SAF Commercialization Update

GREAT PLAINS INSTITUTE | Better Energy. Better World.

September Hydrogen Economy Collaboration Meeting
Virtual, 11Sep'25

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COMMERCIAL AVIATION ALTERNATIVE FUELS INITIATIVE

First flight from continuous commercial production of SAF

UAL 0708, 10 March 2016, LAX-SFO

Fuel from World Energy - Paramount (HEFA-SPK 30/70 Blend).

23 April 2025

Overall industry summary on SAF:
SAF are key for meeting industry's commitments on carbon reductions

- Aviation enterprise aligned, representing a 26B+ gpy US & 100B+ gpy worldwide opt'y
  - Jet fuel demand expected to increase for foreseeable future ... 3 - 5% per year
- SAF delivers net GHG reductions of 65-100+%, other enviro services, available today
  - Allows decarbonization to commence while other technologies mature at appropriate paces
- Segment knows how to make it; Activities from FRL 1 to 9, with many in "pipeline"
  - First facilities on-line (biorefineries and co-processing), increasing run-rates, multiple offtakers
  - Numerous commercial agreements being pursued, fostered by policy and other unique approaches
- Pathways identified for fully synthetic SAF (50% max blend today), enhancing SAF value proposition by enabling deeper net-carbon reductions
- Additional work needed on "appropriate conversion process for targeted feedstocks" enabling affordability
- SAF costs are higher than petro-jet - Can policy (or buyer signals) close the gap to enable sufficient progress?

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Overall industry summary on H_2 for SAF:

H_2 is key for SAF production; Other wide-scale aviation use debateable

- Every SAF pathway approved to date requires the use of H_2 for 'fuel finishing'
  - In stand-alone facilities, most from SMR of NG
  - In existing refineries, from facility integration and/or excess hydogen
  - Use of RNG can be attractive for policy support tied to CI reductions
- Higher utilization probable with advances in MTJ from sustainable sources
  - E-fuels require significant amounts of H_2 ($C_{11}H_{23}$ aggregate fuel composition). Issue with e-fuels is their significantly higher production cost, versus other biofuels.
- Use of H_2 as the primary fuel for future, mainline aircraft is fraught with challenge, and is presently waning in favor of traditional or hybrid configurations for next-gen designs
  - Challenges: Volume (system weight and drag), cost, ubiquitous renewable energy production, additional significant power required for liquefaction, lack of post-production and airport refueling infrastructure, storage, combustion vs fuel cell, aerospace materials compatibility, …

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	
A8	ATJ-SKA	Hydroprocessed SPK derived from C2-C5 alcohols Processed through dehydration, oligomerization, hydrogenation and fractionation, with aromatics from dehydration, aromatization, hydrogenation, and fractionation	

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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SAF is projected to be critical to meeting Aviation Climate Goals through and beyond 2050

	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-50 seats » <60 minute flights » <1% of industry CO_2	SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO_2	SAF	SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF
Short-haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO_2	SAF	SAF	SAF	SAF	Electric, hydrogen combustion and/or SAF	Electric, hydrogen combustion and/or SAF	Electric, hydrogen combustion and/or SAF
Medium-haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen
Long-haul » 250+ seats » 150 minute + flights » ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Ref: ATAG – Waypoint 2050 Report

"SAF &" remains our primary means of decarbonizing aviation

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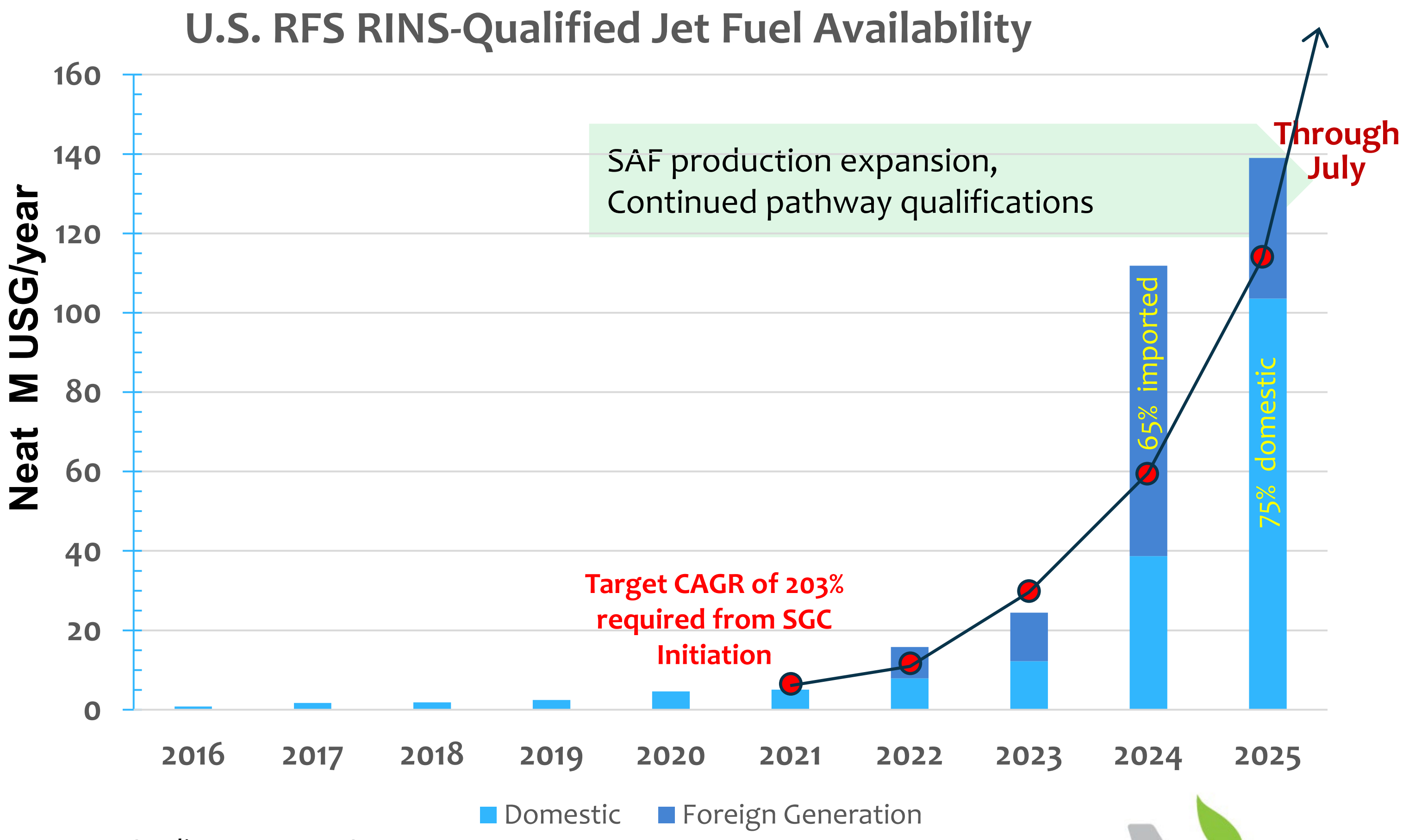
Where we stand on U.S. neat SAF consumption
Expansion underway, still early

- **Surpassed 9 years of sustained commercial production and use**
- **Commercial, BizAv, Corporates engaged; U.S.G. fostering R&D**
- **Facilities in com'l operation & upgrading, others in physical construction or commissioning**
- **Cost delta still a challenge, with practicalities favoring renewable diesel, policies transient**
- **Worldwide: IATA expects 2 M tonnes production in 2025** (660 M usg, representing 0.7% of airline usage)



Credit: FAA, EPA, CAAFI
2016-2025: Reflects EPA Reported RINS Data (as of 22Apr'25 summary)

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U.S. SAF production capability forecast

Announced intentions, neat*

Est. Year-end Production (M gpy)

Current: ~39 M

By YE '25 — ~508 M
- LanzaJet Freedom Pines 10
- Phillips 66 Rodeo 150
- Diamond Green Diesel Port Arthur 235
- Par Hawaii Honolulu 36
- New Rise Renewables Reno 38

2026 — ~688 M
- Montana Renewables Great Falls' +120
- gevo ATJ-60 SD 60

2027 — ~1.53B
- New Rise Renewables Reno 2 40
- World Energy Paramount B +230
- Montana Renewables Great Falls'' +150
- Summit Agricultural Group (A Principled Approach.) Houston 250
- USA BioEnergy (Renewable Energy Solutions) Bon Wier, TX 53
- LanzaJet Hennepin 120

2028 — ~2.02 B
- New Rise Renewables FL & NC 80
- Aemetis Carbon Zero #1 Riverbank 45
- World Energy Houston 250
- DG Fuels St. James, LA 120

2029 — ~2.23 B
- Aemetis Carbon Zero Riverbank+ 44
- Green Plains / Tallgrass Blue Blade Energy Tbd, Midwest 135
- SkyNRG Americas NW #1 30

2030 — ~2.35 B
- DG Fuels Nebraska 120

SAFGC 3.0 B

Exact Timing & Production tbd

Unannounced or In-development efforts:
- ~200 additional new-entrants collaborating with CAAFI
- Outlined expansion goals of existing/pending producers
- Refinery co-processing / conversion
- Renewable Diesel switching resulting from policy shifts

- Not comprehensive; CAAFI estimates (based on technology used & public reports) where production slates are not specified. Does not include various small batches produced for testing technology and markets. New companies engaging at about 2-3 per month
- Does not include fractions of substantial Renewable Diesel capacity (existing and in-development) that can be shunted to SAF based on policy support
- Similar dataset from Argus suggests about 3.4 B gpy from 29 U.S. facilities by YE 2030

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SAF Progress - technical

- SAF are becoming increasingly technically viable
  - Aviation now knows we can utilize numerous production pathways: biochemical, thermochemical, combined bio-thermos:

    8 D7566 pathways, 12 in process – more in ‘pipeline’

    3 D1655 pathways (co-processing), 4 in-process
- Challenge remaining is achieving reasonable cost and expanding production
  - Exploring expanded use of all major sustainable feedstocks
    - Fats, oils, and greases; sugars & starches; recalcitrant lignocellulose
    - Newer crops associated with improved farming practices (covers, rotations, intercropping)
  - Additional focus on 24x7, aggregated, low-cost types to enable affordability and capitalization
    - Circular economy byproducts
    - ‘Waste streams’ – anything with a disposal cost
      - Food processing
      - Industrial processes

What's next? (ASTM D4054)

Early data & discussions

Tier 1 & 2

OEM review

Tier 3 & 4

OEM & regulatory agency review

ASTM balloting

Qualification

ATJ-SAK
(Vertimass)
ATJ
(UFT)
HBTJ
(Visolis)
…

PTJ-SKA
(OMV)
MTJ
(multiple entities)
Tall Oil SAF
(UPM)
CycloSAF
(CleanJoule)
SBTJ
(Firefly)
TBD
(REVO)

HEFA-SKA
(CSIR-IIP)

CPK-0
(Shell)

HDO-SAK
(Marathon)

ASTM D7566

A1: FT-SPK
A2: HEFA-SPK
A3: SIP
A4: FT-SKA
A5: ATJ-SPK
A6: CHJ
A7: HHC-HEFA
A8: ATJ-SKA

Acronyms:

ATJ-SKA:	Alcohol-to-Jet Synthetic Kerosene with Aromatics
ATJ-SPK:	Alcohol-to-Jet Synthetic Paraffinic Kerosene
CHJ:	Catalytic Hydrothermolysis Jet
CPK-0:	Cycloparaffinic Kerosene
FT-SKA:	Fischer-Tropsch Synthetic Kerosene with Aromatics
FT-SPK:	Fischer-Tropsch Synthetic Paraffinic Kerosene
HBTJ:	Hybrid Bio-Thermocatalytic Jet
HDO-SAK:	Hydro-deoxygenation Synthetic Aromatic Kerosene
HEFA-SKA:	Hydro-processed Esters and Fatty Acids Synthetic Kerosene with Aromatics
HEFA-SPK:	Hydro-processed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HHC-HEFA:	Hydroprocessed Hydrocarbons, Esters and Fatty Acids
MTJ:	Methanol-to-Jet
PTJ-SKA:	Plastics-to-Jet Synthetic Kerosene with Aromatics
SATF:	Synthetic Aviation Turbine Fuel
SBC:	Synthetic Blending Component
SBTJ:	Sewage Biosolids to Jet
SIP:	Synthetic Iso-paraffins

100% SATF Task Forces

100% Drop-in: Qual of pathways good for drop-in; also allow blends of SBCs

100% non-Drop-in: Standardization only; for testing/certification

ASTM D1655 co-processing of alternate crude with petro-crude

Lipids

Fischer-Tropsch

Hydroprocessed biomass

ASTM Task Force to increase current lipids blend

ASTM Task Force for pyrolysis oil from used tires

ASTM Task Force for waste plastics

Gurhan Andac, GE Aerospace, ASTM D02.J06 Chair

Meeting the U.S. SAF Grand Challenge

Goal: 3B gpy U.S. domestic production by 2030

- Likely 3 primary contributors in 6 yr timeframe remaining
  - Continued development of F.O.G. supply & conversion
  - Low CI ethanol and ATJ
    - Leveraging 17.5+B gpy truncated capacity, currently under perceived threat
    - Likely dependent on policy - specificity and duration
  - Refinery integration
    - Co-processing, MTJ, new biocrude and hub & spoke bio-intermediate concepts
    - Moving forward under EU mandates
- Beyond 2030: new pathways, higher blends, cost reductions

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Co-Processing

* Might use of Co-Processing significantly accelerate the production and expansion of synthetic aviation turbine fuel with suitable characteristics meeting sustainability policy?
  * Significant scale with lower CapEx?
  * Multiple introduction points in the refinery
  * Hub & Spoke conversion of recalcitrant biomass enabling quick energy densification, minimizing cost and CI
  * Source of petro-jet readily available for blending
  * Leverage current outgoing supply chain
  * Expectation of changes to refineries of the future - incorporating renewable crudes

SAF Progress: Headwinds and Tailwinds

- Actively working to ascertain Administration support and alignment
  - Mixed Agency views, amidst staffing and funding curtailments, redirections
  - Potential for new SAF-dedicated MOU uncertain
  - Await further congressional actions & budget reconciliation
- U.S. Airlines facing difficult year – bookings well off expectations – annual restatements
  - Potentially dampening SAF engagement, investments, and offtakes
- BizAv still a bright spot – e.g. Avfuel now delivering SAF blends to 35 airports
- State policy development & support continuing
- New producers continue emerging
- Research interest still robust
- Perhaps several years of low-profile development work in store

EPA: 5 New SRE Petitions Filed, 161 SRE Petitions Currently Pending

APRIL 10, 2025

Senators Marshall and Klobuchar Lead Bipartisan, Bicameral Legislation Fighting for Farmers with Biofuel Tax Credit

Forbes

BREAKING

4 Major U.S. Airlines Just Cut Their Forecasts—Citing Dip In Consumer Confidence And Economic Uncertainty

Suzanne Rowan Kelleher Forbes Staff

Suzanne Rowan Kelleher covers travel for Forbes.

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Lipid multi-generational product plan (MGPP)
Addressing the perceived shortfall of available lipids from FOGs

1) **Waste lipids (getting to ‘entitlement levels’ of capture & aggregation)**
   * Tallows, white grease, chicken fat, yellow grease, brown grease, …
2) **Industrial effluents and byproducts**
   * Tall oil, food processing oils (seafood processing), PFAD, culled veg./nut oils,
3) **Existing oilseed / row crop expansion (building-in aspects of improved sustainability)**
   * Rapeseed, canola, soy, sunflower, DCO, hemp seeds, …
4) **New oilseed / row crops (with mitigated LUC/ILUC, e.g. intermediate oil crops or “winter cover crops”)**
   * Winter canola, camelina, carinata, pennycress, other dual use crops
5) **Tree / bush oils (seed or leaf (eucalyptus) extraction)**
   * Pongamia, coconut, hazelnut, jatropha (prevalent in tropics and subtropics; India reports 400 species, 7-10 of focus)
   * Palm [noting that not all palm (e.g. macauba) is the same as that associated with the African Oil Palm issues of SE Asia]
6) **Conversion of lignin post-hydrolysis**
7) **Engineered oil excrescence in biomass itself**
   * E.g. the work of ARPA-E PETRO (similar to crushing sugarcane or sugar beets to release a sugary juice, the crush of a modified tobacco or energy grass could produce a lipid stream)
8) **Advanced microbial conversion of lignocellulose**
   * Acetogens, oleaginous yeasts, cyanobacteria, fungal, methanogens…
9) **Algae – micro, macro,**
   * Bio-derived triglycerides, perhaps full algal cell conversion, and pure hydrocarbons (e.g. *Botryococcus braunii)*

Trump Administration SAF alignments

Consistent with multiple elements outlined in the following EO's & subsequent memos addressing biofuels

14154 - Unleashing American Energy

14156 - Declaring a National Energy Emergency

14213 - Establishing the National Energy Dominance Council

14225 - Immediate Expansion of American Timber Production

23Jul'25 Fact Sheet on Japan Trade Agreement $8B purchase including SAF

… regarding the U.S. need for a:

"… reliable, diversified, and affordable supply of energy to drive our Nation's manufacturing, transportation, agriculture, and defense industries, and to sustain the basics of modern life and military preparedness", and;

"Moreover, the United States has the potential to use its unrealized energy resources domestically, and to sell to international allies and partners a reliable, diversified, and affordable supply of energy. This would create jobs and economic prosperity for Americans forgotten in the present economy, improve the United States' trade balance, help our country compete with hostile foreign powers, strengthen relations with allies and partners, and support international peace and security."

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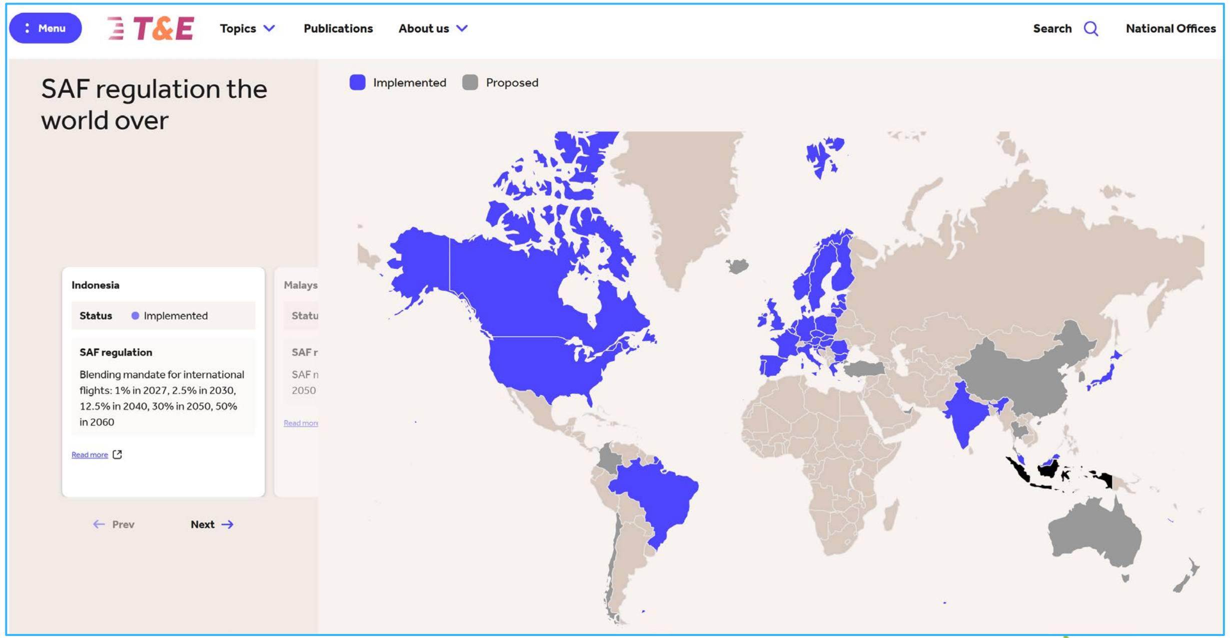
Drivers: Strong & Expanding

- **Avoidance of adverse industry-emission-spotlighting due expected continuous aviation growth trend**
  - IATA goals – NZE by 2050 (majority of reduction, and likely to increase, is reliant of SAF)
  - Airlines own individual commitments (e.g. NZE op’s by 2040-2070)
- **Policy**
  - CORSIA: 129 State voluntary participation at present; compulsory from 2027;
    - LTAG & stringency development likely to continue
  - Mandates on SAF usage multiplying in line with CORSIA ambitions (-5% by 2030)
    - Implemented in: Indonesia, Malaysia, Cyprus, India, EU, Brazil, Norway, Canada, Japan
    - Developing/Proposed in: Chile, China, S. Korea, UAE, Turkey, Lichtenstein, Thailand, Columbia, Australia, Iceland, Singapore, New Zealand
- **Aviation-reliant industries addressing predominance of jet fuel in their carbon footprints, demanding solutions**

https://www.transportenvironment.org/topics/planes/saf-observatory/saf-around-the-world



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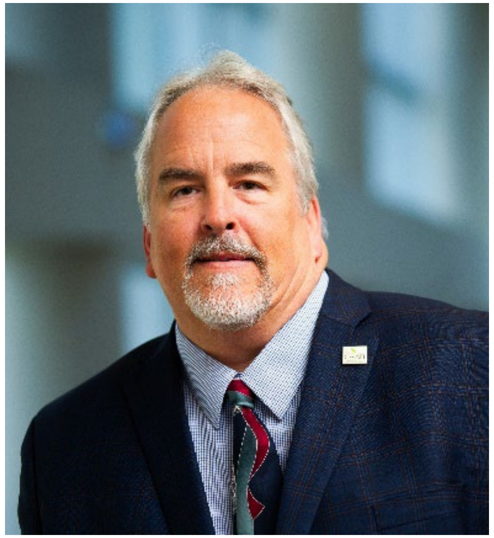

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Enablers

* Policy Support: RDD&D, subsidies, capital
  * Continued interest to wean-off petroleum in many countries
  * Support driven by recognition of value to economy where feedstocks are prevalent
* Proliferation of enabling organizations/frameworks: industry, academia, PPPs
  * Sustainability protocols, SAF registries, Book & Claim systems, Regional Initiatives, …
* Continued technical breakthroughs & addition of pathways
* Engagement of oil majors on issues like co-processing and refinery of the future
* Continued removal of technical barriers (blending reqs., distribution)
* Reductions in criteria pollutants from use of SAF
* Bioeconomy Transition offers solutions to difficult challenges
  * E.g. year round land coverage, nutrient management, blighted citrus, marginal land restoration, biodiversity, pollinator habitat, farm income, …

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