Sustainable Aviation Fuel Progress Overview

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

Discover more about CAAFI at www.caafi.org
Commercial Aviation commitments on CO₂ reductions

GOAL 1: +1.5%/2.0% annual efficiency

Emissions trajectory if we were still operating at the same efficiency levels as in 1990

Through new technology, improved operational measures and more efficient infrastructure, the industry has avoided 8.5 billion tonnes of CO₂ since 1990

CORSIA

Savings already achieved

Where emissions would be if efficiency does not improve from today.

With constant efficiency improvement through the pillars of technology, operations and infrastructure.

With gradual introduction of radical new technologies and sustainable alternative fuels.

27 February 2021

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 CO₂ emissions come from medium- and long-range flights, and larger aircraft

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

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Flight Range Category (km)</th>
<th>Total Share CO₂ Emissions</th>
<th>Global Fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter &lt;19</td>
<td>0-500</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
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<tr>
<td></td>
<td>501-1000</td>
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<td>1001-2000</td>
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<td>2001-3000</td>
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<td>3001-4500</td>
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<td></td>
<td>&gt;4500</td>
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<tr>
<td>Regional 20-80</td>
<td>1.2%</td>
<td>3%</td>
<td>13%</td>
</tr>
<tr>
<td>Short Range 81-165</td>
<td>1.6%</td>
<td>24%</td>
<td>53%</td>
</tr>
<tr>
<td>Med. Range 166-250</td>
<td>1.1%</td>
<td>43%</td>
<td>18%</td>
</tr>
<tr>
<td>Long Range &gt;250</td>
<td>0.1%</td>
<td>30%</td>
<td>12%</td>
</tr>
<tr>
<td>Total</td>
<td>~4.5%</td>
<td>~12.4%</td>
<td>~25.6%</td>
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<tr>
<td></td>
<td>~25.6%</td>
<td>~14.1%</td>
<td>~10.7%</td>
</tr>
<tr>
<td></td>
<td>~14.1%</td>
<td>~10.7%</td>
<td>~32.7%</td>
</tr>
</tbody>
</table>

Source: World Economic Forum – Mission Possible Platform, DiioMi
Jet fuel usage will continue …
Through several decades, with tomorrow’s technology

2005 2010 2020 2030 2040 2050

Aircraft model intros “2015-2022”
- E-Jet E2, MRJ, A220
- ARJ-21, C919, MC-21
- 737 Max, A320 Neo
- 787 FBO, A330 Neo
- A350 FBO
- 777-X

Business as usual
“Radical New Technologies”
& SAF

15 year min production runs
20 year min useful service life following EIS

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

27 February 2021
**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 CO2 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
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)
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 C<sub>7</sub>-C<sub>17</sub>, which is typically a mixture of:
  - ~25% / 11% normal / branched paraffins
  - ~30% / 12% / 1% mono- / di- / tri-cycloparaffins
  - ~16 / 5% mono- / di-nuclear aromatics
    (25% max aromatics – air quality concern)

* A Gaussian distribution of hydrocarbons, represented as C<sub>12</sub>H<sub>23</sub>

There is no standard “formula” for jet fuel

* Composition that delivers the physical properties and performance-based requirements / characteristics of ASTM D1655 specification
How is SAF made?

1. **Feedstocks** (source of H & C)
   - Lipids
   - Lignocellulose
   - Starches / Sugars
   - Waste streams
   - Circular economy byproducts

2. **Conversion Processes**
   - Biochemical (microbes, e.g. fermentation)
   - Thermochemical (heat, pressure, catalysts)

3. **Refinery Processes**
   - Hydrotreatment
   - Hydrocracking
   - Hydroisomerization
   - Distillation

4. **SAF Blending Agents:**
   - ASTM D7566 Annex A1 - Ax

5. **SAF Blending Agent**
   - ASTM D7566 Annex A1 - Ax

6. **Blending Tank**
   - ASTM BLEND CERTIFIED AS BEING ASTM D7566 & D1655 COMPLIANT (CoA);
     THEN RE-IDENTIFIED AS ASTM D1655

*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.*
Achieving net Lifecycle GHG Reductions with SAF

Result is a net reduction of additional GHG (CO₂) being introduced into our biosphere.

Continuing to pull additional carbon from the ground and releasing it into the atmosphere as CO₂

Acquiring the majority of our carbon from the atmosphere, via biology or recycling, and turning it back into fuel.
Achieving net Lifecycle GHG Reductions with SAF

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

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

Waypoint 2050 scenario requirements for SAF in 2050
(range depends on the emissions reduction factor of the fuels)

Analysis of SAF production potentials
(very conservative estimate using strict sustainability criteria)

- Municipal solid waste
- Forestry waste residues
- Wood processing waste
- Agricultural waste residues
- Waste food production oils
- Industrial off-gases
- Oil and cellulosic crops
- Power-to-Liquid*

Theoretically unlimited supply
*depends on availability, allocation of renewable energy and technical development of PTL as an aviation option.

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

<table>
<thead>
<tr>
<th>ASTM D7566 Annex</th>
<th>Technology Type</th>
<th>Process Feedstock</th>
<th>Process Feedstock Sources</th>
<th>Blend Requirement</th>
<th>Certification Date</th>
<th>Technology Developer*/Licensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)</td>
<td>Syngas (CO and H₂)</td>
<td>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.</td>
<td>Yes, 50% max</td>
<td>2009</td>
<td><strong>Sasol, Shell, Velocys, Johnson Mathey/BP, …</strong></td>
</tr>
<tr>
<td>A2</td>
<td>Hydropyrolyzed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)</td>
<td>Fatty Acids and Fatty Acid Esters</td>
<td>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.</td>
<td>Yes, 50% max</td>
<td>2011</td>
<td>Honeywell UOP, Neste, Haldor-Topsoe, UPM, …</td>
</tr>
<tr>
<td>A3</td>
<td>Hydropyrolyzed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)</td>
<td>Sugars</td>
<td>Sugars from direct (cane, sweet sorghum, sugar beets, tubers, field corn) and indirect sources (C5 and C6 sugars hydrolyzed from cellulose);</td>
<td>Yes, 10% max</td>
<td>2014</td>
<td>Amyris</td>
</tr>
<tr>
<td>A4</td>
<td>Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)</td>
<td>Syngas</td>
<td>Same as A1</td>
<td>Yes, 50% max</td>
<td>2015</td>
<td>Sasol</td>
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<tr>
<td>A5</td>
<td>Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)</td>
<td>C2-C5 alcohols, (limited to ethanol and iso-butanol at present)</td>
<td>C2-C5 alcohols derived from direct and indirect sources of sugar (see A3), or those produced from microbial conversion of syngas</td>
<td>Yes, 50% max</td>
<td>2016</td>
<td>Gevo, Lanzatech, (others pending including Swedish Biofuels, Byogy, …)</td>
</tr>
<tr>
<td>A6</td>
<td>Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)</td>
<td>Fats, Oils, Greases</td>
<td>Same as A2</td>
<td>Yes, 50% max</td>
<td>2020</td>
<td>Applied Research Associates (ARA) / CLG</td>
</tr>
<tr>
<td>A7</td>
<td>Hydropyrolyzed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HH-SPK, or HC-HEFA)</td>
<td>Algal Oils</td>
<td>Specifically, bio-derived hydrocarbons, fatty acid esters, and free fatty acids. Recognized sources at present only include the terpenes produced by the Botryococcus braunii species of algae.</td>
<td>Yes, 10% max</td>
<td>2020</td>
<td>IHI Corporation</td>
</tr>
</tbody>
</table>

* 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
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
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.
### Worldwide SAF production capacity forecast

**Announced intentions – most supported by offtake agreements**

<table>
<thead>
<tr>
<th>Year-end Production Capacity (M gpy)</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paramount</td>
<td>~59+M</td>
<td>~72+M</td>
<td>~746+M</td>
<td>~830+M</td>
<td>~990–1336 M</td>
<td>1 B +</td>
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<tr>
<td>Gevo Silsbee Demo quant’s</td>
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<tr>
<td>Fulcrum Bioenergy</td>
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<tr>
<td>SkyNRG Nordic</td>
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<tr>
<td>LanzaJet Freedom Pines</td>
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<tr>
<td>LanzaJet 3 International locations</td>
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<tr>
<td>IATA reports as much as 1.9B gpy capacity (Waypoint 2050 analysis)</td>
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</tbody>
</table>

*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 biodiesel / 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 CO2 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 H2 for their manufacture, preferably low carbon H2
- H2 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 H2 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

<table>
<thead>
<tr>
<th>Annex</th>
<th>Fuel Type</th>
<th>Description</th>
<th>Hydrogen Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>FT-SPK</td>
<td>Paraffins and olefins derived from synthesis gas via FT: Subsequent processing (hydrotreating, hydrocracking, or hydroisomerization) ... and subsequent refinery processes</td>
<td>From 0.2% to 14.0% of mass of feedstock: sometimes coming from feedstock itself or process water</td>
</tr>
<tr>
<td>A2</td>
<td>HEFA-SPK</td>
<td>Paraffins derived from hydrogenation and deoxygenation of FAE and FFA: Subsequent processing (hydrocracking, or hydroisomerization) ... and subsequent refinery processes</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>HFS-SIP</td>
<td>Hydroprocessed synthesized iso-paraffins derived from farnesene / fermentable sugars: Subsequent processing (hydroprocessing and fractionation) ... and subsequent refinery processes</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>FT-SPK/A</td>
<td>Same as A1 with addition of synthesized aromatics</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>ATJ-SPK</td>
<td>Hydroprocessed SPK derived from ethanol/isobutanol Processed through dehydration, oligomerization, hydrogenation and fractionation</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>CHJ</td>
<td>Comprised of hydroprocessed SKA from the HTL conversions of FAE and FFA Subsequent processing (hydrotreating, hydrocracking, or hydroisomerization) ... and subsequent refinery processes</td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>HHC-SPK</td>
<td>Paraffins derived from hydrogenation and deoxygenation of FAE and FFA: Subsequent processing (hydrocracking, or hydroisomerization) ... and subsequent refinery processes</td>
<td></td>
</tr>
</tbody>
</table>

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