CASCADE

SUSTAINABLE AVIATION TECHNOLOGY SYMPOSIUM

November 12-13, 2025
Cambridge, MA, USA

Copyright © Boeing. All rights reserved.

Event Overview

A technical symposium to discuss challenging obstacles and identify promising solutions

- Brought together 100+ thought leaders from academia, government, and industry from around the world
- Utilized short talks to set the stage for extended breakout sessions wherein the assembled leaders identified key challenges and paths forward to address these challenges
- Developed a proceedings with key outputs and recommended next steps
- Symposium considered four themes related to the high costs and low availability of sustainable aviation fuels and the opportunities to improve fuel efficiency and reduce the impacts of contrails

Themes	Objectives
Low Carbon Energy	Determine the amount of low net-carbon biomass and electricity available for aviation – both in the near and longer terms
Energy Carriers and Infrastructure	Determine the relative effectiveness of different energy carriers to use low net-carbon biomass and electricity to power aviation – both in the near and longer terms
Safety and Certification of New Energy Carriers	Identify the issues from a safety and certification perspective that must be overcome to use different energy carriers – both in the near and longer terms
Operations for Fuel Efficiency and Contrail Impact Mitigation	Assess the potential for operations to improve fuel efficiency and reduce the impacts of persistent contrails

Copyright © Boeing. All rights reserved.

Event Flow – from Level Set Presentations

Day 1

Level Set Presentations & Discussion

Identify Top Challenges

- Review objective and key questions
- Identify top challenges

Day 2

Explore the Solution Space

- Identify goal
- Current state
- Knowledge impediments
- Identify priority actions

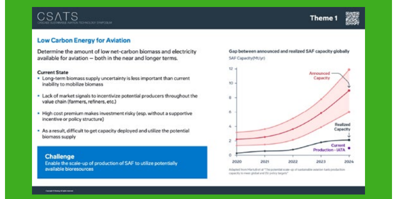
Develop a Path Forward

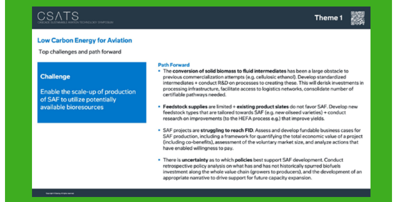
- Describe priority actions
- Identify needs and performers
- Timeframes

Refine the Thinking

- Systems-level and cross-theme considerations
- Pull it all together

Proceedings





Moderators led discussions with attendees in four parallel sessions

Copyright © Boeing. All rights reserved.

Level Set Presentations

Opening and Scene Setting *(Moderator: Jim Hileman, Boeing)*

- Welcome and Imperative *(Todd Citron, Boeing)*
- Setting the scene with Cascade and insights from pre-event user poll *(Ellen Ebner, Boeing and Florian Allroggen, MIT)*

Theme 1

Low Carbon Energy for Aviation
Determine the amount of low net-carbon biomass and electricity available for aviation – both in the near and longer terms.
(Moderator: Mike Wolcott, WSU)

- What is the credible range of low carbon energy availability for aviation? *(Doug Phillips, IATA)*
- What is the situation in individual countries for biomass availability? *(Matt Langholtz, ORNL)*
- What challenges need to be overcome to get low carbon energy into aviation fuel? *(Florian Allroggen, MIT)*

Theme 2

Aviation Energy Carriers and Infrastructure
Determine the relative effectiveness of different energy carriers to use low net-carbon biomass and electricity to power aviation – both in the near and longer terms.
(Moderator: Jim Hileman, Boeing)

- What is the status of aviation energy today? *(Brent Novak, BP)*
- How could we best use our limited low carbon energy to power aviation? (Jim Hileman, Boeing)
- How would changes in fuel composition and novel energy carriers impact persistent contrails? (Ziming Wang, DLR)

Theme 3

Safety and Certification of New Energy Carriers
Identify the issues from a safety and certification perspective that must be overcome to use different energy carriers – both in the near and longer terms.
(Moderator: Matthew Clarke, UIUC)

- What are the issues surrounding the certification of alternative jet fuels? *(Mark Rumizen, Chair, ASTM Aviation Fuel Subcommittee)*
- What are issues around the use of new energy carriers from an OEM perspective? *(Andrew Murphy, P&W)*
- What are the issues around the use of new energy carriers from a system perspective? *(Bjorn Nagel, DLR)*

Theme 4

Operations for Fuel Efficiency and Contrail Impact Mitigation
Assess the potential for operations to improve fuel efficiency and reduce the impacts of persistent contrails.
(Moderator: Josh Hansman, MIT)

- What is the potential for operations to improve fuel efficiency and reduce the impacts of contrails? *(Emily Dallara, Boeing)*
- What are the bottlenecks in implementing operational contrail avoidance? *(Marc Shapiro, Breakthrough Energy Contrails.org)*
- What is the actual efficiency of aircraft operations today? *(John Hansman, MIT)*

Copyright © Boeing. All rights reserved.

Low Carbon Energy for Aviation

Determine the amount of low net-carbon biomass and electricity available for aviation – both in the near and longer terms

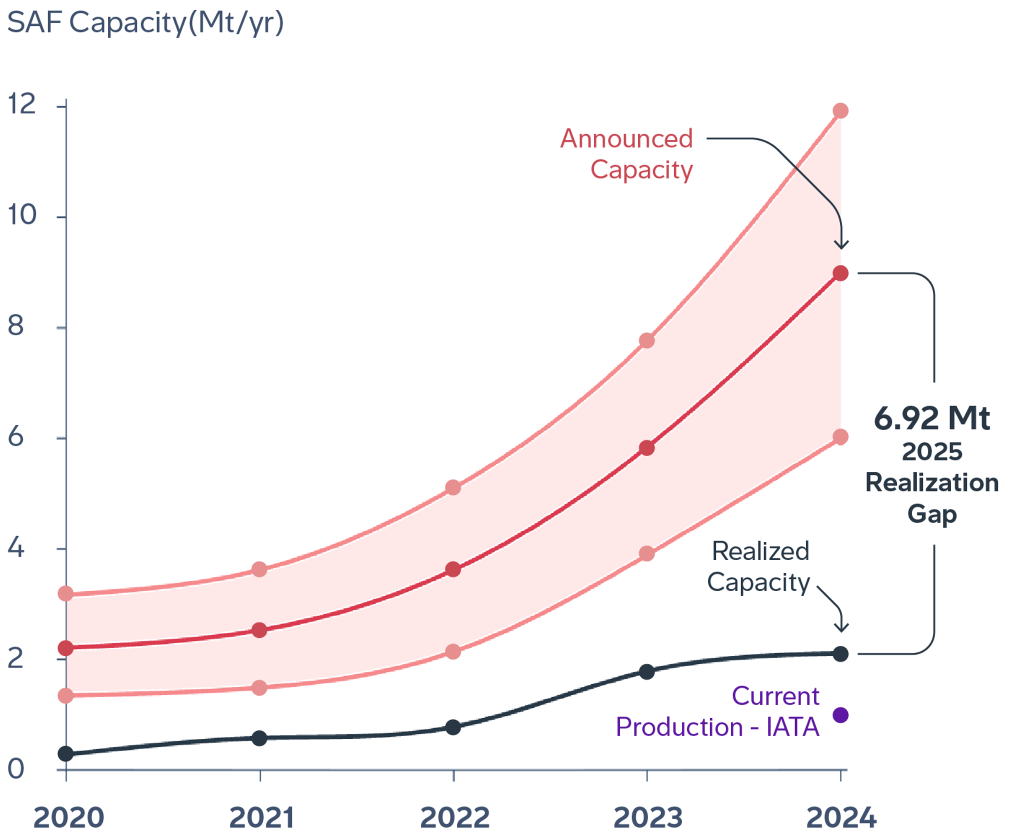
Current State

- Long-term biomass supply uncertainty is less important than current inability to mobilize biomass
- Lack of market signals to incentivize potential producers throughout the value chain (farmers, refiners, etc.)
- High cost premium makes investment risky (esp. without a supportive incentive or policy structure)
- As a result, difficult to get capacity deployed and utilize the potential biomass supply

Challenge

Enable the scale-up of production of SAF to utilize potentially available bioresources

Gap between announced and realized SAF capacity globally



Adapted from Martulli et al "The potential scale-up of sustainable aviation fuels production capacity to meet global and EU policy targets"

Copyright © Boeing. All rights reserved.

Low Carbon Energy for Aviation

Top challenges and path forward

Challenge

Enable the scale-up of production of SAF to utilize potentially available bioresources

Path Forward

- The **conversion of solid biomass to fluid intermediates** has been a large obstacle to previous commercialization attempts (e.g. cellulosic ethanol). Develop standardized intermediates + conduct R&D on processes to creating these. This will de-risk investments in processing infrastructure, facilitate access to logistics networks, consolidate number of certifiable pathways needed

- **Feedstock supplies** are limited + **existing product slates** do not favor SAF. Develop new feedstock types that are tailored towards SAF (e.g. new oilseed varieties) + conduct research on improvements (to the HEFA process e.g.) that improve yields

- SAF projects are **struggling to reach FID**. Assess and develop fundable business cases for SAF production, including a framework for quantifying the total economic value of a project (including co-benefits), assessment of the voluntary market size, and analyze actions that have enabled willingness to pay

- There is **uncertainty** as to which **policies** best support SAF development. Conduct retrospective policy analysis on what has and has not historically spurred biofuels investment along the whole value chain (growers to producers), and the development of an appropriate narrative to drive support for future capacity expansion

Copyright © Boeing. All rights reserved.

Aviation Energy Carriers and Infrastructure

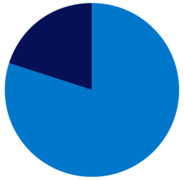
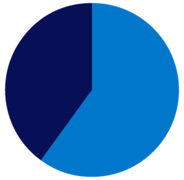
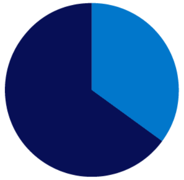
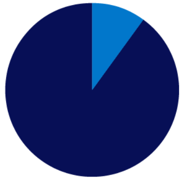
Determine the relative effectiveness of different energy carriers to use low net-carbon biomass and electricity to power aviation – both in the near and longer terms

Current State

- Fats, oils, and greases and sugars and starches are currently limited and being used by other sectors
- Solid wastes and residues are an under-utilized resource
- Lack of collated knowledge on infrastructure capable of converting wastes and residues to SAF and associated costs
- Green electricity is scarce and in extremely high demand
- Interdependencies across aviation and non-aviation stakeholders.
- Low level of integration across energy and transportation communities

Challenges

- Minimize the cost of safely powering aviation with low net carbon biomass and electricity, accounting for infrastructure, aircraft, energy transition, and other costs
- Develop a framework to manage risk of long-term strategic decision-making

Feedstocks	**Fats, Oils, & Greases**	**Sugars & Starches**	**Solid Wastes, residues, and Novel Energy Crops**	**Power to Liquid / E-Fuels**
Production Cost ● Operating Expense ● Capital Expense				
Current Cost	$$	$$$	$$$$	$$$$$$$
Cost Reduction Operating Expense	• Enable today's feedstocks • Expand feedstock options	• Enable today's feedstocks • Use sugarcane bagasse	• Create feedstock supply chain	-
Capital Expense	• Co-processing at refinery • Affordable hydrogen	• Co-production at refinery • Affordable hydrogen	• Co-processing at refinery • Improved technology • Biocrude as intermediate • Affordable hydrogen	• Improved technology • Affordable hydrogen
Current Competition	Diesel Engines	Gasoline Engines	-	Data Centers

Notes: Production cost pie charts are notional. Current costs are based on ICAO Rules of Thumb for ASTM approved fuel pathways (i.e., HEFA, Alcohol to Jet, and F-T synthesis). Cost reduction examples are provided on how these production costs could be reduced. The current competition chart represents some, but not all, competing uses for the feedstocks.

Copyright © Boeing. All rights reserved.

Aviation Energy Carriers and Infrastructure

Top challenges and path forward

Challenge 1

Minimize the cost of safely powering aviation with low net carbon biomass and electricity, accounting for infrastructure, aircraft, energy transition, and other costs

Path Forward

Short-term

- **Identify range of feedstocks and conversion technologies** that could lower cost of SAF production
- To enable accelerated production at lower costs, **identify supply chains that use existing infrastructure** to gather feedstocks, produce SAF, and distribute the fuel
- **Identify existing infrastructure that allows for co-processing** of solid wastes and residues and co-locating of alcohol-to-jet at refineries and **quantify the economics of co-processing**
- Identify the **lower cost non-SAF aviation abatement methods** (methane, removals, SAF, hydrogen, etc.)

Long-term

- Screen, down-select, and mature technology to **enable use of solid wastes/residues** (e.g., biocrudes in petroleum refineries and HEFA/RD facilities)
- **De-risk use of non-drop-in fuels** in the airport and on the aircraft

Challenge 2

Develop a framework to manage risk of long-term strategic decision-making

Path Forward

Short-term

- **Facilitate communications** across energy and transportation communities, including using a **common cost of abatement metric**
- Examine **environmental impact** and **lifecycle costs** of different end state options

Long-term

- Gradually add complexity to analysis including **transition and technology development costs** and **identify dependencies** across aviation and non-aviation stakeholders
- Create the ultimate value proposition – **environmental benefit and cost analysis** and are we willing to accept the **inevitable tradeoffs**
- Plan for limited investment for development – phased approach of evaluating options and learning from other industries. **Deploy small first**. Seek **government support/investment**

Copyright © Boeing. All rights reserved.

Safety and Certification of New Energy Carriers

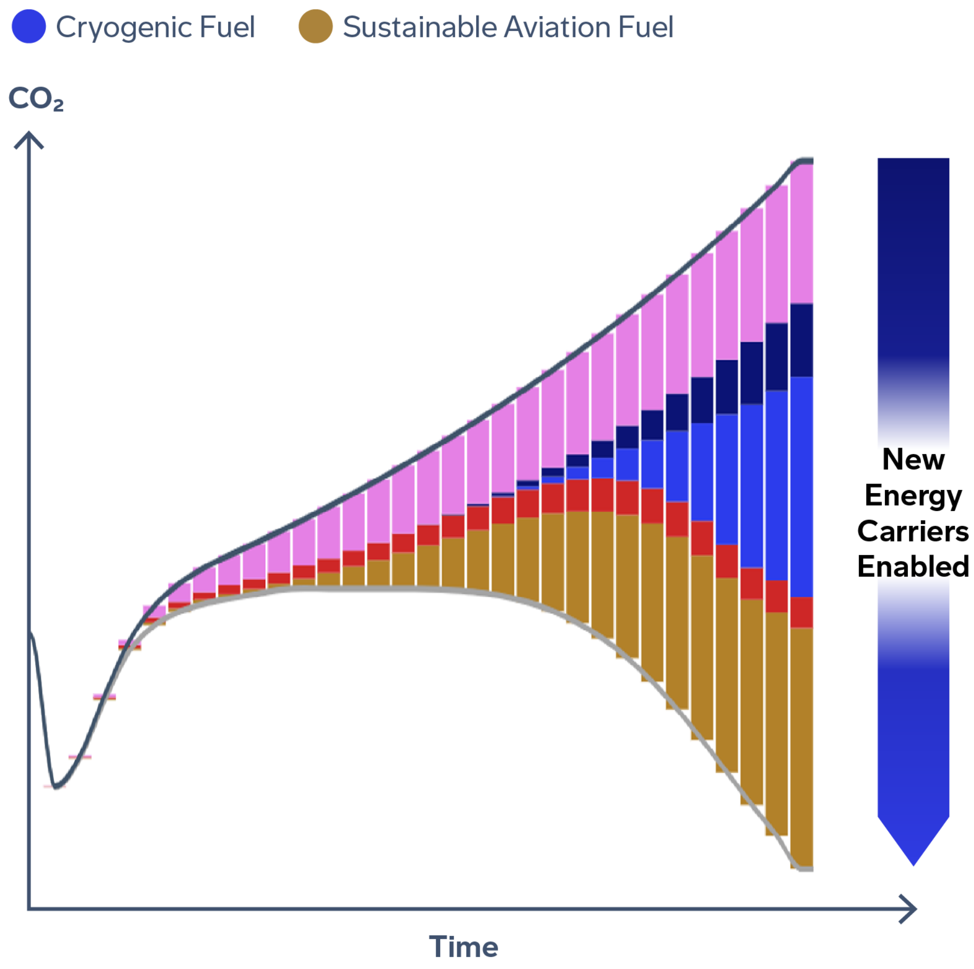
Identify the issues from a safety and certification perspective that must be overcome to use different energy carriers – both in the near and longer terms

Current State

- **Cryogenic Fuels**: Aerospace system-level safety requirements for cryogenic fuels do not exist
- **Drop-In SAF**: Drop-in SAF qualification is based on manufacturing method

Challenges

- Insufficient data and experience currently prevent cryogenic fuels from achieving an equivalent level of safety as conventional kerosene jet fuel
- No comprehensive synthetic fuel annex exists



Copyright © Boeing. All rights reserved.

Safety and Certification of New Energy Carriers

Top challenges and path forward

Challenge 1 - Cryogenic Fuels

Insufficient data and experience currently prevent cryogenic fuels from achieving an equivalent level of safety as conventional kerosene jet fuel

Path Forward

- Create global collaborative R&D initiative
- Identify **priorities in safety and certification** relevant to the lifecycle of cryogenic fuels
- **Propose sample CONOPS** for a cryogenic-fueled aircraft
- **Create test capabilities** and **gather data** pertinent to cryogenic fuel systems

Challenge 2 - SAF

Drop-in SAF qualification is based on conversion process – no generic synthetic fuel annex exists

Path Forward

- **Develop consensus** among OEMs regarding which fuel properties are necessary and sufficient to comprise a generic fuel annex
- **Improve test capabilities** for fuel property measurement and testing; collect relevant kerosene fuel property data
- **Formulate and validate correlation** between drop-in SAF specification properties and fit-for-purpose properties

Copyright © Boeing. All rights reserved.

Operations for Fuel Efficiency and Contrail Impact Mitigation

Assess the potential for operations to improve fuel efficiency and reduce the impact of persistent contrails

Current State

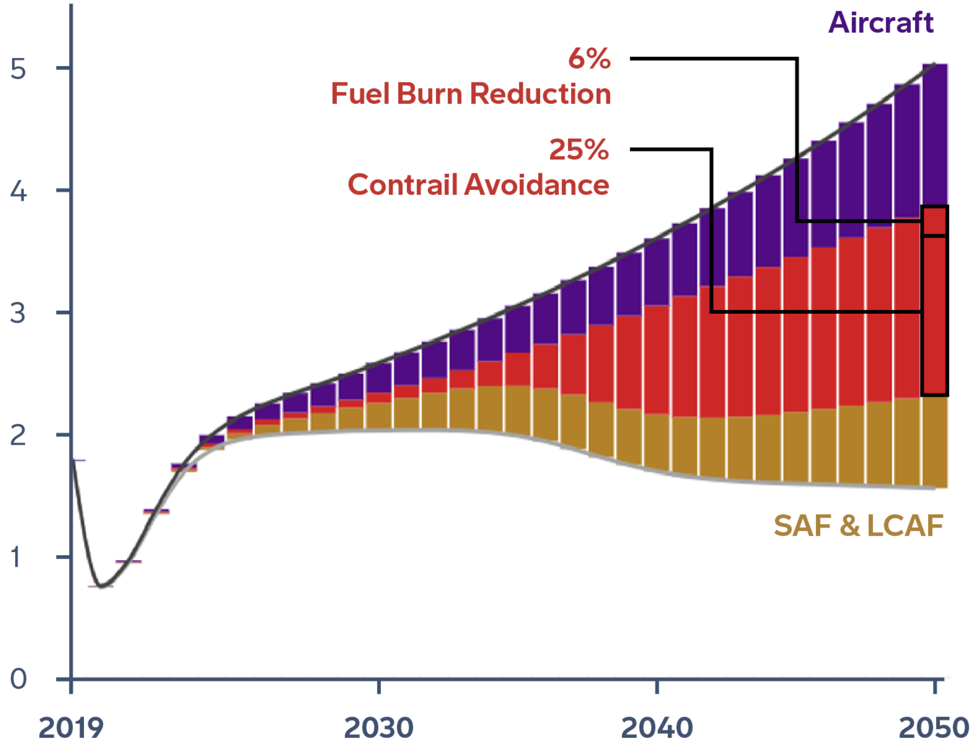
- Structural inefficiencies exist in the current system
- Technology investments have not been fully capitalized
- Emerging awareness of contrail impact on climate

Challenges

- Enable enhanced user-preferred routings that include contrail avoidance
- Accurate prediction of contrails for verifiable, efficient, contrail avoidance at scale
- Minimize on-ground fuel burn by improving airport infrastructure & standardizing procedures

Net Climate Impact by Mitigation Strategy

(Gt CO_2-eq as GWP100)



Source: Boeing Cascade Climate Impact Model (beta version) Results subject to change. Highest ambition contrail avoidance scenario: 20% of contrails avoided, 2% fuel burn penalty, 90% forecast success rate. 3.4% traffic growth, moderate fleet renewal, 20-25% fuel efficiency improvement from new aircraft, 6.3% improvement to operational efficiency, 39% SAF.

Copyright © Boeing. All rights reserved.

Operations for Fuel Efficiency and Contrail Impact Mitigation

Top challenges and path forward

Challenge 1

Enable enhanced user-preferred routings, which could include contrail avoidance

1. **Put air traffic control procedures in place:**
   - Take advantage of existing capability (controller-pilot data link, satellite-based ADS-B Out,...), potential future mandates (ADS-B In), and air traffic control modernization
2. **Enable decentralized self-separation**

Path forward for both:
- Build the benefits case
- Concept of operations
- Requirements
- Demonstrate

Challenge 2

Develop actionable contrail prediction capability

1. **Measure and improve contrail prediction performance**
   - Combine and develop observational data to benchmark forecasts and observations
   - Advancement of weather models including data assimilation to improve forecasts
2. **Demonstrate** airspace-scale trials to determine operational feasibility
3. **Motivate** design incentives for avoidance on a system level

Challenge 3

Minimize on-ground fuel burn by improving airport infrastructure & standardizing procedures

1. **Fully utilize existing capability and procedures**
   - System-level optimization tools to include fuel
   - Deploy reliable ground power and air-conditioning
   - Assist airports in achieving adequate electrical grid service
   - Ensure single engine taxi capability is available for all models
   - Standardization of green operating procedures
   - Aircraft data access to support sustainability
2. **Minimize consumption of fossil fuel on ground other than operationally necessary**
   - Auxiliary power unit improvement and alternatives
   - Auto electric taxi bots w/ enabled airports

Copyright © Boeing. All rights reserved.

Attendees

Attending Organizations | over 100 global experts in sustainable aviation from four continents

- **Academia**: Cambridge University, Georgia Tech, Hasselt University, Imperial College, MIT, NTU Singapore, Penn State, Purdue University, Stanford, TU Munich, University of Illinois, University of Michigan, University of Tennessee, Washington State University
- **Airlines and Leasing**: Airlines for America, Air New Zealand, Alaska Airlines, American Airlines, British Airways, IAG, IATA< SMBC Aviation Capital, United Airlines
- **Airports**: Massport, Rotterdam Airport
- **Energy**: Alder Renewables, BP, Exxon Mobil, Firefly, Linde, Preem, Shell, World Energy
- **Aviation Original Equipment Manufacturers**: Boeing, GE Aerospace, KHI, Lufthansa Technik, MHI, Pratt & Whitney, Rolls Royce, Safran, Toray
- **Government and National Labs**: Aerospace Technology Institute (ATI), Argonne National Laboratory, Bauhaus Luftfahrt, CSIRO, DLR, International Center for Aviation Innovation, Oak Ridge National Laboratory, Volpe Center,
- **Non Governmental Organizations**: Breakthrough Energy, International Energy Agency, Roundtable on Sustainable Biomaterials

Steering Team | Top 10 thought leaders in sustainable aviation

- ATI, Boeing, University of Cambridge, CSIRO, DLR, University of Illinois Urbana-Champaign, MIT, NASA, Pratt & Whitney, Stanford University, Washington State University

Copyright © Boeing. All rights reserved.