INAUGURAL REPORT:

2024 AIAA Sustainable Aviation Workshop Outcomes

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Introduction

The aviation community has set an ambitious goal to reach net-zero CO2 emissions across the global industry by the year 2050. Achieving this goal will require significant developments in aircraft technologies, power and energy systems, operational strategies, policy and regulation, supply chain and infrastructure, as well as other related areas. Such endeavors will require an unprecedented level of coordination between airports, energy suppliers, aircraft operators, aerospace product suppliers, and regulatory agencies.

The 2024 Sustainable Aviation Workshop, hosted by AIAA at AVIATION in July 2024, convened a range of stakeholders involved in the air transportation community with the purpose of understanding the socio-techno-economic considerations that will further foster sustainability in aviation. Workshop activities, including audience participation via polls and focused breakout sessions, were used to identify cross-cutting developmental needs and maturation strategies to meet future sustainability goals for the industry.

The Sustainable Aviation Workshop aimed to mobilize the AIAA community to:

- Establish a unified vision for sustainable aviation
- Foster connections between stakeholder groups
- Inform technological and infrastructure developments necessary for sustainability goals
- Identify critical gaps in progress by assessing outcomes of sustainable development efforts

The workshop began with an introduction and summary of sustainability, consisting of aviation's impact on the environment and description of its role in a sustainable transportation ecosystem. This was followed by an audience-engaged discussion where participants shared their visions for a sustainable aviation ecosystem of the future. The second part of the workshop consisted of presentations by panels of experts on their views regarding the future of aircraft configurations and technologies, energy systems, and sustainable aviation policy. Further audience-engaged discussion followed, and participants shared what key technologies, economic developments, and societal viewpoints will best facilitate a transition toward sustainable aviation into the future.

The workshop concluded with breakout sessions during which participants engaged in focused discussions about the sustainable aviation topics presented during the workshop. The outcomes were intended to assist in establishing objective sustainable development goals and strategies to address the climate, economic, and societal priorities of the industry.

This report provides a summary of the technical challenges, multidisciplinary developmental priorities, and community-driven consensus on future needs for sustainable aviation. An overview of technical discussions is provided, followed by a summary of audience opinions on pivotal sustainability issues in aviation. This report concludes with a summary of outcomes resulting from breakout discussions.

Technical Overview of Sustainable Aviation Topics

A series of topical overviews were provided by field experts during the Sustainable Aviation Workshop:

- **What is Sustainable Aviation?:** Phil Ansell, Associate Professor of Aerospace Engineering at University of Illinois Urbana-Champaign
- **Impact of Aviation on the Climate:** Jerry Cline, Senior Scientist at GE Aerospace
- **Aviation in a Transportation Ecosystem:** Yolanka Wulff, Executive Director, Community Air Mobility Initiative
- **Airports as a Transportation-Energy Nexus:** John Wagner, Airport Program Administrator, Clark County, Nevada, Department of Aviation
- **Future of Aircraft Configurations and Technology:** Rich Wahls, Sustainable Flight National Partnership Integration Manager, Aeronautics Research Mission Directorate, NASA
- **Future of Energy Systems:** Scott Cary, Ports and Airports Project Manager, NREL
- **Sustainable Aviation Policy:** Arthur Orton, CLEEN Program Manager, FAA

These presentations provided the technical context underpinning sustainability challenges and opportunities facing the broad aviation community. Key discussion points from these presentations are provided in the following.

What is Sustainable Aviation?

Sustainable aviation as described during the workshop is an air transportation system that maintains the connectivity of communities and mobility of people, goods, and services while minimizing negative impacts to human health, fostering productive quality of life, and conserving natural resources [1]. The United Nations' sustainability goals, which are centered on humans flourishing, provide a framework for this definition. This definition provides a description of the role of aviation within local and global society, as well as the environmental, economic, and social developmental constraints necessary to ensure longevity of this industry.

Despite notable technological efficiency improvements in aviation of approximately 2% annually, aviation activity continues to grow in revenue passenger kilometers (RPKs) 3.6% annually, resulting in continuous increases in emissions. A representation of the evolution in global fleet fuel efficiency (kg CO_2/RPK), air traffic (RPK/yr), and emissions (kg CO_2/yr) is shown in Fig. 1, alongside a forecast that assumes similar 2% efficiency improvements and 3.6% increases in flight activity across future decades. This comparison underscores how a business-as-usual approach could result in a growth in direct CO_2 emissions associated with aviation growing by approximately 50% by the year 2050. Technology improvements alone are not the answer to fostering sustainability, and a more fundamental shift in the art and practice of aviation will be required to achieve sustainable development goals. Several components must be considered to support a sustainable aviation transportation system, including rethinking aviation's purpose, its beneficiaries, and how success is defined.

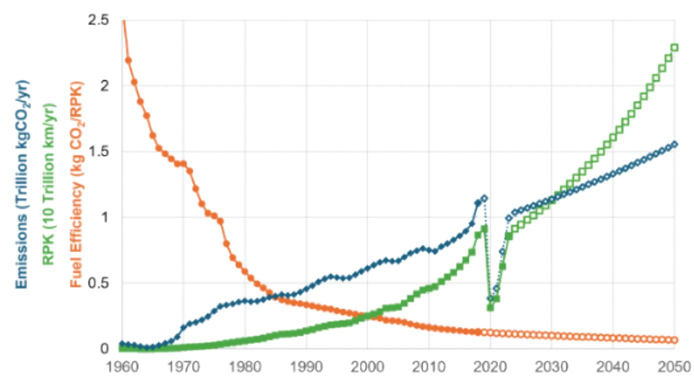

Fig. 1 *Historical development (solid symbols) and future forecast (open symbols) of aircraft fuel efficiency, flight activity (RPKs), and annual CO2 emissions with no adoption of alternative fuels.*

Impact of Aviation on the Climate

There is a need to balance near-term incremental advances in air transportation and transformative developments in advanced airframes, propulsion, and infrastructure to handle environmental and climate challenges in the long term. Aviation, which relies heavily on fossil fuels, has a negative impact to the climate due to emissions such as CO_2, NO_x , and other species, as well as the production of contrails. A summary of the products of combusting 1 kg of jet fuel is summarized in Fig. 2. Aviation currently contributes to 2–3% of all human produced CO_2. NO_x contributes to negative local air quality as well, having a net warming effect driven by ozone creation. The net warming effect from the production of high-altitude contrails is significant, even when compared to aviation CO_2, though with a much shorter lifetime impact. A summary of the change in global surface temperature imposed by various emissions across a range of industries is shown in Fig. 3, based on the IPCC AR5 report [2]. Without new technologies including airframes and propulsion systems, operations and infrastructure, energy sources, and market changes, these impacts are projected to grow.

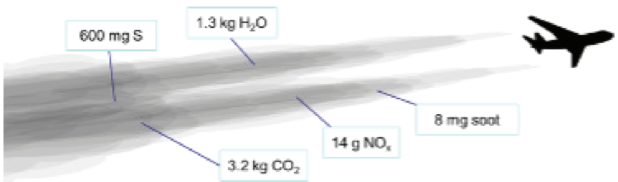

Fig. 2 Emissions produced by combustion of 1 kg of kerosene jet fuel.

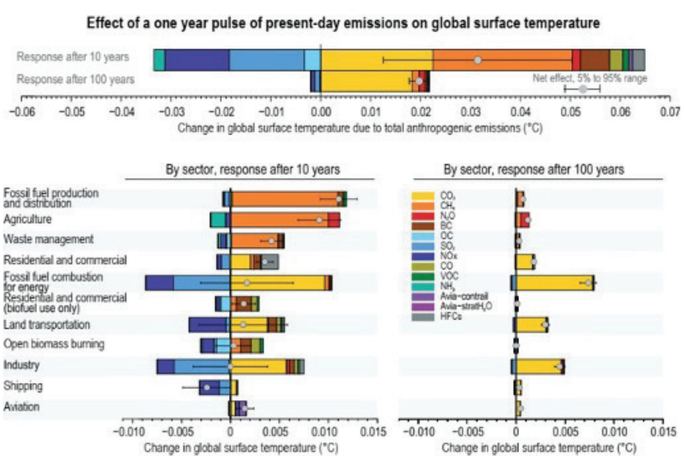

Fig. 3 Global surface temperature impacts imposed by various emissions, including short-term (10 year) and long-term (100 year) response times [2].

Aviation in a Transportation Ecosystem

When determining the role that aviation takes within a sustainable transportation ecosystem, it is important to contextualize the built environment and how transportation interfaces within this infrastructure. Currently, within the United States and many other parts of the world, the built environment takes the form of one of five different categories, summarized in Fig. 4. Currently, aviation predominantly facilitates long-distance travel and cargo transport between edge city regions, or other locations adjacent to high population density, though strategies should be tailored to meet a diverse array of needs, use cases, and urban contexts. Such a centralized approach to long-distance transportation also requires consideration of multimodal integration to achieve a connected airport, as well as careful consideration of air traffic flow management logistics. To ensure that the sustainability goals inherent to mobility and transportation are sufficiently met, an application of the STEPS equity framework [3] is recommended, which is recast here as:

- **Spatial:** Spatial factors that compromise travel needs (e.g., excessively long distances between desired destinations, lack of public transit to/from transportation access point)
- **Temporal:** Travel time barriers that inhibit a user from completing time-sensitive trips
- **Economic:** Direct costs (e.g., fares) and indirect costs (e.g., smartphone, Internet, credit card access) that create economic hardship or preclude users from completing travel
- **Physiological:** Physical and cognitive limitations that make using standard transportation modes difficult or impossible (e.g., infants, older adults, and disabled)
- **Social:** Social, cultural, safety, and language barriers that inhibit a user's comfort with using transportation

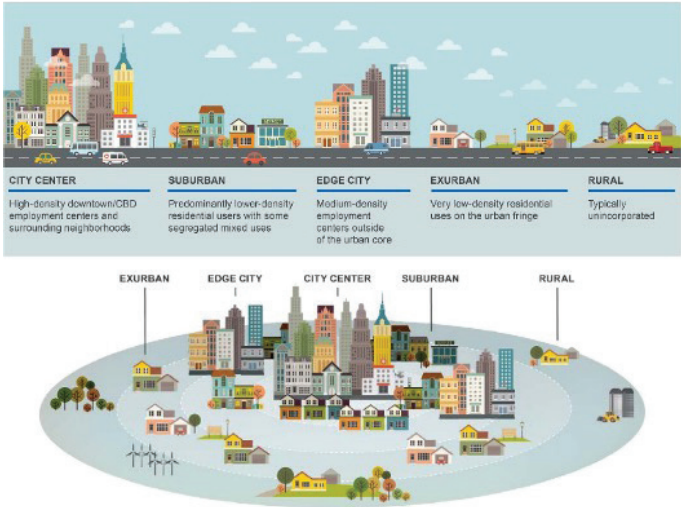

Fig. 4 *Five classifications of the built environment, after Shaheen et al. [4].*

Airports as a Transportation-Energy Nexus

Airport infrastructure development involves extensive planning, regulatory approval, construction, and capital expense. For this reason, airports are intentionally designed to be future-ready wherever possible, requiring foresight into evolving technologies, passenger expectations, and opportunities to accommodate future growth. New large airport projects are commonly associated with lifetimes well beyond a decade. The long-distance nature of aerial transportation, as indicated in Section II.C, imposes a highly localized concentration of dispensed energy. For this reason, reconfiguring conventional energy systems at airports requires substantial redevelopment and capital expense. The long lifetimes of airport infrastructure underscore the need to accurately capture the future energy requirements of future aircraft fleets. With the future of aviation energy being a current source of uncertainty, it is important to ensure that future trajectories of aircraft power and energy systems will be communicated to and considered as a component of airport infrastructure developments.

Future of Aircraft Configurations and Technology

The development of advanced technologies for aircraft and advanced, ultra-efficient integrated platforms remains an area of continued development within the aviation industry. Currently, there are numerous future concepts being explored, all of which require varying degrees of readiness, aspiration, and infrastructural/operational change. These trades are effectively captured by the ICAO Long Term Aspirational Goal (LTAG) report [5], which establishes sustainability improvements enabled by aircraft technology across a range of future scenarios. Contributions by alternative airframes, advanced propulsion systems, and renewable energy integration are characterized through the year 2050. An example forecast of the fleet-wide energy consumption of narrowbody jet aircraft is shown in Fig. 5, assuming natural advancements in tube-and-wing aircraft, inclusion of advanced concept aircraft, and substantial aircraft and propulsion architecture changes that include non-drop-in fuels. However, it was emphasized that commercial viability is about more than just technology readiness, but also availability of resources, market demands, and other elements of practicality. Investments in potential game-changing options are currently happening, though substantially more capital investment will be required before these advanced future aircraft technologies are realized.

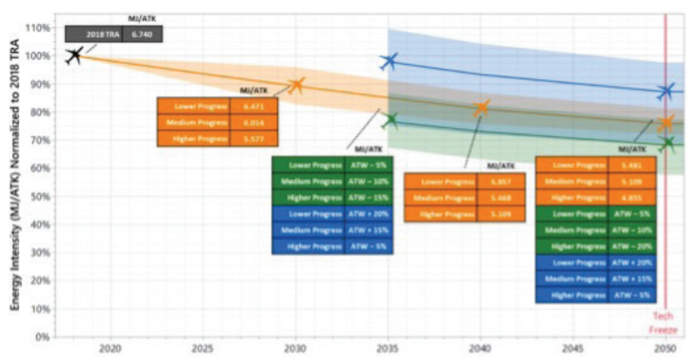

Fig. 5 *Narrowbody technology and concept energy intensity trend of ICAO LTAG report [5].*

Future of Energy Systems

The industry goals for net-zero CO_2 aviation by 2050 will require significant development in renewable and alternative energy systems for aircraft. These advancements in transportation energy will require partnerships across stakeholders within the aviation sector, including airports, airlines, utilities, fuel producers, and others. Current approaches to next-generation energy supply systems for aviation include biogenic SAF, power-to-liquid E-Fuels, hydrogen, and stored electrical energy, as summarized in Fig. 6. Successfully integrating any one of these renewable energy approaches is a substantial challenge due to the extreme power and energy requirements of individual transport-class aircraft, which rivals the full suite of existing power used to operate entire airport systems. However, the broader sustainable aviation ecosystem is more than just about aviation fuels but rather about requiring the entire value stream to be decarbonized. Doing so is a recognized challenge, owing to the highly dynamic supply chain, multitude of energy sources and technologies utilized, coordination across new and existing stakeholders, and competing trends in resource availability, community goals, and societal pressures.

Fig. 6 Conceptual representation of next-generation aviation energy supply chain.

Sustainable Aviation Policy

Aviation is, by nature, a global enterprise that connects people, supports trade, and enables exploration. However, consistency is necessary to ensure safe, secure, and orderly aerial transportation. Policy provides key contributions that ensure these priorities are maintained within and across nations and states. One example is the International Civil Aviation Organization (ICAO), which has established a harmonized vision to achieve sustainable growth of the global civil aviation system. The ICAO Committee on Aviation Environmental Protection (CAEP) has provided pivotal policy intervention, Standards and Recommended Practices (SARPs) related to aircraft noise and emissions. An example of the various policy outcomes of CAEP across the past four decades is shown in Fig. 7.

When considering future sustainable development goals for aviation, policy plays several key roles in facilitating progress, including:

- **Setting goals:** Assist in establishing aspirational goals and roadmaps to align the broader international and/or domestic community
- **Setting standards:** Ensure that the latest and greatest technologies are being used in production aircraft
- **Incentivizing development:** Directly investing to overcome technical risks, achieve economies of scale, and driving development of new technologies, science, and solutions
- **Establishing alternate measures:** Identifying and enacting a basket of other measures when direct improvements in technology, operation, and fuels cannot address sustainability goals.

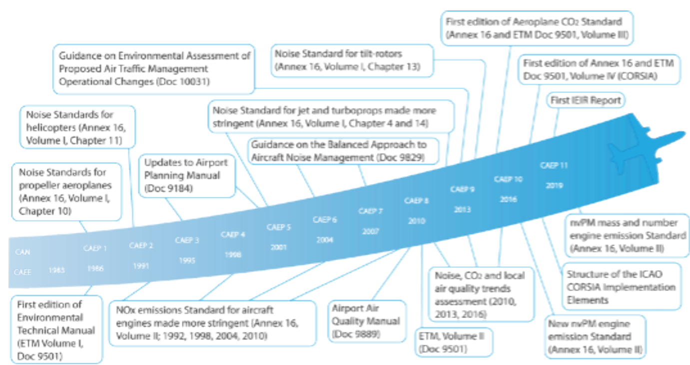

Fig. 7 Summary of ICAO CAEP meetings and set standards for Member States.

Summary

To foster sustainability across the breadth of the aviation industry, several areas of development were presented:

- *Airframes:* While conventional tube-and-wing configurations are likely to continue to dominate the industry in the near term given current investment, further improvements on such optimized configurations are difficult.

  Alternative airframe configurations, such as hybrid or blended-wing-body aircraft, transonic truss-braced wing, and novel fuselage concepts such as the double bubble D-8 could enable significant fuel burn and noise reductions.

- *Propulsion:* Development of new airframes may also be driven by advanced propulsion concepts, such as propulsion-airframe-integration including boundary-layer ingestion and open-rotors, as well as electrified aircraft propulsion in both hybrid and mega-watt class configurations.
- *Operations:* Many additional approaches that do not necessarily involve new airframes. Such innovations include technologies to optimize ground operations and flight routes locally and globally.
- *Energy:* A departure from traditional fossil fuels into alternative energy sources can also contribute to significant reductions in emissions. Examples include the use of sustainable aviation fuels (SAFs), hydrogen, and electrification. Infrastructure modifications will support refueling and supply of alternative energy sources. In addition, the rapid development of electrification has opened the possibility for emerging markets previously underserved by aviation.
- *Integration:* It was emphasized that changes in airframe and propulsion configurations would require extensive financial and time investments and flight demonstrations to reduce risk. In addition, collaboration among various stakeholders, such as airports, airlines, utilities, and fuel providers is essential to enable a diverse and sustainable energy landscape. New markets also raise questions with regards to integration into the current airspace as well as environmental, social, and economic impacts of congested flight paths.

Outcomes of Workshop Activities

Responses from Poll Questions

Poll questions were presented throughout the workshop, giving participants an opportunity to respond to various questions related to aviation and sustainability. The workshop consisted of approximately 30 participants, with 11% identifying their professional role as student, 13% as academic, 55% as industry, 16% as government, and 2% as other. The initial poll questions were used to gauge participant mindsets regarding sustainable aviation and what kinds of impacts are relevant. Participants were asked what key themes should be included in AIAA's definition of sustainable aviation. The results, shown in Fig. 8, indicate a strong emphasis on emissions, fuel, energy, and CO_2.

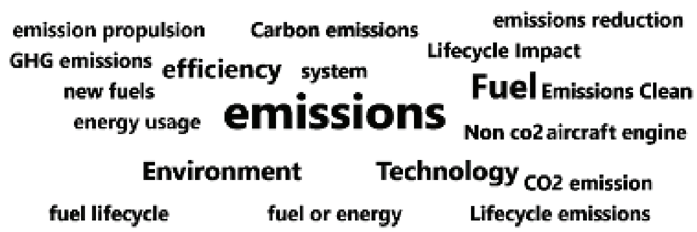

Fig. 8 *Poll Responses: What key themes should be included in sustainable aviation?*

Participants were asked what kind of climate impacts are part of their organization's strategy toward sustainability. According to the results shown in Fig. 9, there is a common consensus on importance of CO_2 and non-CO_2 emissions.

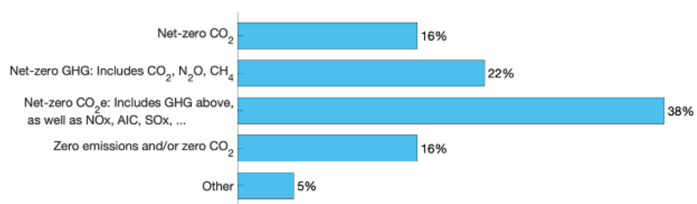

Fig. 9 *Poll Responses: What emissions metrics are important to your organization?*

The participants were asked to rank the transportation roles that are most important for aviation to serve in a sustainable transportation ecosystem. According to the results shown in Fig. 10, greater importance is placed on long-range and mid-range travel, followed by freight and shipping, and then shorter forms of travel such as regional and thin-haul local travel.

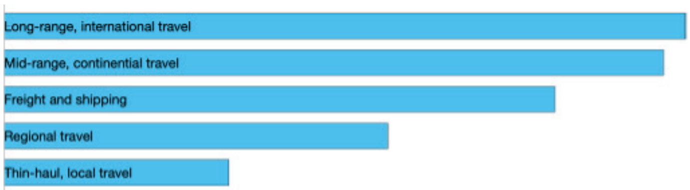

Fig. 10 *Poll Responses: Which transportation roles are most important for aviation to serve?*

The following polls centered around which areas of improvement are needed to enable sustainable aviation. The participants were asked which areas are perceived as being the current bottleneck to sustainable aircraft development. According to the results in Fig. 11, fewer participants viewed the challenges being fundamental limits in technology, access, or the implementations of new standards. Rather, a majority viewed the challenge as being investment requirements for bringing sustainable aviation technologies into market.

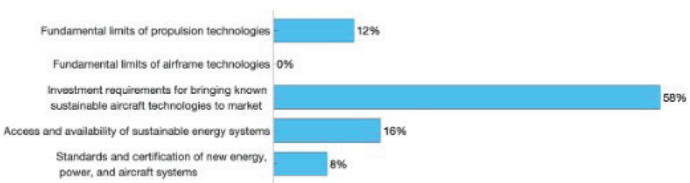

Fig. 11 *Poll Responses: What bottlenecks prevent technology-to-market progress of sustainable aircraft?*

Participants were asked to rank where energy system developments are needed in the short term (current–2035) and long term (current–2050). Responses differed for both long and short term. According to the responses in Fig. 12, renewable electricity generation and/or biogenic feedstock cultivation was ranked highest, followed by issues in standards and certification in the near term. In the far term however, according to Fig. 13, more focus is placed on energy processing and infrastructure. Carbon capture and storage ranked low in the responses for both the near term and far term.

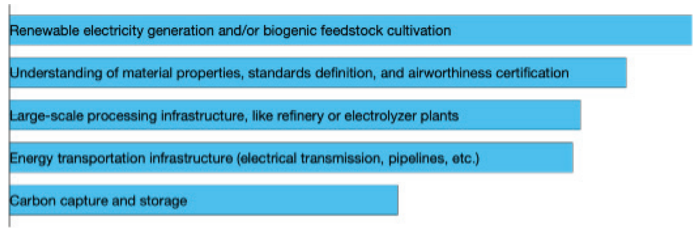

Fig. 12 *Poll Responses: What energy system developments are needed in the near term (current–2035)?*

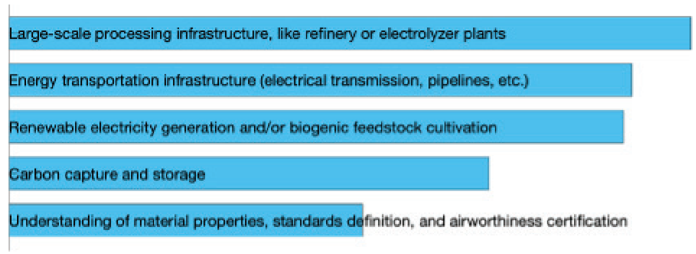

Fig. 13 *Poll Responses: What energy system developments are needed in the far term (current–2050)?*

Finally, participants were asked which policy roles require the most immediate action in the current landscape to facilitate progress in sustainable aviation. Consistent with the bottlenecks shown in Fig. 11, incentivizing development was perceived as the highest priority, followed by setting standards.

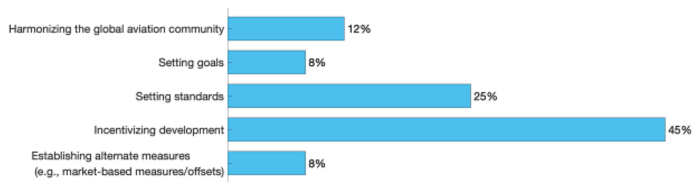

Fig. 14 *Poll Responses: Which policy roles require the most immediate action for sustainable aviation?*

Responses from Breakout Sessions

Four groups:

- Atmospheric and Climate Impacts of Aviation
- Aircraft Technologies: Airframe and Configuration
- Aircraft Technologies: Power and Propulsion
- Aviation Energy, Infrastructure, Markets, and Operations

Discussion topics related to two themes:

- What is sustainable aviation and what are the key problems that we need to solve? How can AIAA contribute as a community?
- What are the barriers to sustainability inherent to specific technical areas? What is needed to advance?

Responses from the participants:

Atmospheric and Climate Impacts of Aviation:
This group highlighted the need for awareness that while aviation contributes a small percentage to CO_2 emissions today, it may contribute to larger portions or be dominate in the future. The group highlighted the system-level development needs to address sustainability challenges, including attention to beyond just the aircraft. Sustainability efforts that could include market case or top-down decisions were noted, such as in the case for Apollo missions. In particular some actions that should be undertaken by AIAA were discussed, including developing an AIAA sustainability statement, serving as a central hub for the community to track progress, and acting as a convening point for the involved interdisciplinary groups that are contributors to these efforts.

Aircraft Technologies: Airframe and Configuration: The group participants highlighted the inherent conservatism and hesitance to change of the aviation industry that is in need of improvements beyond simple increments. Large changes in support of sustainable solutions may impose potential economic costs and development risks that are a key challenge to companies, which also can raise additional concerns on impacts to customers and access to air travel. Thus, market opportunity, market forcing, or mandates are seen as a necessity to promote the development of sustainable solutions. The group noted that the economic challenges may be larger than the technical ones. Other comments included potential improvements that could be made via better communication of critical data or information between original equipment manufacturers (OEMs) and the aircraft operators, as well as between different global regions to assist in understanding the sustainability problem. This is especially important given that aviation is expected to contribute a higher percentage of current CO_2 emissions compared to current industry in the future.

Aircraft Technologies:
Power and Propulsion: Participants highlighted that simply reducing the number of flights is not a viable solution to sustainability, as sustainability implies performance of flight activity. This group also noted the importance of communication of information pertaining to aircraft and engines, with emphasis on collaborative system design, and that policy and markets are drivers for pushing these efforts forward. The need for better tools for aircraft modeling and sustainability assessment is also important.

Aviation Energy, Infrastructure, Markets, and Operations:
Participants highlighted that climate is typically cited as the primary focus in discussions about sustainability; however, it is difficult to reconcile the economic implications of climate-friendly solutions. Sustainable aviation fuels were noted as a safe option, requiring little changes to the aircraft systems and products in comparison to other options, but this places the burden of the problem in the hands of the energy markets, and it is unclear where the energy is going to come from. The group also noted complexities in the exchange of information between OEMs and customers like airlines, as there is often lack of alignment in what they desire.

Conclusions and Recommendations

To retain the relevance of the aviation sector, sustainability efforts must be fostered and prioritized, as alternatives such as flight avoidance are not feasible options. Addressing emissions requires more than incremental improvements that necessitate harmonized approaches to energy and technology, in addition to further financial support. A significant factor in promoting sustainability is either a clear market opportunity or policy mandates/accountable sector commitments that are imposed. Promoting sustainable aviation also requires better coordination between stakeholders within the aircraft product supply chain, as well as new and existing adjacent groups. In addition, advancing sustainable aviation requires further development of tools and practices that engage at the system level, including factors beyond the aircraft.

Finally, AIAA's role in sustainable aviation should be to develop a sustainability statement, serve as a convening nucleus for the community, and build value-added content within programming and products.

Appendix

Notes from Breakout Sessions

Atmospheric and Climate Impacts of Aviation:

- Sustainability requires us to consider development and outcomes from a system level, which includes contributors beyond the aircraft
- Awareness that aviation is a modest percentage of today's CO_2 emissions, but in the future will become a dominant proportion of all sources
- Methods of driving sustainability include market case or top-down decisions (e.g., Apollo missions)
- AIAA should: (a) have a sustainability statement, (b) be a place where we monitor progress, and (c) serve as a convening point for the interdisciplinary groups involved
- AIAA should start adding content and work to expand cross-functional efforts with other communities
- We do not need a roadmap, as there are numerous we can use

Aircraft Technologies: Airframe and Configuration:

- The need for leaps beyond increments, but much of the community is uncomfortable with the way this will change the landscape of developing aerospace systems
- Aviation is inherently a conservative business, so much of the industry is unwilling to make big leaps that are tied to appreciable risk
- Concerns about economic costs of "sustainable" solutions (impact to consumers and who can fly)
- Awareness that aviation is a modest percentage of today's CO_2 emissions, but in the future will become a dominant proportion of all sources
- The importance of market forcing to enable opportunities for sustainability (business case)
- Developments are only anticipated if there is: (a) a market opportunity or (b) a mandate
- The challenge is not making a net-zero CO_2 aircraft, but rather making it economically feasible
- Need to have better conversations between OEMs and the aircraft operators
- Often difficult to obtain necessary information from certain global regions, which would help to understand the sustainability problem

Aircraft Technologies: Power and Propulsion:

- Sustainability implies the permanence of flight activity – cannot rely on limited resources and the trivial solution (no flight) is not viable
- Need more tailoring of systems between aircraft and engines
- Need better tools for aircraft modeling and sustainability assessment
- Driving arm of policy and markets
- Why not use some of the tools we have readily available (e.g., fly slower)? This was mentioned in a different group as well
- More collaborative system design, where suppliers can help drive airframe topology rather than top-down performance requirements. Set standards early for better collaboration between companies (pseudo-vertical integration)

Aviation Energy, Infrastructure, Markets, and Operations:

- Climate serves as the area of priority in most concerns about sustainability
- Difficult to reconcile with economic implications of climate-friendly solutions
- SAF is a safe option as it requires very little change to the aircraft systems, products, etc., but this effectively punts the problem to the energy markets. Unclear where the energy is going to come from
- Complexity in connecting across OEMs and customers, and lack of alignment in what customers (airlines) want

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