – summarized below)	Hydrogen Demand
A1	FT-SPK	Paraffins and olefins derived from synthesis gas via FT: Subsequent processing (hydrotreating, hydrocracking, or hydroisomerization) … and subsequent refinery processes	**From 0.2% to 14.0% of mass of feedstock:** sometimes coming from feedstock itself or process water
A2	HEFA-SPK	Paraffins derived from hydrogenation and deoxygenation of FAE and FFA: Subsequent processing (hydrocracking, or hydroisomerization) … and subsequent refinery processes	
A3	HFS-SIP	Hydroprocessed synthesized iso-paraffins derived from farnesene / fermentable sugars: Subsequent processing (Hydroprocessing and fractionation) … and subsequent refinery processes	
A4	FT-SPK/A	Same as A1 with addition of synthesized aromatics	
A5	ATJ-SPK	Hydroprocessed SPK derived from ethanol/isobutanol Processed through dehydration, oligomerization, hydrogenation and fractionation	
A6	CHJ	Comprised of hydroprocessed SKA from the HTL conversions of FAE and FFA Subsequent processing (hydrotreating, hydrocracking, or hydroisomerization) … and subsequent refinery processes	
A7	HHC-SPK HC-HEFA	Paraffins derived from hydrogenation and deoxygenation of FAE and FFA: Subsequent processing (hydrocracking, or hydroisomerization) … and subsequent refinery processes	

Find additional details in either ASTM D7566 or keep up to date at:
http://www.caafi.org/focus_areas/fuel_qualification.html

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Overall industry status of SAF:

* SAF are key for meeting industry's commitments – starting yesterday
* We're making progress, but still significant challenges – only modest production
* Focus on enabling commercial viability for which policy may play significant role
* Potential for acceleration a function of engagement, first facilities' success replication, additional technologies that continue to lower production cost, and preventing all governmental support from going to other tech. approaches
* Let's not allow a focus on less pragmatic options to distract from the fact that we need to be making progress today

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