Sustainable Aviation Fuels: Marketplace Overview

Steve Csonka
Executive Director, CAAFI

First flight from continuous commercial production of SAF, 10Mar'16: Fuel from World Energy – Paramount, CA

UTAgResearch
INSTITUTE OF AGRICULTURE
THE UNIVERSITY OF TENNESSEE

ASCENT
AVIATION SUSTAINABILITY CENTER

Developing an Action Plan for the Southeast
Knoxville, TN, 24-25Apr'19

CAAFI®
COMMERCIAL AVIATION ALTERNATIVE FUELS INITIATIVE

24Apr'19

SAF – What is it, what's different, why now, why here?

* Aviation pull
* Other vested interests
* Policy is partially enabling
* CORSIA coming
* Societal interest coalescing around resiliency and sustainability, even if not yet around GHG and GWP
* Commercialization commencing – but not a linear process
* Opportunities for the Southeast
* FAA fostering improvements to the environmental performance of aviation through ASCENT, CLEEN II, and CAAFI

Aviation takes its environmental responsibility seriously …

Industry commitments in 2009, 2012, 2015

Aviation Industry Commitment to Action on Climate Change

As leaders of the aviation industry, we recognise our environmental responsibilities and agree on the need to:

- build on the strong track record of technological progress and innovation that has made our industry the safest and most efficient transport mode; and
- accelerate action to mitigate our environmental impact, especially in respect to climate change while preserving our driving role in the sustainable development of our global society.

Therefore, we, the undersigned aviation industry companies and organisations declare that we are committed to a pathway to carbon-neutral growth and aspire to a carbon-free future.

To this end, in line with the four-pillar strategy unanimously endorsed at the 2007 ICAO Assembly, we will:

1. push forward the development and implementation of new technologies, including cleaner fuels;
2. further optimise the fuel efficiency of our fleet and the way we fly aircraft and manage ground operations;
3. improve air routes, air traffic management and airport infrastructure; and
4. implement positive economic instruments to achieve greenhouse gas reductions wherever they are cost-effective.

We urge all governments to participate in these efforts by:

1. supporting and co-financing appropriate research and development in the pursuit of greener technological breakthroughs;
2. taking urgent measures to improve airspace design including civil/military allocation, air traffic management infrastructure and procedures for approving needed airport development; and
3. developing and implementing a global, equitable and stable emissions management framework for aviation through ICAO, in line with the United Nations roadmap agreed in Bali in December 2007.

Our efforts and commitment to work in partnership with governments, other industries and representatives of civil society will provide meaningful benefits on tackling climate change and other environmental challenges.

We strongly encourage others to join us in this endeavour.

Robert J. Aaronson, Director General — James C. Cherry, Chairman
Alexander ter Kuile, Secretary General — Ashley Smout, Chairman
Giovanni Bisignani, Director General & CEO — Fernando Pinto, Chairman
Marion C. Blakey, Chair — Takatoshi Hosoya, Vice Chair
Thomas Enders, President & CEO
Scott Carson, President & CEO
Steve Ridolfi, President, Regional Aircraft
Eric Bachelet, CEO
Frederico Fleury Curado, President & CEO
Scott C. Donnelly, President & CEO, GE Aviation
Stephen Finger, President
Mark King, President, Civil Aerospace
Philippe Rochat, Executive Director

3rd Aviation & Environment Summit, 22nd April 2008, Geneva, Switzerland

Aviation Industry Commitment to Action on Climate Change: 3 Goal Approach

GOAL 1

PRE-2020 AMBITION

1.5% ANNUAL AVERAGE FUEL EFFICIENCY IMPROVEMENT FROM 2009 TO 2020.

T O I

GOAL 2

IN LINE WITH THE NEXT UNFCCC COMMITMENT PERIOD

STABILISE NET AVIATION CO_2 EMISSIONS AT 2020 LEVELS WITH CARBON-NEUTRAL GROWTH.

T O I +M

GOAL 3

ON THE 2°C PATHWAY

REDUCE AVIATION'S NET CO_2 EMISSIONS TO 50% OF WHAT THEY WERE IN 2005, BY 2050.

T O I

Four Pillars of the Commitment:

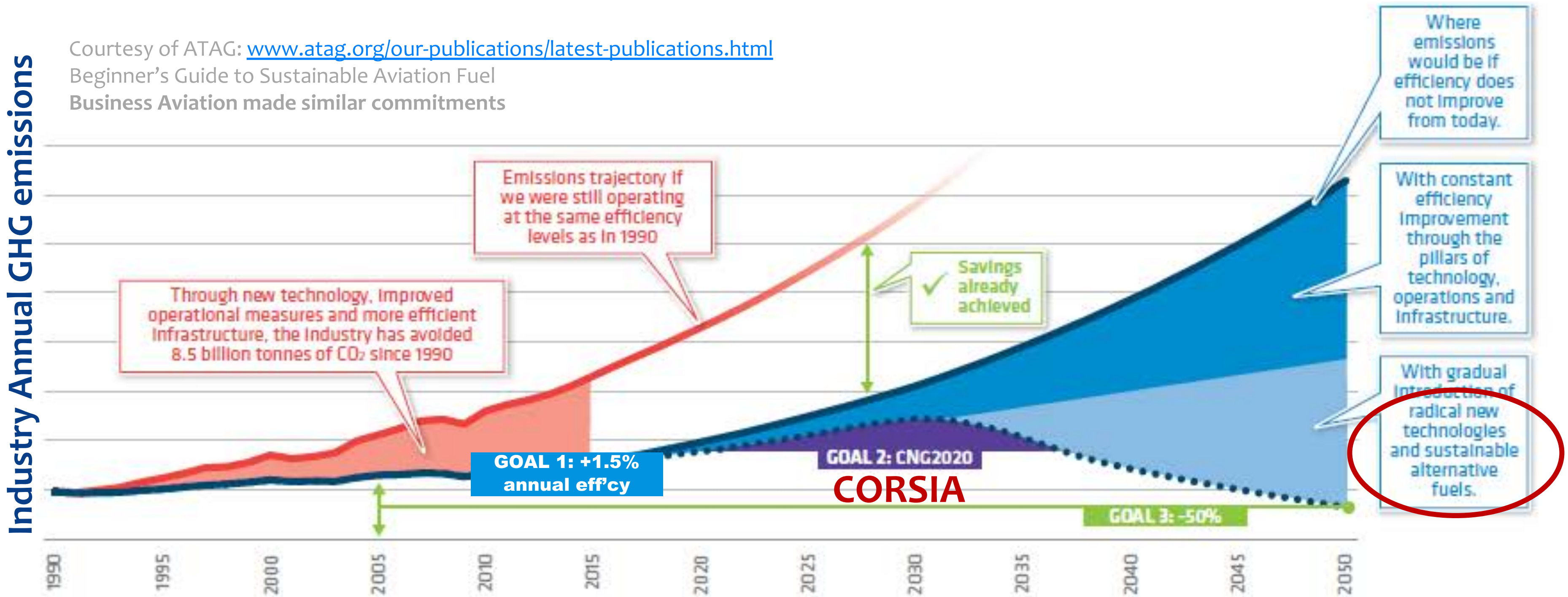
Technology, **O**perations, **I**nfrastructure, and **M**arket-Based Measures

Technology includes the development and commercialization of Sustainable Aviation Fuels

Source: Boyd, Robert (IATA). 2018 CBGM. Policy Panel Discussion. Available at: http://caafi.org/resources/pdf/1.9_Policy_Discussion.pdf

Aviation Industry Commitment to Action on Climate Change: 3 Goal Approach

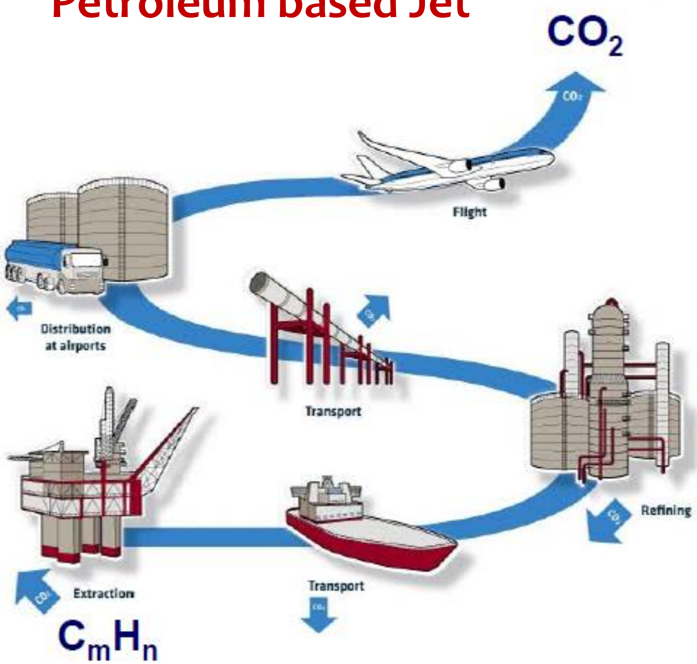
Courtesy of ATAG: www.atag.org/our-publications/latest-publications.html
Beginner's Guide to Sustainable Aviation Fuel
Business Aviation made similar commitments



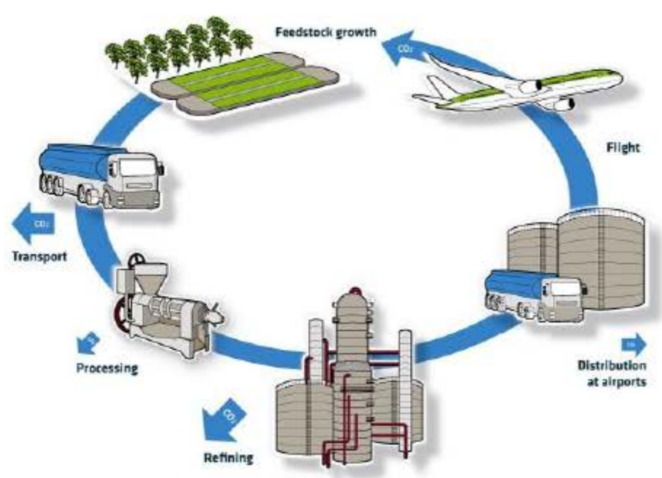
SAF a key component of the Technology Pillar; enabler for GHG containment strategy

Achieving net Lifecycle GHG Reductions with SAF

Petroleum based Jet



Sustainable Aviation Fuel



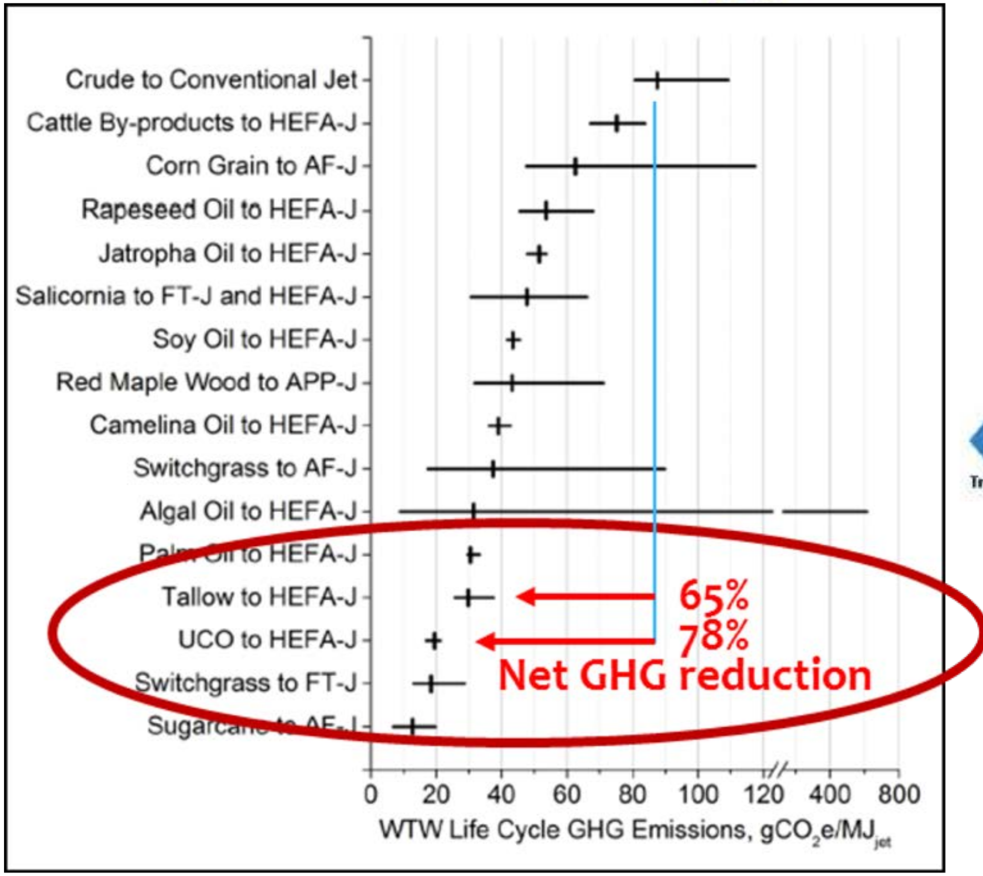
Result is a net reduction of additional carbon being introduced into our biosphere

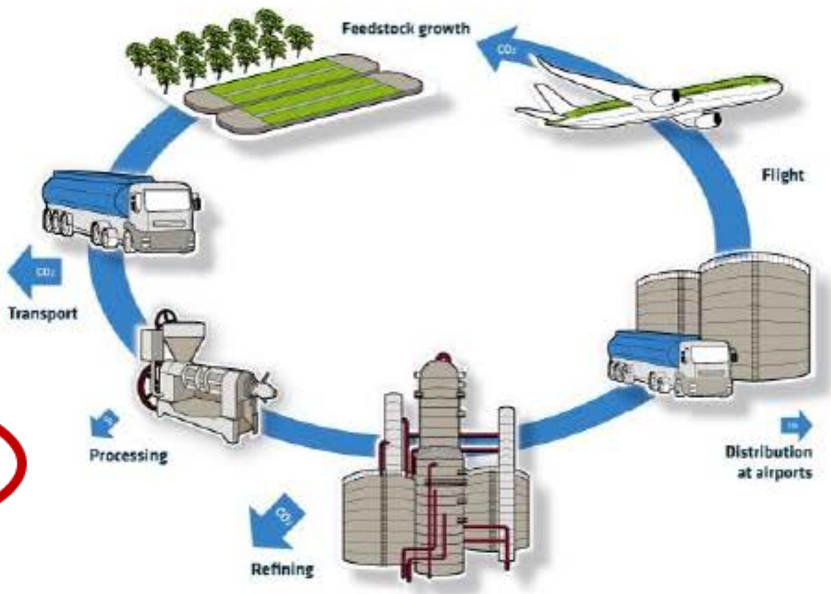
Continuing to pull additional carbon from the ground and releasing it into the atmosphere as CO_2

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

Achieving net LCA GHG reduction

Reduction in carbon being introduced to biosphere





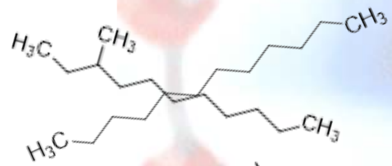
Sustainable Aviation Fuel

Jet Fuel / Kerosene

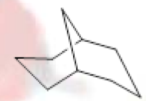
Aviation Enterprise optimized around the fuel

A middle distillate kerosene stream is used for aviation fuel

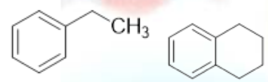
* Comprised of mixtures of aliphatic and aromatic hydrocarbons with carbon numbers predominantly in the range of C7-C17, which is typically a mixture of:
    - 25% / 11% normal / branched paraffins



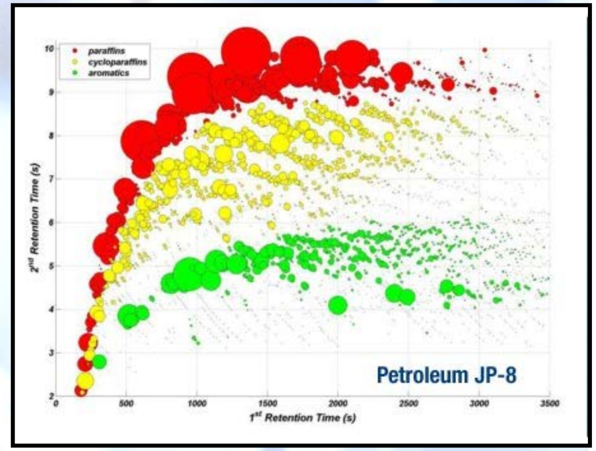
    - 30% / 12% / 1% mono- / di- / tri-cycloparraffins



    - 16 / 5% mono- / di-nuclear aromatics



      (25% max aromatics – air quality concern)

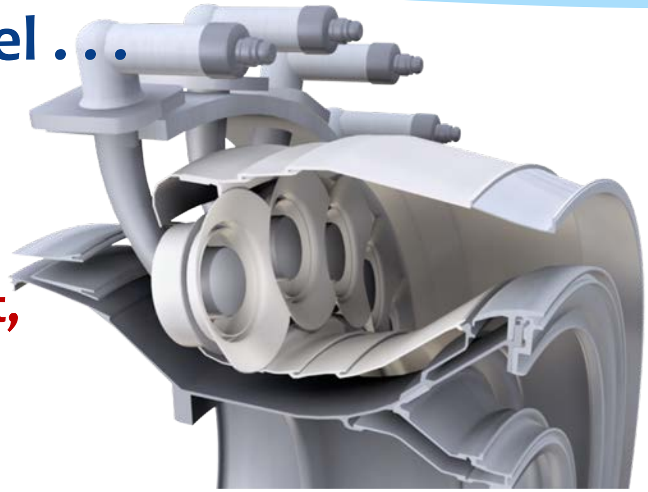


There is no standard "formula" for Jet Fuel

* Composition that delivers the physical properties and performance-based requirements / characteristics of ASTM D1655 specification
* A Gaussian distribution of hydrocarbons, represented as C12H23

Turbine fuel functional requirements
Foundation for certification basis

How does the aircraft use fuel . . .
- As a coolant
- As a lubricant
- As a hydraulic fluid
- As a ballast fluid, swelling agent, capacitance agent, …
- And finally, as an energy source



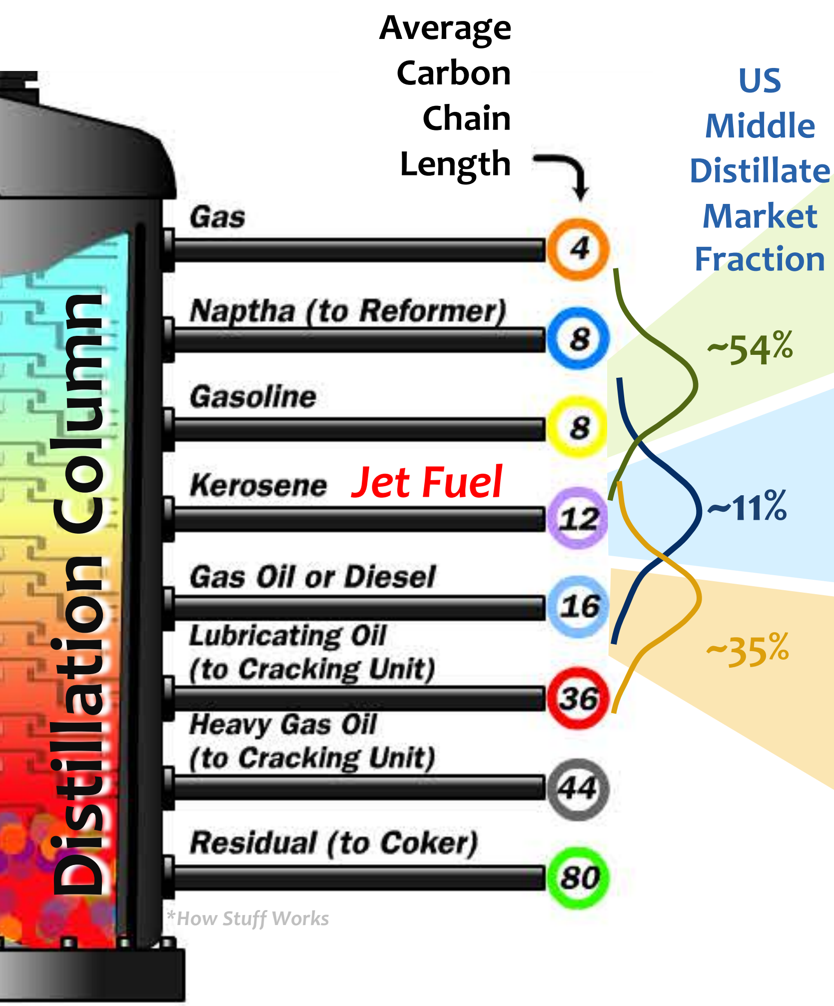
ASTM D-1655
- Acidity
- Aromatics, max%
- Sulfur
- Distillation
- Flash Point
- Density
- Freeze pt
- Viscosity
- Heat of Combustion
- Copper strip corrosion
- JFTOT
- Existent gum
- MSEP
- Electrical conductivity

Need: Efficiency and safety paramount
- High energy content: volumetric & mass
- Stable: high flash point (no explosions), low freeze point (liquid at -40C)
- Unique properties enable required Operability

Aviation fuel used for multiple purposes… So its creation has to be carefully controlled to get the right fit-for-use properties

Jet Fuel and the refinery paradigm

Airlines prefer to avoid any refinery "pinch"



Segment Observations	Energy Options
Cars / Lt. Trucks / Misc. Refineries optimized for gasoline Gas consumption ↓ (CAFE pressure) Future ICE need octane boost ↓ product life, ↓ production runs	**Yes, Too Many!:** • X-OH blends • Hybrids • CNG, LNG, H_2 • Fuel Cell, Electric
Jet Aircraft Minority volume; gas/diesel squeeze Jet consumption ↑ Fuel requirements stringent – estab. ↑ product life, ↑ production runs	**Nothing practical:** • Kerosene, from fossil or renewable H/C sources
Trucks, O/R & HVs, Ships Still need liquid fuels Diesel consumption ?? Future C-IE need cetane boost?	**Yes:** • Biodiesel blends • Hybrids • CNG, LNG, H_2

Overall industry summary:
Sustainable Aviation Fuel (SAF) activity

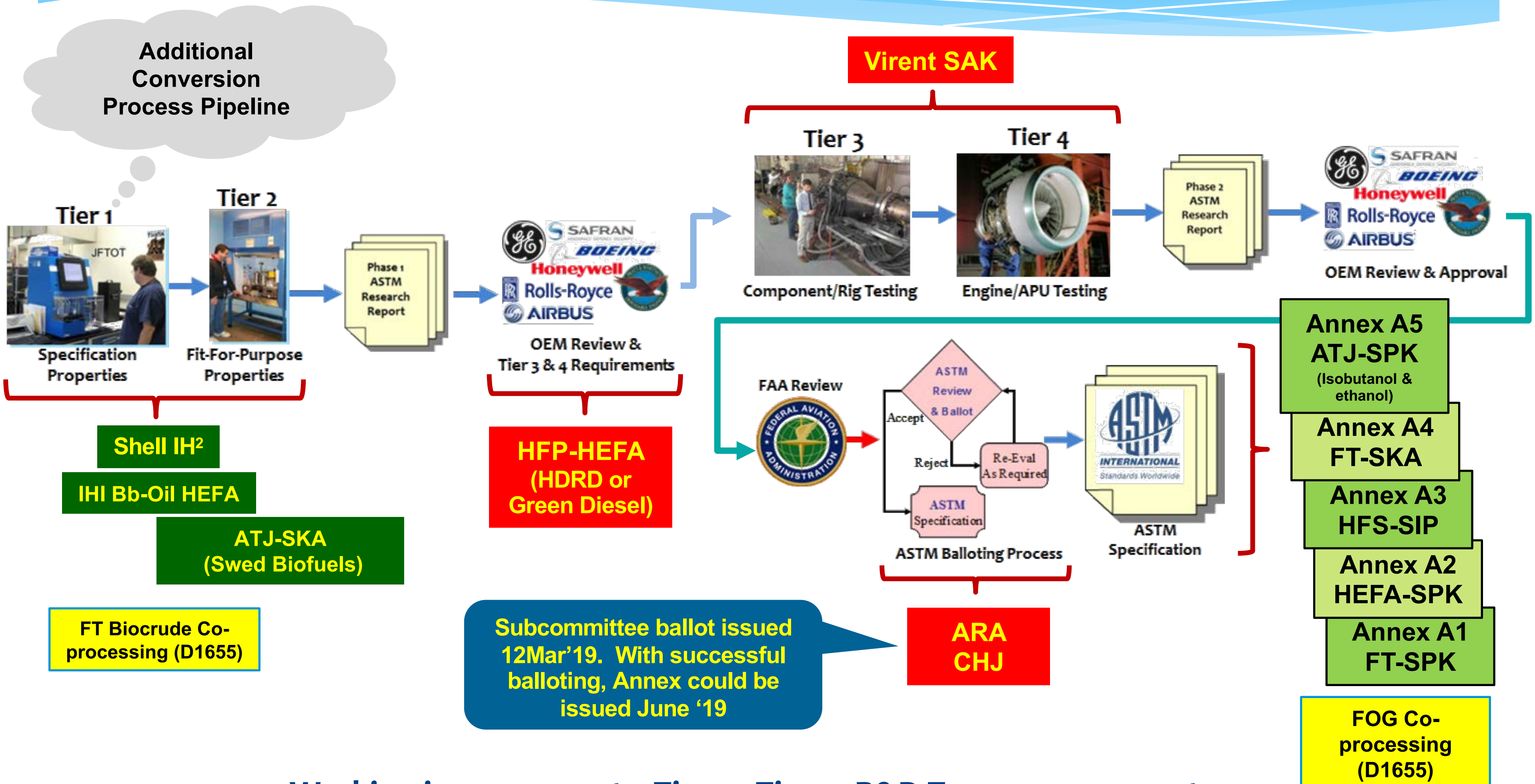
* SAF are key for meeting industry's commitments
  * Aviation enterprise aligned; 26B gpy US & 90B GPY worldwide opt'y
  * Delivers net GHG reductions of 65-100%, other enviro services
  * CAAFI and others (e.g. AIREG) are working to foster, catalyze, enable, facilitate, participate
  * Segment knows how to make it; Activities from FRL 1 to 9
  * First facilities on-line, producing SAF at various run-rates
  * Commercial agreements being pursued
  * Pathway identified for fully synthetic (50% max blend today)
* Making progress, but still significant challenges – only modest production – focus on enabling <u>commercial viability</u>
* Potential for acceleration a function of engagement & first facilities' success replication

SAF Progress - technical

* SAF are becoming increasingly technically viable
  * Aviation now knows we can utilize numerous production pathways (5 approved, others pending)
  * Enabling use of all major sustainable feedstocks (lipids, sugars, lignocellulose, H & C sources)
  * 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 refinerys
* Significant "pipeline" of new production pathways
* Continuing streamlining of qualification – time, $, methods

Technologies applicable to SAF

Industry approval of SAF via ASTM D4054 Process



Working improvements: Tier α, Tier 0, R&D Team engagement, 4054 Clearinghouse, Quick Entry Annex, …

ASTM D4054 pipeline

Approach	Feedstock	Companies
ATJ Expansion	Alcohols (via sugars)	Swedish Biofuels, Byogy
HDCJ (direct or co-processing)	Lignocellulose	Ensyn/Envergent, REC
Microbial conversion	Isobutene (via sugars)	Global Bioenergies
HTL	Lignocellulose	Steeper, Genifuel, …
Catalytic HTL	Lignocellulose	Licella, Muradel, QUT
Thermal Deoxyg.	Lipids	Forge Hydrocarbons
SBI CGC PICFTR	Lipids - biodiesel	SBI Bioenergy / Shell
Acid Deconstruction	Lignocellulose	Mercurius
CCL	Lipids	Tyton
CHyP (syngas, non-FT)	Lignocellulose	Proton Power
Hydrogenotrophic Conv.	CO_2 / Producer Gas	Kiverdi
Cyanobacterial Prod.	CO_2	Joule
STG+ GTL	C1-C4 Gas / Syngas	Primus
Ionic Liquid Decon.	Lignocellulose	JBEI, tbd
Metal Catalytic Conversion	Lignocellulose	Purdue research
Enzymatic Conversion	Lignin	GLBRC & JBEI

Why do we care about the pipeline

* We need SAF affordability
  * Processes applicable to lower cost, available feedstocks
  * Lower CapEx, OpEx
* We need SAF availability
  * Available for processing regionally, world-wide, with available feedstocks
* We need commercialization activity / fuels soon
  * Leverage existing biofuel infrastructure or adjacent production
* Some will shift strategies and may never produce jet fuel (Amyris), or produce compounds of lesser interest (Virent)

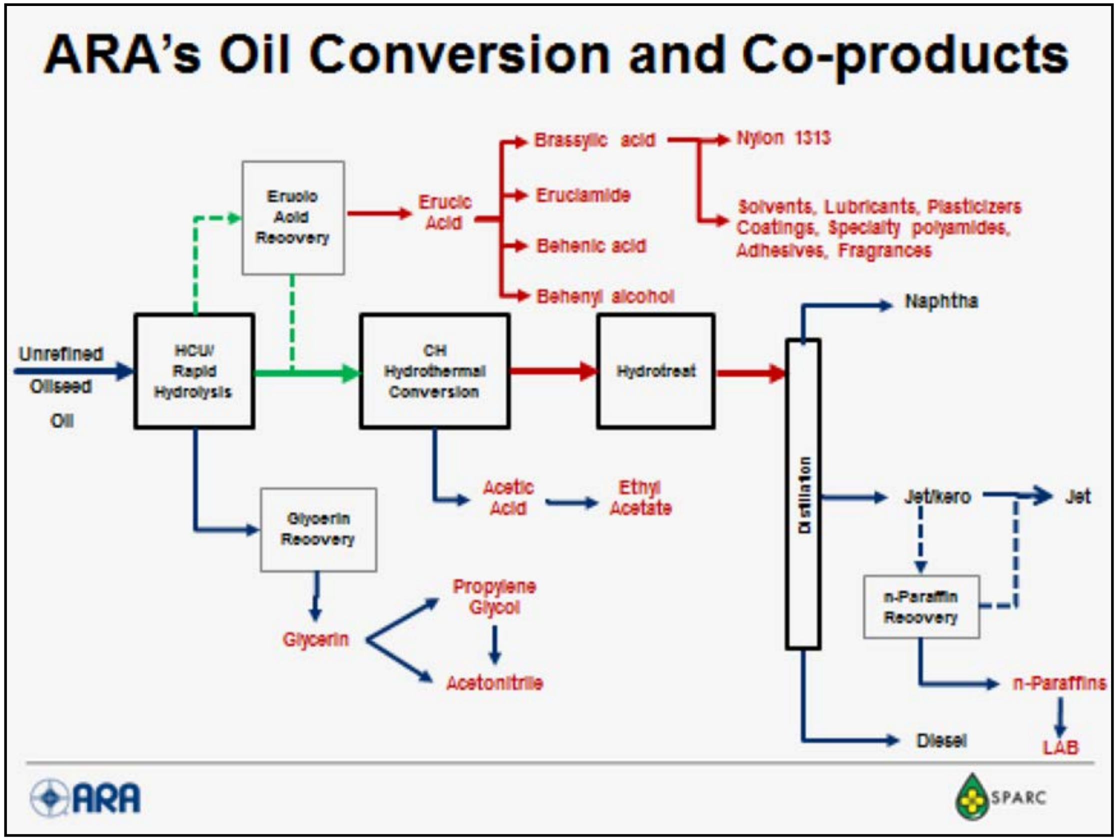
SAF commercial progress

* The path to SAF commercialization has perhaps commenced
  * In production; in construction; in final design; in conceptualization
  * Some will be readily replicable
  * May be able to leverage existing refineries, as well as alcohol and renewable diesel production facilities
* The primary impediments to rapid growth:
  * A production cost delta versus petroleum-jet, and;
  * Competition from diesel (road and maritime), and;
  * A policy environment that may not close cost delta, creates market distortions, and continues to foster uncertainty
* Given a policy framework that addresses the above, SAF is perhaps on the cusp of rapid expansion and replication
  * Many members of entire supply-chains are working to enable such (academia, national labs, entrepreneurs, big oil, fuel suppliers, pipeline companies, farmers and foresters, facilitators, aviation partners)

CAAFI®

Cost-focus is only part of the need

* Techno-economic assessments don't address total value
* Expectation that viability will be enabled via other revenue, other services, and integration with existing facilities and industries



CAAFI®

SAF commercial progress

* Airline engagement continues, strongly with key instigators
  * BizAv and Corporation engagement initiated and expanding
* Other convening activities
  * Fuel Suppliers – new business opportunities
  * Refiners – maintaining markets and meeting policy obligations
    * Co-processing activities
  * NGOs – assisting w/ demand aggregation & market signals
  * Airports – misc explorations, starting w/ infrastructure evaluations
  * Feedstock development – flight demos whet investor interest
  * SAJF & HDRD Producers – continuous stream of exploration and announcements
  * OEMs have their own fuel needs

Additionally, SAF can contribute environmental services…

* Via feedstock scenarios
  * Improved water quality, from erosion control, reduced nutrient leaching
  * Improved soil retention, from extended ground cover
  * Improved soil carbon uptake, from additional biomass residues
  * Reduce pesticides and herbicides, via improved rotational strategies
  * Improve biodiversity and pollinator health
  * Reduce wildfire risk
  * Create new biomes for food, fiber, materials, and revenue
  * Reutilize marginal lands, winter fallow, chem fallow, …

CAAFI®

SAF reduces criteria pollutants

* SAF usage has been shown to, as a function of the specific type of fuel and SAF blend ratio:
  * Significantly reduce SOx and PM (40-90%)
  * Generally reduce CO and UHC emissions (15-25%)
  * Minimally reduce or have no effect on NOx emissions
  * HAPs impact tbd, but some is expected
* See details in pending reports from ACRP 02-80 (YE 2018) which summarizes pollutant testing results to date, and creates:
  * State of the Industry Report (comprehensive bibliography)
  * Emissions Quantification Methods
    * Creation and Validation of Impact Factors and Emissions Indices
  * Case Studies
  * Fact Sheet Summary

SAF offtake agreements

Beyond numerous demonstration programs

Producer	Partner(s)	neat quantities
World Energy Paramount *	+ United	= Up to 5 M gpy from 2016 (LAX)
	+ World Fuel Services, Gulfstream	= 3 yr agreement 30/70 blend
	+ KLM	= 3 yr agreement Enabling LAX flts
	+ SkyNRG Nordic, air bp, OSLO Airport, SAS, Lufthansa Group	= Bioports on demand, et al. (Halmstad, Arlanda, Bromma, Goteborg, Leeuwarden)
Fulcrum Bioenergy	+ Cathay Pacific	= 37.5M gpy
	+ United	= 90-180 M gpy
	+ air bp	= 50 M gpy
	+ Japan Airlines, JOIN, Marubeni	= Project Development, License, and Offtake

10 yr agreements

* WEP also continues supplying fuel for multiple trial and research activities

SAF offtake agreements

Beyond numerous demonstration programs

		neat quantities
Red Rock Biofuels	+ Southwest	= 3 M gpy each, 7 yrs (Bay Area, CA)
	+ FedEx	=
Total | Amyris	+ Cathay Pacific, China Airlines	= A350 deliveries 10% blend (ex-TLS)
SG Preston	+ jetBlue	= 10M gpy, 10 yrs (JFK)
	+ Qantas	= 4M gpy, 10 yrs (LAX)
gevo	+ Avfuel	= Up to 1M gpy, 5 yrs+
	+ Virgin australia	= Brisbane Supply Demonstration

These offtakes/efforts represent >250 M gpy, and account for the total production slate of the first several commercialization efforts

CAAFI®

Other recent announcements

				effort
VELOCYS	+	BRITISH AIRWAYS, Shell	=	MSW-based FT-SPK evaluations
	+	In negotiation	=	BTL #1, Natchez, MS 1,400 bpd
NESTE	+	American Airlines, DFW DALLAS FORT WORTH INTERNATIONAL AIRPORT	=	SAJF Supply exploration
	+	Alaska	=	MOU to design & implement adoption
	+	air bp	=	Collaboration on supply expansion
AGRISOMA	+	QANTAS	=	Carinata supply development
SkyNRG NORDIC	+	Shell	=	SAJF Supply collaboration

Other recent announcements

effort

DG Energy	+	GE Aviation	=	0.5M gpy, 10 yrs
Multiple Producers, TBA	+	World Fuel Services	=	Full production slate offtakes
preem Gothenburg Refinery	+	SAS	=	Long-term supply negotiation (from 2023). Fueling all domestic flights by 2030.
LanzaTech capturing carbon fueling growth	+	virgin atlantic	=	UK DfT F4C Funding: ATJ Development Demo flight MCO-LGW
TBA	+	FINNAIR	=	Customer funding of SAJF purchase from 2019
Multiple Producers & Suppliers	+	Airports and Airline Tenants (Port of Seattle, Seattle-Tacoma International Airport; SFO)	=	Exploration of Greater ambition

CAAFI®

Commitments of Greater Ambition

UNITED

First U.S. Airline to Pledge to Reduce Own Emissions by 50 Percent (vs. 2005) by 2050; 13Sep'18

FedEx

Obtain 30% of jet fuel from alternative sources by 2030; 06Nov'17

Norway's government introduces 0.5 % blending mandate for advanced aviation biofuels from 2020; 04Oct'18

world energy Paramount

Moving forward with $350M expansion to enable 306M gpy total capacity, including infrastructure for jet capacity of 150M gpy; 24Oct'18

Netherlands committed to transition all military aircraft to 20/80 AJF blend by 2030 and 70% by 2050

Near-term solutions - MSW

MSW – a problem needing a solution

* Aggregated, low / zero / negative cost feedstock, well defined locations and opportunities
* Major waste handler companies engaged
* Several conversion processes, numerous gasification entities, major players in gas clean-up
* Commercialization entities (e.g. Fulcrum) haven't communicated a need for supply-chain development activity

Near-term solutions - lipids
Positive attributes

- Straightforward – nature gives us something very nearly fuel
- Significant domain knowledge and infrastructure around grains and oils
  - Handling, storage, processing, transport
  - Rapid energy densification via crush
  - Subsequent fungibility, and ease of working with fluid feedstock
- Main byproduct is protein meal – addresses other key concern – feeding a world of 10B
  - Other co-product markets in chemicals and materials
- Less farmer fear with annuals versus perennial lignocellulosics
- Promise of winter cover oilseeds with minimal LUC/ILUC
- Potential for use of brown greases – relatively untapped market
- Eventual promise of ubiquitous algae production? Microbial lipids?
- Advanced work on oil production from non-traditional plants, or sequestration in lignocellulose
- Multiple conversion technologies & technology vendors

Near-term solutions - lipids
“Negative aspects”

* Poor opportunity for demand response from waste FOG
  * But, estimated by some at from 5-25% of US potential
* “Only so much viable acreage” and “Food versus Fuel”
  * Only some will be viable on marginal lands (e.g. halophytes)
  * Restrictions incorporated in RED II (7% max from “cropland growth”)
* LUC/ILUC, biodiversity challenges with wholesale land conversion
  * Palm-pushback already influencing policy against FOG
  * Also taints all palm, several types of which don’t have the negative aspects of concern in SE Asia
* Perceived need for significant hydrogen for conversion
* Purpose-grown lipid feedstocks not ready for primetime

CAAFI®

U.S. commercialization activity / intent

HDRD (& SAF?) from lipids/F.O.G.

* Diamond Green: Norco, LA
* REG: Geismar, LA
* World Energy: Paramount, CA

In Production:
390 M gpy @ YE '18
Nameplate

* Diamond Green expansion (275 -> 550M gpy)
* REG Geismar expansion (75 -> 122M gpy)
* World Energy Paramount (40 -> 305M gpy)
* Andeavor Dickinson, ND conv. (180+M gpy)
* Phillips 66 / REG: Ferndale, WA
* Rhyze / Phillips 66: Reno/Las Vegas, NV
* SG Preston (duplicate 240M gpy facilities)
* ARA licensing build-out (4+ activities)
* NEXT / Shell (575M gpy)
* Emerald (110M gpy)

In Development:
Greater than 2.2B gpy capacity by 2023 !?!

… necessitates serious engagement with purpose grown oilseed & F.O.G. development / expansion

* Licensing for additional refinery retrofit(s)
* Refinery co-processing
* Neste, UPM, … additional potential US pivots

CAAFI®

U.S. lipid feedstocks

Potentially enabling of significant production …

Multiple:

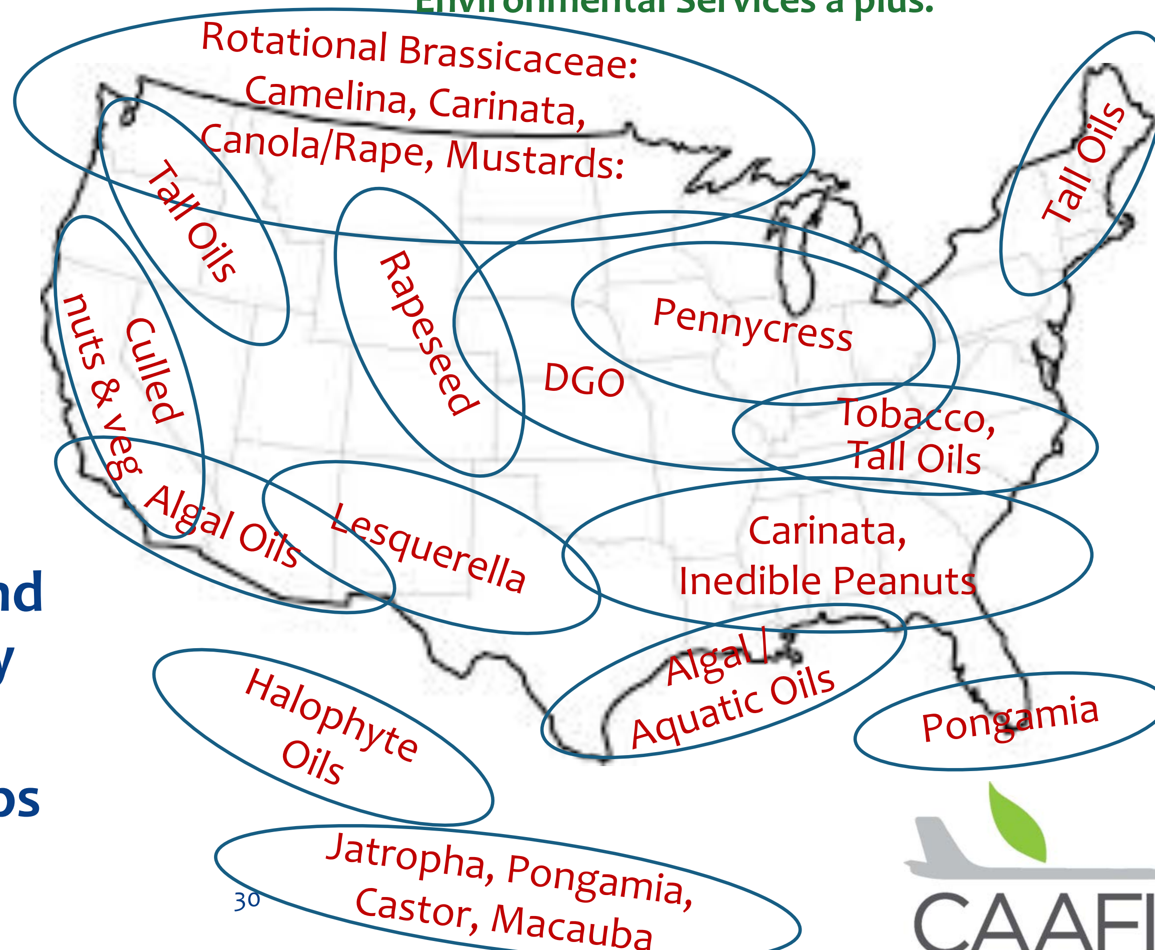
* Conversion processes
* Feedstock developers
* Producers
* Low LUC/ILUC agri-based feedstocks
* Waste F.O.G.
  * White Grease, Poultry Fat, Tallow
  * UCO / Yellow Grease
  * Brown Grease, Biosolids

Easier supply chain scale-up leveraging biodiesel and HDRD production capacity

Lowered H2 cost & availability (from NG) helps

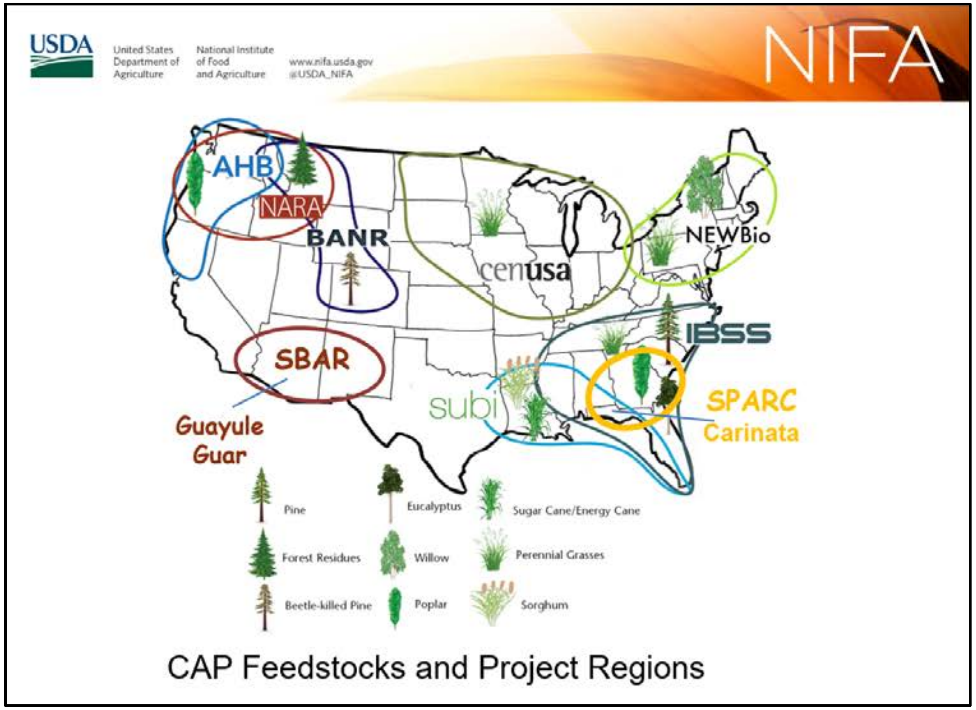
Targeting most sustainable solutions:

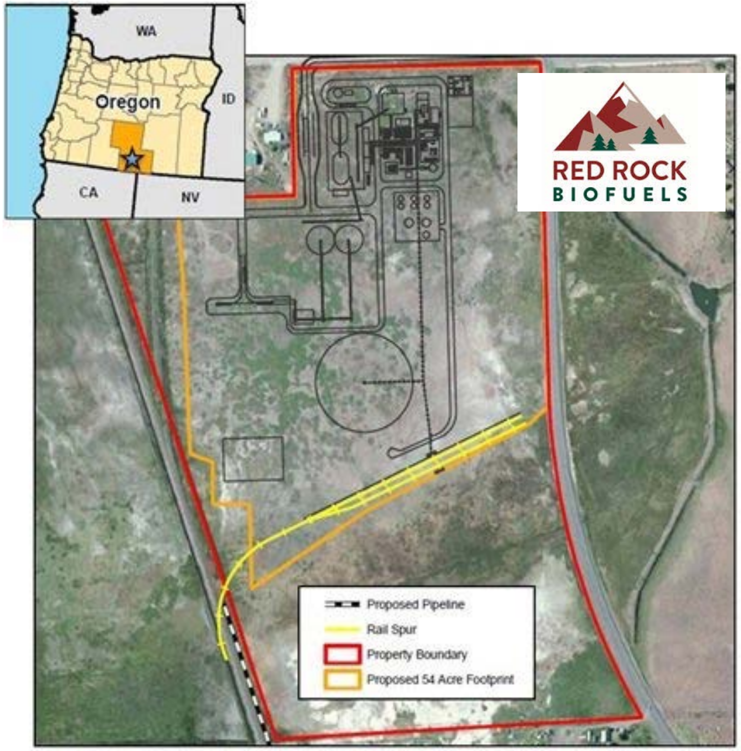
Low, or Zero, impact LUC/ILUC & F-v-F solutions; Environmental Services a plus.



CAAFI®

Near-term solutions - lignocellulose





SAF status summary:

* SAJF technically viable – slowly being commercially developed
  * Opportunities actually continuing to expand
* Challenge is achieving price-point equivalency to petro-jet
  * Policy support has been shown to close some business cases
  * Some producers remain bullish on their costs without policy
* Feedstock availability might be pacing for some pathway families, but not envisioned to be an ultimate constraint
* Full range of activities ongoing to try to bring down cost, reduce risk, incentivize production, develop feedstocks, …
  * Crude oil price and policy mechanisms will be key determinants
* Industry still counting on execution of SAJF, commensurate with progress on other pillars

CAAFI®

Southeast collaboration

* Abundant forestry, row-cropping, …
* SPARC/carinata, ASCENT/pennycress
* Airbus/Mobile and Boeing/Charleston
* LanzaTech focus in GA
* HDRD in LA: Norco and Geismar
* Velocys in MS

Steve Csonka
Executive Director, CAAFI
+1-513-800-7980
Csonka.CAAFI.ED@gmail.com
Steve.Csonka@caafi.org
www.caafi.org

CAAFI®

FUELING SOLUTIONS FOR
SECURE & SUSTAINABLE AVIATION

SAF segment attractiveness

Yes, jet is a commodity, but …

- Many production concepts will allow for high-value co-products
- Demand pull of ~90 Bgpy from global market
  - Enables SAF producer business growth over time
- Expected continuation of demand growth
  - Other tech. will not diminish demand over economic life of facility
  - More certain than potential impacts on ground transport fuels
- Long term offtakes for significant levels of production possible
  - Non-fragmented, B2B market (either supplier or end-use customer)
  - Few infrastructure issues following blending (customer can assist)
- CORSIA mechanism will provide additional carbon monetization under global policy framework
  - Assisting with gap closure to diesel

CAAFI®

First U.S. SAJF refinery online!

World Energy Paramount (aka AltAir Fuels)

- First dedicated US production facility for HEFA-SPK (primarily HDRD, and reformate blending components) fuels with ongoing production
- Repurposing of Alon asphalt refinery, now owned via World Energy
- Tallow and waste FOG

* 40M gpy nameplate capacity in "Phase 1"
  * Less than 5% output as SAJF due economics and policy
* SAJF being delivered to airlines and suppliers
* HDRD (F76) being delivered to Navy via DLA FY'18-'19 contracts
* Ownership evaluating 3-5X expansion opportunity

DPA Recipient: Fulcrum Bioenergy
"Groundbreaking" 16May'18, First Fuel 2020

* 10.5 M gpy syncrude production plus power – FT process
  * From 200,000 tons of post-recycled waste
  * Perhaps 4m gpy directed to jet after some time
* Subsequent plants at 3-6X size; targeting 8 plants by 202x delivering 300 M gpy middle distillates

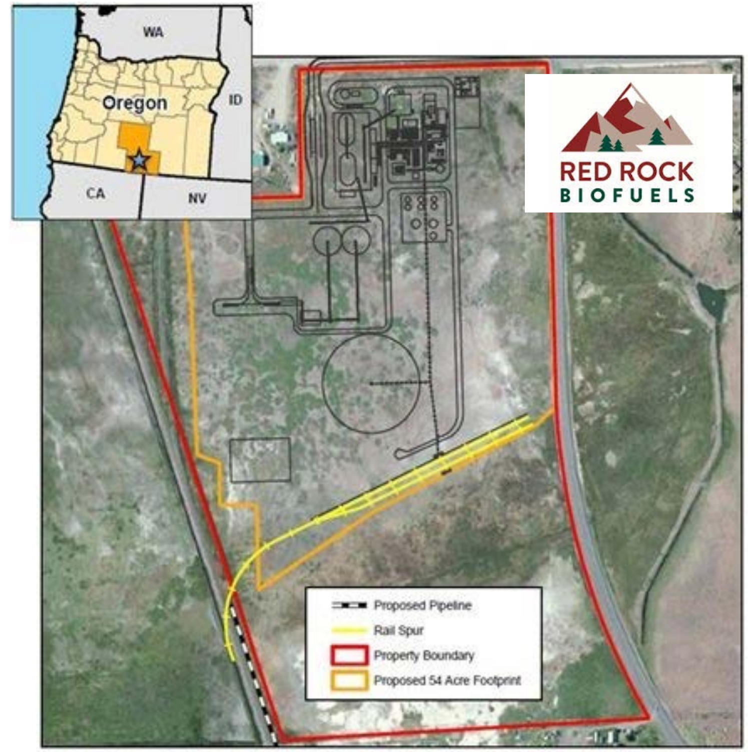
TRI Gasifier, EFT FT unit
Waste agreements comprising ~4% of US total landfill volume

* Replication approach →

Courtesy Fulcrum-Bioenergy
http://www.fulcrum-bioenergy.com/index.html

DPA Recipient: Red Rock Biofuels
"Groundbreaking" 18Jul'18, First Fuel 2020

- 15.1 M gpy of renewable, liquid transportation fuels – FT process
  - From 136,000 tpy of woody biomass
  - 3M gpy SAJF offtake agreement from each of Southwest Airlines and FedEx
  - $70 million DPA Title III award for ~$200 million refinery
- Replicable approach targeting 10 additional sites
  - E.g. - working with CAAFI in southeast F2F2 State Initiative



TCG Global gasifier
Velocys FT reactors
Haldor Topsoe / Valero upgrading

Courtesy Biofuels Digest

Commercialization intent - lipids

“Declared” nameplate capacities: significant opp’ty