HORIZON 2050

A Flight Plan for the Future of Sustainable Aviation

AEROSPACE INDUSTRIES ASSOCIATION & ACCENTURE

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Airlines for America (A4A)
Alaska Airlines
Bell Textron
Boom Supersonic
easyJet
Embraer
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GE Aviation
Georgia Institute of Technology (Georgia Tech)
Gulfstream
Honeywell
Hyundai
Joby Aviation
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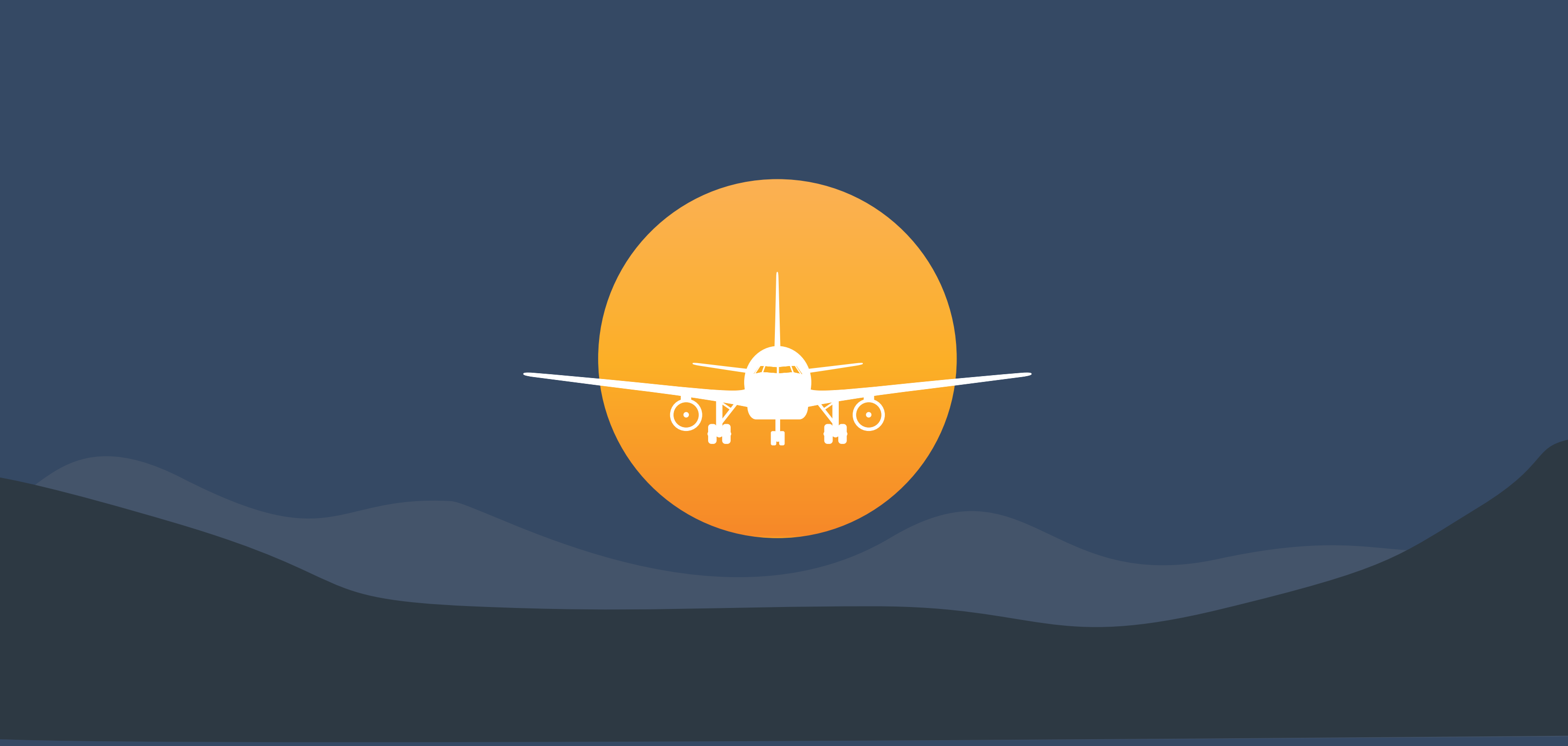

EXECUTIVE SUMMARY

The challenge facing aviation today is a steep one: The number of global air passengers is projected to nearly double over the next 20 years, despite the current constraints of the pandemic.[1] This growth will drive higher fuel consumption, which is expected to climb to 370 million gallons per day. All else being equal, more fuel consumption means more carbon emissions, and without action, aviation-related emissions are likely to increase 40% by 2040.[2]

The aviation industry is committed to action and has made strong commitments to achieve net-zero emissions by 2050 globally and in the United States.

This climate study is centered around a key question: How can the aviation industry reach its goal of net-zero carbon emissions by 2050?

The objective is to minimize the use of carbon offsets and maximize the potential contributions of other strategies. It will take a commitment to embracing a suite of solutions large and small. It will take dramatic changes to airport operations and infrastructure. It will take massively scaling up the production of sustainable aviation fuel (SAF) and building new energy infrastructure for green hydrogen and electricity supplies at airports. And, crucially, it will take cutting-edge aerospace technologies. Reaching decarbonization targets will depend on a combination of policies, regulations, incentives, and technological solutions. Different solutions will be available for different aircraft on different time horizons.

The industry has, in fact, been committed to sustainability for some time. Today's modern aircraft are 80% more fuel efficient than the first airliners and produce 50% less CO_2 than the same ones in 1990. Data shows that each new generation of aircraft improves fuel efficiency by 15-25% on a per-passenger-mile basis. Still, much work remains to be done.

"Horizon 2050: A Flight Plan for the Future of Sustainable Aviation," a new report from Accenture LLP and the Aerospace Industries Association (AIA), is a comprehensive guide to prioritizing onboard decarbonization technologies based on technology-specific data and analysis.

The study found that offsets and operational benefits alone are insufficient and that original equipment manufacturers (OEMs), airplane platform technologies, and associated ecosystem partners are instrumental in reducing emissions.

It identifies technology solutions based on emission-reduction potential, maturity status, and applicability within time horizons relevant to aircraft entry into service (EIS):

- Near-term and market-ready technologies (today-2030)
- Mid-term technologies, typically in planning stages (2030-2040)
- Longer-term technologies, mostly in research and development (2040 and beyond)

The time horizons help to sort technologies by their applicability to specific market segments, providing an important assessment lens. It is unlikely that there will be multiple new narrow-body or wide-body aircraft programs in the next two decades, so the industry has a finite opportunity for maturing technologies in time for these aircraft programs to enter service.

Between now and 2030, we anticipate several solutions for market entry. Technologies such as composite structures and flight deck optimization software are already progressing toward adoption at scale.

In the following decade, the industry anticipates increased electrification, such as hybrid-electric propulsion for regional aircraft, new aerodynamics like transonic truss-braced wing [TTBW] for regional and narrow-body aircraft, advanced composites, new propulsion (e.g., open rotor and high-pressure ratio core for wide-body, narrow-body and regional aircraft) and geared turbofan engine for wide-body aircraft. We also expect laminar flow control technologies to be available for regional and narrow-body aircraft. These technologies are advancing, and additional funding to accelerate readiness in time for aircraft Entry into Services (EIS) opportunities will ensure that they reach their emission-reduction potential.

Beyond 2040, we expect to see more innovative solutions, such as hydrogen propulsion for regional and narrow-body aircraft, all-electric propulsion for regional aircraft and revolutionary fuselage designs, including blended-wing body (BWB) for wide-body aircraft. Other technologies—like TTBW for wide-body aircraft and fuel cells for onboard power for regional and narrow-body aircraft—are also expected to enter the market in the long term.

To maximize impact, these technologies could be used in combination—for instance, a wide-body hydrogen-powered aircraft with a BWB fuselage. The impact of different technologies over time is highly dependent on the system, mission profiles and evolving emission-reduction potential. Due to market uncertainty, it's difficult to predict the success of technologies in early development stages.

One main consideration for longer-term technologies, such as all-electric and hydrogen propulsion, is that although these technologies improve vehicle (or direct) carbon emissions by up to 100%, the likelihood of realization is less certain. In addition, the upstream emissions costs must be weighed against the potential benefits: Only fully renewable electricity and green hydrogen deliver 100% benefit across the energy supply life cycle. Making hydrogen propulsion a reality will require significant research and development investment, along with infrastructure upgrades to accommodate and refuel hydrogen aircraft in airports. At present, green hydrogen production does not exist at scale and will require significant investment and development.

All-electric propulsion can only reach its potential with the aid of high-density batteries, electricity from renewable energy sources and new airport delivery infrastructure. Hydrogen propulsion promises significant emission improvement but will require a massive investment in R&D and infrastructure to mature the technology and an energy supply base to provide a continuous supply of renewable, green hydrogen fuel at airports. The industry must also ensure that the emissions costs in production don't negate the benefits of the technology once applied to an aircraft.

This report focuses solely on aircraft and engine platform technologies, but it is important to note that the industry will not achieve its net-zero ambitions without substantially decarbonizing the energy supply—whether in the form of SAF, hydrogen or electricity stored in batteries. Success requires addressing both the energy supply and the aircraft and engines platforms in tandem.

Finally, for these technologies to succeed, government and industry need to be aligned. The AIA Policy Roadmap outlines various tools and recommendations for how government can play a role in advancing these technologies, including creating a cohesive, multiyear strategic plan tied to reliable funding, working with international organizations to shape industry standards and ensuring that new technologies can be incorporated as quickly as possible while maintaining safety as the top priority.

Stakeholders must align on the timing of market entry of these technologies. Success will require an ecosystem approach involving government, public-private partnerships and academia.

AIA and Accenture recognize the challenges the industry faces in turning its aspirations into actions, and our goal is to help stakeholders do just that. We hope that "Horizon 2050" will serve as a flight plan for the journey to a more sustainable future in aviation and beyond.

PART ONE
TECHNOLOGY REPORT

A. SECTION OVERVIEW

To understand how the aviation industry could mitigate growing carbon emissions, the Air Transport Action Group (ATAG) commissioned the Waypoint 2050 report. In participation with the International Air Transport Association (IATA),[3] that report details how to achieve decarbonization through improvements in operations and infrastructure, offsets, sustainable aviation fuels (SAFs) and aircraft technologies.

Addressing the issue of carbon emissions in the aviation industry requires sustained commitments and solutions from the supply chain and manufactures, as well as the operators. Through a series of executive interviews with stakeholders—including aircraft original equipment manufacturers (OEMs), tier-one suppliers, airlines, airports, government agencies and academia—and a research and literature review, we identified an initial set of 35 technologies. We selected a focused set of 11 technologies that are the most promising to help the industry achieve their goal.

The maximum addressable emission-reduction potential for each technology is an estimate that may change over time.

This study is meant to provide well researched recommendations to achieve the goal of net zero by 2050.

B. TECHNOLOGY SELECTION METHODOLOGY

In the beginning stages of data collection, the team interviewed stakeholders from various industry segments. The sample size was varied enough to balance out inherent stakeholder biases.

The organizations and companies that participated in the stakeholder interviews included airframe and engine OEMs, technology companies, suppliers of components and systems, airlines, airports, academia and government bodies. Senior-level executives, as well as technical, sustainability, technology, and government affairs experts were consulted.

We first assessed the initial candidates using a five-step methodology. Then technologies were selected based on their stated emission-reduction capabilities. Third, we confirmed that the technologies are being actively pursued by the industry. The fourth step identified the applicable market segment, and the fifth and final step determined the time horizon for market entry. This methodology, as shown is Figure 1, resulted in the focused list of technologies that was used to drive final assessments of the study.

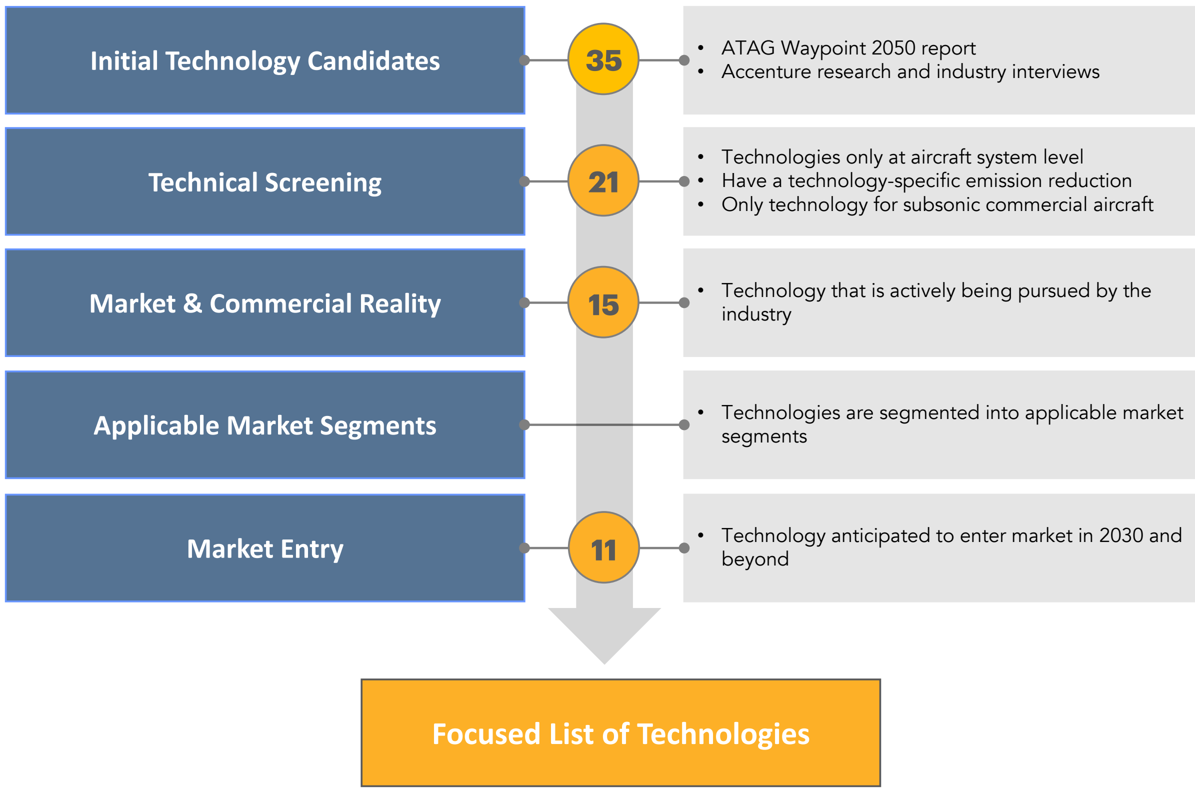

Figure 1 – Aircraft Technology Decarbonization Selection Methodology

Initial Technology Candidates

The stakeholder interviews explored a wide range of topics, including technology and solution time horizons, maturities, investment required, allocated research and development, partnership opportunities, disruption and innovation, potential improvements, anticipated roadblocks, and regulatory or policy changes needed to accelerate adoption. This ecosystem approach revealed several common themes across the stakeholder segments as depicted in Figure 2.

Airframe & Engine OEMs

- **Scale SAF** adoption by enforcing **government regulations** and **incentives** to stimulate use
- **Accelerate engine tech development** (e.g., propulsion, fans, thermal) for med/long haul
- Increase investment into improving batteries for **long-range electrification**
- Increase investment into **hydrogen fuel cells**
- Integrate **hybrid power** for mid term
- Develop more **advanced materials** (e.g., composite, alloys) for weight reduction

Technology Companies

- **Digital Twin/Thread**
- Infrastructure investments
- **Rapid innovation** with test-and-learn approaches (e.g., start-up mindset)
- Rapid advancements in **autonomous flight and electrification**
- Collaborate with **regulators**

Airlines

- **Short-term** focus is **on SAF** scale-up
- **Initial commitments** have been made **for electric aircraft**
- **Adoption concerns** remain for novel propulsion technologies

Airports

- **Direct communication between OEMs and airports** on fleet modifications/new technologies can facilitate adoption of new technologies
- **Analysis and further data** are required to plan for hydrogen/electric

Academia

- **Increase partnerships** between industry and academia to funnel knowledge toward practice
- Academia could assist with **dampening public concerns** for new technologies (e.g., open rotor) by providing research to increase consumer confidence

Government & Regulatory Bodies

- **Accelerate deployments/certificati**on processes of new technology and extend **harmonization**
- **Increase investment for infrastructure** changes for new technology (hydrogen, electric power)
- **Increase investment** in accelerating novel technologies (e.g., hydrogen)
- **Upskill/educate** government employees to keep up with technology development

Figure 2 – Common Themes and Insights From Stakeholder Executive Interviews

The initial list of 35 technology candidates emerged from the ATAG Waypoint 2050 report, as well as through our stakeholder interviews and industry research. This initial list is shown below in Figure 3.

Identified Technologies

- Bladeless Propulsion (UAM)
- Advanced Composites
- Morphing Wing
- Double Bubble Fuselage
- Electric/Advanced Auxiliary Power Units (APUs)
- Canard
- Box Wing
- Transonic Truss-Braced Wing (TTBW)
- Blended-Wing Body (BWB)
- Open Rotor
- Active Load Alleviation
- Riblets
- FlightPulse
- Electric Vertical Takeoff and Landing (eVTOL)
- Advanced Turbomachinery
- Autonomous Flight
- Civil Supersonic Jet Engine
- Plasma Combustion
- All-Electric Propulsion
- Advanced Fly-by-Wire System
- Laminar Flow Control Technology (Natural and Hybrid)
- Digital Thread
- Structural Health Monitoring
- EV Charging
- Folding Wing Tip
- Adaptive Trailing Edges
- Direct Air Carbon Capture
- Aircraft Surface Treatment Technologies (LEAF)
- High-Pressure Ratio Core Engine
- Geared Turbofan Engine
- Hybrid-Electric Propulsion
- Wingtip Devices
- Fuel Cells for Onboard Power
- Electric Taxiing
- Hydrogen Propulsion

Figure 3 – Technology and Solution Candidates

Technical Screening

We conducted a technical screening of the above technology candidates based on the following criteria:

» Technology must be on-aircraft (for either in-production or retrofit applications) for use on current-generation aircraft or integrated into the systems of new-generation aircraft.

» Technology must have a stated emission reduction.

» Technology must be for subsonic commercial aircraft.

The technical screening resulted in **21 technology candidates** as shown in Figure 4 below.

Identified Technologies

- Bladeless Propulsion (UAM)
- Advanced Composites
- Morphing Wing
- Double Bubble Fuselage
- Electric/Advanced Auxiliary Power Units (APUs)
- Canard
- Box Wing
- Transonic Truss-Braced Wing (TTBW)
- Blended-Wing Body (BWB)
- Open Rotor
- Active Load Alleviation
- Riblets
- FlightPulse
- Electric Vertical Takeoff and Landing (eVTOL)
- Advanced Turbomachinery
- Autonomous Flight
- Civil Supersonic Jet Engine
- Plasma Combustion
- All-Electric Propulsion
- Advanced Fly-by-Wire System
- Laminar Flow Control Technology (Natural and Hybrid)
- Digital Thread
- Structural Health Monitoring
- EV Charging
- Folding Wing Tip
- Adaptive Trailing Edges
- Direct Air Carbon Capture
- Aircraft Surface Treatment Technologies (LEAF)
- High-Pressure Ratio Core Engine
- Geared Turbofan Engine
- Hybrid-Electric Propulsion
- Wingtip Devices
- Fuel Cells for Onboard Power
- Electric Taxiing
- Hydrogen Propulsion

Note: Grayed-out technologies were eliminated based on criteria set at this evaluation stage.

Figure 4 – Resulting Technology Candidates Based on Technical Characteristics

Market & Commercial Reality

Market realities play a critical role in identifying those technologies with the greatest potential. The commercial aerospace industry does not introduce large airplanes frequently, so technology-adoption cycles are lengthy. If a technology promises high emission reduction but is early in the research phase or is unlikely to be pursued due to funding or other commercial factors, we excluded it from the final list. In addition to understanding the timeline of commercial airplanes entering service, other factors that play into identifying these high-potential technologies include market acceptance, public perception and commercial viability.

After addressing these market and commercial realities, we were left with **15 technology candidates** as identified in Figure 5.

Identified Technologies

- Bladeless Propulsion (UAM)
- Advanced Composites
- Morphing Wing
- Double Bubble Fuselage
- Electric/Advanced Auxiliary Power Units (APUs)
- Canard
- Box Wing
- Transonic Truss-Braced Wing (TTBW)
- Blended-Wing Body (BWB)
- Open Rotor
- Active Load Alleviation
- Riblets
- FlightPulse
- Electric Vertical Takeoff and Landing (eVTOL)
- Advanced Turbomachinery
- Autonomous Flight
- Civil Supersonic Jet Engine
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- Advanced Fly-by-Wire System
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- Folding Wing Tip
- Adaptive Trailing Edges
- Direct Air Carbon Capture
- Aircraft Surface Treatment Technologies (LEAF)
- High-Pressure Ratio Core Engine
- Geared Turbofan Engine
- Hybrid-Electric Propulsion
- Wingtip Devices
- Fuel Cells for Onboard Power
- Electric Taxiing
- Hydrogen Propulsion

Note: Grayed-out technologies were eliminated based on criteria set at this evaluation stage.

Figure 5 – Resulting Technology Candidates Based on Market and Commercial Reality

Applicable Market Segment

These 15 technology candidates are applicable across three market segments based on aircraft type and range: regional (R), narrow body (NB) and wide body (WB). By dividing technologies into different market segments, we were able to estimate what the level of carbon emissions will be when these technologies are adopted into the market. Industry research and stakeholder interviews helped inform the technological limitations that some of these technologies face when being developed and scaled to different applications. These limitations are referenced in the technology descriptions found in the Appendix of this section. Figure 6 is the list of 15 technologies and the applicable market segments.

Technologies	Market Segment
Advanced Composites	R, NB, WB
Riblets	R, NB, WB
Adaptive Trailing Edges	R, NB, WB
Transonic Truss-Braced Wing (TTBW)	R, NB, WB
Blended-Wing Body (BWB)	WB
Open Rotor	R, NB, WB
Hydrogen Propulsion	R, NB
All-Electric Propulsion	R
Laminar Flow Control Technology (Natural and Hybrid)	R, NB
Electric Taxiing	NB
High-Pressure Ratio Core Engine	R, NB, WB
Geared Turbofan Engine	R, NB, WB
Hybrid-Electric Propulsion	R
Wing Tip Devices	R, NB, WB
Fuel Cells for Onboard Power	R, NB

Figure 6 – Technology Candidates Segmented Into Applicable Market Segments

Market Entry

We determined the time horizon for market entry by assessing each technology's maturity and rate of progression using NASA's Technology Readiness Level (TRL),[4] the ATAG Waypoint 2050 report[5] and stakeholder interviews for classification. The technologies are broadly classified into the four stages of development using NASA's definitions: research, development, deployment and adoption.

Descriptions and associated TRL stages are shown in Figure 7 below.

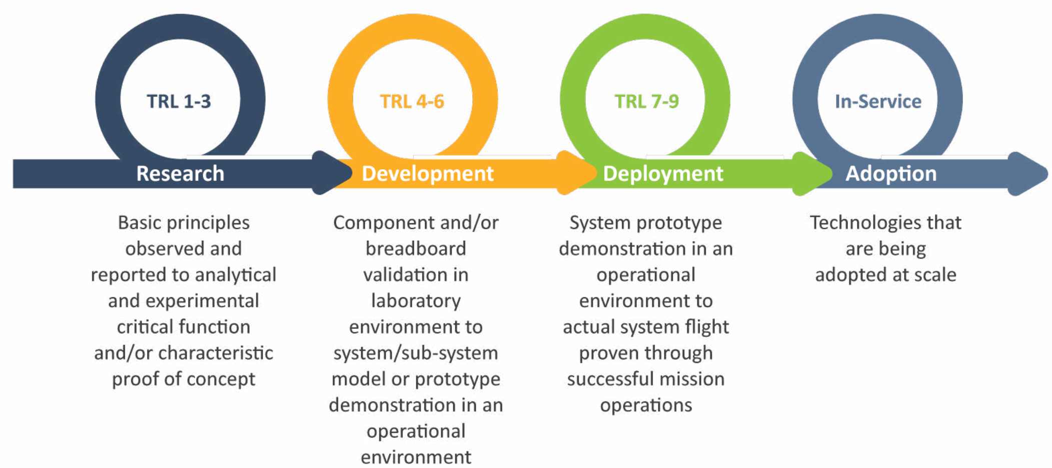


Figure 7 – Technology Readiness Level Stages

Most technologies are in the research and development stages, but further investment from research institutions and industry partnerships would increase their potential to scale.

As a technology evolves into the deployment stage, the last step in technology maturation is to move to the demonstrator level.[6] After a technology has been demonstrated and decarbonization gains are proven, those solutions can progress to the adoption phase, providing an accelerated path for entry into the market.[7] Technologies mature at different rates, and the TRL stage is not meant to be a determining factor for technology progression. They serve as a way to determine maturity and the likely path for entering market.

Figure 8 below shows each technology, its applicable market segment and its TRL stage. This broad classification can help inform decisions about investment and strategic priorities that align with the overall industry direction.

Technology	Market Segment	TRL Stage
Blended-Wing Body (BWB)	WB	Research
Transonic Truss-Braced Wing (TTBW)	WB	Research
Hydrogen Propulsion	R, NB	Research
All-Electric Propulsion	R	Development
Transonic Truss-Braced Wing (TTBW)	R, NB, WB	Development
Geared Turbofan Engine	WB	Development
High-Pressure Ratio Core Engine	R, NB	Development
Open Rotor	R, NB, WB	Development
Hybrid-Electric Propulsion	R	Development

Continued on next page

Figure 8 – Technology Candidates Technical Readiness Level Stage Assessment[8]

(Figure 8, continued)

Technology	Market Segment	TRL Stage
Laminar Flow Control Technology (Natural and Hybrid)	R, NB	Development
Fuel Cells for Onboard Power	R, NB	Development
Advanced Composite	R, NB, WB	Development
Adaptive Trailing Edges	R, NB, WB	Deployment
Electric Taxiing	NB	Deployment
Geared Turbofan Engine	R, NB	Adoption
High-Pressure Ratio Core Engine	WB	Adoption
Riblets	R, NB, WB	Adoption
Wing Tip Devices	R, NB, WB	Adoption

Figure 8, cont. – Technology Candidates Technical Readiness Level Stage Assessment[9]

Although advanced composites are currently in service, widescale application will yield a greater impact on emissions. A new aircraft program would benefit greatly from such improvements in composite technology, and increasing production rates could result in a greater quantity of the structural components of an aircraft.

Assessing the timing for market entry for each technology is essential in determining its potential impact on emissions once deployed and adopted.

Since emission reduction cannot be realized until these technologies are adopted by an airplane that has entered service, identifying the time horizon for deployment is critical.

We developed three time horizons based on stakeholder interviews: now-2030, 2030-2040 and 2040 and beyond.

By mapping the time horizon with the technologies' maturity stages, we can infer that those technologies in the now-2030 time horizon are in deployment and adoption stages, while mid-term to long-term technologies are in the research and development stages.

Technologies	Market Segment
Advanced Composites	R, NB, WB
Riblets	R, NB, WB
Adaptive Trailing Edges	R, NB, WB
Transonic Truss-Braced Wing (TTBW)	R, NB, WB
Blended-Wing Body (BWB)	WB
Open Rotor	R, NB, WB
Hydrogen Propulsion	R, NB
All-Electric Propulsion	R
Laminar Flow Control Technology (Natural and Hybrid)	R, NB
Electric Taxiing	NB
High-Pressure Ratio Core Engine	R, NB, WB
Geared Turbofan Engine	R, NB, WB
Hybrid-Electric Propulsion	R
Wing Tip Devices	R, NB, WB
Fuel Cells for Onboard Power	R, NB

Figure 9 – Technology Entry Into Market Time Horizon Assessment

Several technologies are currently in service or are estimated to enter the market within the next decade, but most of the technologies are anticipated to enter in 2030 or later, paced by new platform availability.

As shown in Figure 9, industry stakeholders anticipate moving toward increased electrification, new aerodynamic and wing technology, increasing advanced composites usage, and next-generation propulsion in the 2030-2040 time horizon. Beyond 2040, industry stakeholders anticipate more novel solutions becoming available, such as hydrogen, full electrification and revolutionary fuselage designs.

Near-term technologies in the adoption stages are in service or slated to be incorporated on aircraft with entry in service prior to 2030. Since these technologies will produce a meaningful decarbonization impact without much additional investment or industry focus, they were eliminated from our final technology list in this report, as shown in Figure 10, except for high-pressure core ratio and geared turbofan engine, which are being assessed for other market segments.

Progressing the final list of technologies with a market entry expectation of 2030 and later will require additional investment. These technologies are mostly in research and development stages, and further support will help move them along the maturity timeline. Before determining the level of industry focus and investment that these technologies need to increase the likelihood of meeting the above-stated time horizons, a deeper understanding of their emission-reduction potential is required. The emission-reduction potential for the focused list of technologies is covered in the next section.

Identified Technologies

- Bladeless Propulsion (UAM)
- Advanced Composites
- Morphing Wing
- Double Bubble Fuselage
- Electric/Advanced Auxiliary Power Units (APUs)
- Canard
- Box Wing
- Transonic Truss-Braced Wing (TTBW)
- Blended-Wing Body (BWB) Fuselage
- Open Rotor
- Active Load Alleviation
- Riblets

- FlightPulse
- Electric Vertical Takeoff and Landing (eVTOL)
- Advanced Turbomachinery
- Autonomous Flight
- Civil Supersonic Jet Engine
- Plasma Combustion
- All-Electric Propulsion
- Advanced Fly-by-Wire System
- Laminar Flow Control Technology (Natural and Hybrid)
- Digital Thread
- Structural Health Monitoring

- EV Charging
- Folding Wing Tip
- Adaptive Trailing Edges
- Direct Air Carbon Capture
- Aircraft Surface Treatment Technologies (LEAF)
- High-Pressure Ratio Core Engine
- Geared Turbofan Engine
- Hybrid-Electric Propulsion
- Wing Tip Devices
- Fuel Cells for Onboard Power
- Electric Taxiing
- Hydrogen Propulsion

Note: Grayed-out technologies were eliminated based on criteria set at this evaluation stage.

Figure 10 – Focused Technologies for Aircraft Decarbonization

C. FOCUSED TECHNOLOGIES

The technologies that make up the focused list are prioritized based on their high potential. They have the greatest potential to reduce emissions and align with industry priorities. As previously indicated in Figure 8, these technologies are in the research, development and deployment stages, with an anticipated market entry post 2030. These technologies require additional investment and government policy guidance. With the right level of support, they could be brought to market in the stated time horizon and provide a promising emission impact reduction by 2050. Since full adoption could take time, the stated time horizon is not a projection.

Figure 11 shows the focused list of technologies.

Focused List of Technologies		
Group	**Technology**	**Market Segment**
New Energy Pathways	All-Electric Propulsion	R
	Hydrogen Propulsion	R, NB
	Hybrid-Electric Propulsion	R
Engine Technology	Open Rotor	R, NB, WB
	Geared Turbofan Engine	WB
	High-Pressure Ratio Core Engine	R, NB
Airframe Configuration	Blended-Wing Body (BWB)	WB
	Transonic Truss-Braced Wing (TTBW)	R, NB, WB
Structures	Laminar Flow Control Technology (Natural and Hybrid)	R, NB
	Advanced Composites	R, NB, WB
Systems	Fuel Cells for Onboard Power	R, NB

Figure 11 – Focused List of Technologies

The emission share achieved by the above focused list of technologies, once adopted and scaled into the applicable market segments, is calculated in the next section.

Maximum Addressable Emission-Reduction Potential

Each technology identified in the above focused list has its own emission-reduction potential as stated by manufacturers, stakeholders or industry experts. The emission improvement at the technology-specific level is the percentage reduction in emissions achieved when compared to the current technology or an existing alternative.

To account for the emission reduction generated by each technology when deployed in the market, a baseline served to anchor the current emission level and subsequent gains. The 2019 COVID-19air travel capacity level was used as the baseline for emission reduction in our study. Since aircraft market segments, flight range restrictions and technology-specific emission reductions impact CO_2 emissions when the technologies are deployed across the global aircraft fleet, these metrics were used as inputs to accurately calculate the maximum addressable emission-reduction potential for each technology, as depicted in Figure 12 below.

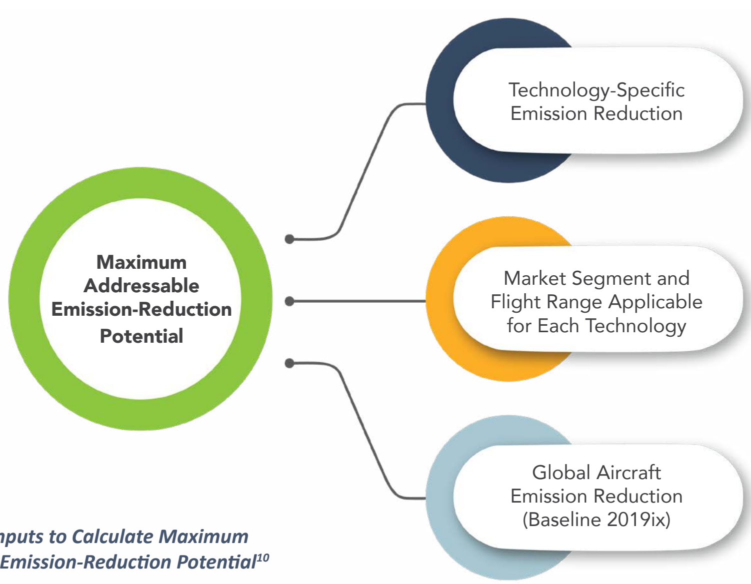


Figure 12 – Inputs to Calculate Maximum Addressable Emission-Reduction Potential[10]

Technology-Specific Emission Reduction and Applicable Market Segments

The fuel-reduction benefits that each individual technology represents and the applicable market segments are important inputs for the maximum addressable emission-reduction potential calculation. As previously described, the applicable aircraft market segments are defined as regional, narrow-body and wide-body aircraft. We considered each technology based on the applicability to these market segments and ranges flown. The technology-specific emission-reduction percentage was gathered from executive interviews, industry research and company-specific press releases and does not necessarily infer to any specific baseline technology. These emissions reductions are vehicle emissions only and do not include any upstream emissions creation. These are further explained in the Appendix.

Focused List of Technologies			
Group	**Technology**	**Market Segment**	**Technology-Specific Emission Reduction ($\%CO_2$ Emission Reduction)**
New Energy Pathways	All-Electric Propulsion	R	100%
	Hydrogen Propulsion	R, NB	100%
	Hybrid-Electric Propulsion	R	20%
Engine Technology	Open Rotor	R, NB, WB	20%
	Geared Turbofan Engines	WB	20%-25%
	High-Pressure Ratio Core Engines	R, NB	5%-10%
Airframe Configuration	Blended-Wing Body (BWB)	WB	20%
	Transonic Truss-Braced Wing (TTBW)	R, NB, WB	8%-10%
Structures	Laminar Flow Control Technology (Natural and Hybrid)	R, NB	5%-15%
	Advanced Composites	R, NB, WB	1%-3%
Systems	Fuel Cells for Onboard Power	R, NB	1%-5%

Figure 13 – Focused List of Technologies and Their Emission-Reduction Benefits

The new energy pathways in Figure 13 will be highly dependent on improvement of the power and energy density of batteries and/or fuel cells to support aircraft missions, as well as the infrastructure to support these technologies. The assumption made in this study are that these technologies will utilize 100% renewable electricity for electricity and hydrogen production. The emission reductions stated above do not account for net emission reductions after the technology is applied to an aircraft as part of a portfolio of technologies.

Global Aircraft Emission-Reduction Baseline

This report uses Accenture's proprietary model for aviation emissions to estimate the commercial aviation CO_2 emissions for each applicable market segment and flight range based on the pre-pandemic flight data (2019). This output served as the baseline for subsequent calculations for emission-reduction potential.

Based on the emissions generated by market segment, we found that narrow-body aircraft produced about 50% of all global aircraft emissions. Wide-body aircraft produced about 45% and regional aircraft produced 5%. [11] These results show that technologies applicable to narrow-body and wide-body aircraft market segments have a larger impact on decarbonization. This can be seen in Figure 14, which shows the commercial aviation 2019 CO_2 emission footprint of the ranges flown by each market segment. Narrow-body and wide-body aircraft contribute significantly more emissions compared to regional aircraft.

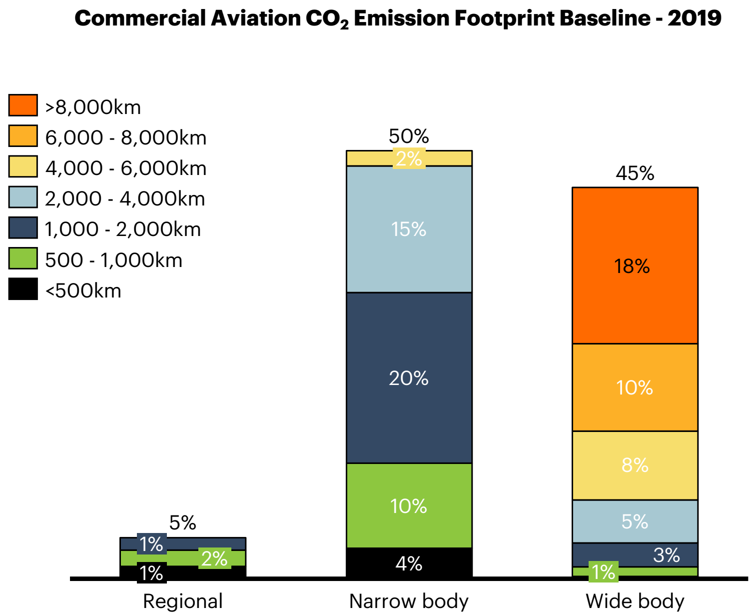


Figure 14 – Baseline 2019 CO_2 Emissions by Market Segment[12]

The emissions for each market segment can be seen in more detail in Figure 15. The current global fleet is split into older- versus newer-generation aircraft types for greater accuracy of emission potential estimation. Older-generation aircraft include regional applications such as E-jets and CRJs, narrow body (A320CEO, 737NG, 757) and wide body (A330CEO, A340, 767, 777). Newer-generation aircraft include the newest regional application variants (E2, MRJ), narrow body (A220, A320NEO family, 737 MAX family) and wide body (787, A350, A330NEO).

		Baseline 2019 Emission Data by Range (million tons CO_2)						
Market Segment		**<500km**	**500 - 1,000km**	**1,000 - 2,000km**	**2,000 - 4,000km**	**4,000 - 6,000km**	**6,000 - 8,000km**	**>8,000km**
R	Old	11.70	15.74	11.85	2.12	-	-	-
NB	Old	27.42	77.58	154.45	113.84	13.32	0.14	-
WB	Old	2.07	8.13	18.06	33.96	52.03	65.33	108.89
R	New	0.01	0.04	0.04	0.01	-	-	-
NB	New	1.79	4.45	9.86	7.90	1.30	0.04	-
WB	New	0.28	1.07	4.96	7.53	14.02	18.67	41.46

Figure 15 – Baseline 2019 CO_2 Emissions Data by Market Segment Used for Calculations

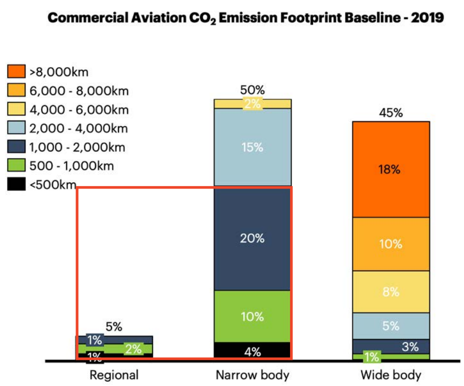
The maximum addressable emission-reduction potential represents the overall industry reduction these technologies would provide, assuming full adoption by the respective market segment. It is a calculation is an estimation and does not factor the estimated market entry of the technology, so the results from this calculation could change as the technology is further developed.

Calculation of Maximum Addressable Emission-Reduction Potential

We calculated the maximum addressable emission-reduction potential—the potential impact on CO_2 emissions if a technology is deployed across the global aircraft fleet—for the focused list of technologies by using the applicable aircraft segments, ranges and emission-improvement potential for the technologies.

An example of the maximum addressable emission-reduction calculation using 2019 CO_2 emissions data is shown below. If a technology can be applied to narrow-body applications and has a range of up to 2,000 kilometers, the sum of the percentage of emissions emitted by that range, as well as all ranges below it, is multiplied by the individual emission improvement of that technology. This results in the maximum addressable emission-reduction potential of that specific technology if deployed across the global narrow-body aircraft fleet.

Technology *(example)*
Applicability: Narrow body
Range: up to 2,000 km
Technology-Specific Emission Reduction: 20%



× **20%** = **Maximum Addressable Emission-Reduction Potential**

Figure 16 – Maximum Addressable Emission-Reduction Calculation Example

Results for Focused List of Technology

The maximum addressable emission-reduction potential for the focused list of technologies is shown below, from highest to lowest potential, based on applicability of the technology and the estimated time horizon for market entry.

The stated emission reduction represents the benefit derived from the specific technology at the market level. Several other factors play a role; for example, we would expect to see different emission-reduction potential from technologies when combined in a single aircraft. Therefore, synergies are expected to drive greater emission reduction when technologies are grouped in a portfolio on the same aircraft program.

Time Horizon: 2030-2040

Grouping	Technology	Market Segment	Maximum Addressable Emission Reduction (% CO_2 Emission Reduction)
Engine Technology	Geared Turbofan Engine	WB	17%-22%
	Open Rotor	R, NB, WB	20%
	High-Pressure Ratio Core Engine	R, NB	4%-9%
New Energy Pathways	Hybrid-Electric Propulsion	R	1%
Airframe Configuration	Transonic Truss-Braced Wing (TTBW)	R, NB	4%
Structures	Laminar Flow Control Technology (Natural and Hybrid)	R, NB	2%-8%
	Advanced Composites	R, NB, WB	1%-3%

Time Horizon: 2040 and Beyond

Grouping	Technology	Market Segment	Maximum Addressable Emission Reduction (% CO_2 Emission Reduction)
New Energy Pathways	Hydrogen Propulsion	R, NB	38%-53%
	All-Electric Propulsion	R	1%
Airframe Configuration	Blended-Wing Body (BWB)	WB	9%
	Transonic Truss-Braced Wing (TTBW)	WB	5%
Systems	Fuel Cells for Onboard Power	R, NB	1%-3%

Figure 17 – Maximum Addressable Emission-Reduction Potential for Focused List of Technology[13]

The maximum addressable emission-reduction percentages shown in Figure 17 are built on the assumption that a clean energy source and a sustainable energy grid will be used when producing the technology, particularly for new energy pathways. This estimate only accounts for the emission reduction of the technology and does not consider the system-level emission-reduction impact when the technology is applied to an aircraft as part of a portfolio of technologies. It is an assessment based on the current technology-specific emission reduction and applicable market segments could change as the technology is further developed.

Most of the addressable emission reduction is produced from technologies that are applicable to larger market segments, such as narrow-body and wide-body aircraft. Since narrow-body aircraft generate 50% of all aircraft emissions and wide-body aircraft generate 45%, based on 2019 CO_2 emissions data, it makes sense to focus on developing technologies that address these market segments.

For the 2030-2040 time horizon, engine technologies produced up to a 22% reduction in addressable aircraft emissions resulting from the technology's applicability to a larger share of the market. On the other hand, hybrid-electric propulsion only produced a 1% reduction in addressable aircraft emissions since this technology has a range restriction that prevents it from having a larger impact (up to 8%), followed by airframe configurations (up to 4%).

In the 2040-and-beyond time horizon, hydrogen propulsion represents up to a 53% reduction in addressable aircraft emissions since the technology has the potential to be applied to narrow-body applications and emits zero CO_2. This assumes no constraint to the supply of green hydrogen, no constraint to the adoption of aircraft due to availability of hydrogen supplies and airport hydrogen infrastructure, and no constraint in the certification and manufacturing of hydrogen-powered aircraft such that the aircraft are assumed to begin deliveries across the market segment once the technology is matured. Although all-electric propulsion also emits zero CO_2, it only produced a 1% reduction in addressable aircraft emissions since this technology also has a range restriction that prevents the technology from having a larger impact. The next-largest addressable emission-reduction impact is generated from airframe configurations (up to 9%), followed by systems (up to 3%).

As previously stated, the emission reductions only look at the individual technologies and not the system-level effects once applied to an aircraft as a portfolio of technologies. They are also dependent on the utilization of a clean energy source and grid and are only representative of the vehicle emission. Additional detail for technology descriptions, considerations and range restrictions can be found in the Appendix as well as the Feasibility Assessment.

D. NEXT STEPS

After calculating the maximum addressable emission-reduction potential for each technology on the focused list, the next step is to understand where these technologies stand in terms of timing and progression toward market launch. A Feasibility Assessment (part two) assesses the current state of these technologies in terms of complexity and maturity and provides a view of how various strategies and initiatives will impact the technology pathways for decarbonization.

Subsequently, the AIA Policy Roadmap (part three) provides recommendations that can be used to guide the industry toward a framework where collaboration between government and industry will increase the likelihood of success in achieving the 2050 sustainability goals.

E. APPENDIX

Focused List Technology Descriptions

Grouping	Technology	Description
New Energy Pathways	All-Electric Propulsion	Engine technology that utilizes electric motors to drive conventional propellers or a set of small fans; power is stored in batteries.
	Hydrogen Propulsion	Hybrid-electric, motor-driven propulsion powered via fuel cells or hydrogen combustion through modified gas turbine engines; liquid hydrogen is used as fuel for combustion with oxygen.
New Energy Pathways / Engine Technology	Hybrid-Electric Propulsion	Propulsion system that utilizes a battery-powered motor and a conventional gas turbine engine. This is categorized as being both an engine technology and new energy pathway since it will need to utilize batteries in conjunction with jet fuel.
Engine Technology	Open Rotor	Engine technology that uses an unducted fan or propfan that increases engine bypass ratios and fuel efficiency.
	Geared Turbofan Engine	Engine technology that utilizes a gearbox between the fan and the compressor; each rotates at the most efficient speed, improving the propulsive efficiency of the engine.
	High-Pressure Ratio Core Engine	Engine technology with an enhanced efficiency compressor that operates at a higher pressure, reducing engine weight and improving thermal efficiency, which delivers more power and increases fuel efficiency.
Airframe Configurations	Blended-Wing Body (BWB)	Aerodynamic technology for a fixed-wing aircraft without clear differentiation between wings and fuselage; airfoil-shaped bodies and high-lift wings significantly improve lift-to-weight drag ratio.
	Transonic Truss-Braced Wing (TTBW)	Aerodynamic technology that utilizes a structural wing support to allow for larger wing spans without increases in structural weight; increasing the span reduces drag and the higher wing position can enable larger engines, like open rotors.
Structures	Laminar Flow Control Technology	Aerodynamic technology that maintains the airflow over the aircraft surface and nacelles turbulence-free; this can be achieved through shaping of the aircraft surface (natural) or boundary layer suction (hybrid). This assessment looks at the combinatory effects of both hybrid and natural.
	Advanced Composites	New class of materials that decrease aircraft weight and provide improved environmental performance for aircraft; the raw materials for advanced composites can be derived from natural renewable resources.
Systems	Fuel Cells for Onboard Power	Power generation technology that utilizes fuel cells instead of engine-driven generators; this creates more-efficient onboard electrical power generation.

Figure 18 – Focused List of Technology Descriptions

All-Electric Propulsion is an engine technology that utilizes electric motors to drive conventional propellers or a set of small fans where power is stored in batteries. All-electric propulsion has an estimated CO_2 emission reduction of 100%.[14] To achieve this emission reduction, high-density batteries and electricity using renewable energy sources need to be utilized to achieve 100% emission improvement.[15] Due to the development required to achieve high-density batteries to support commercial aircraft missions as well as the additional weight of the battery, we anticipate this technology to only scale to regional aircraft applications with a limited range (less than 500 kilometers) in the 2040-and-beyond time horizon.[16, 17] Considering these factors, all-electric propulsion was identified as being in the research TRL stage for regional applications.

Hydrogen Propulsion assesses hybrid-electric propulsion powered by hydrogen combustion and fuel cells through modified gas turbine engines where hydrogen fuel could be used for combustion with the addition of fuel cells for electricity. This technology has an anticipated CO_2 emission reduction of 100%.[18] To achieve this, the hydrogen fuel requires that combustion is produced using renewable energy sources. Current hydrogen production is predominantly from fossil fuels (methane reforming), with only a small fraction being produced from renewable energy (<1%). Although it is not the focus of this study, it should be noted that the combustion of hydrogen can produce dangerously high levels of NO_x gas that can further impact the climate.[19]

Due to the active research being pursued by multiple industry stakeholders, this technology is anticipated to be applicable for regional and narrow-body applications in the 2040-and-beyond time horizon.[20] Since the energy density of hydrogen fuel is less than that of conventional jet fuel, pairing it with the addition of fuel cells will potentially provide a range of up to 2,000 kilometers.[21, 22] Since larger applications of this technology are still in the conceptual phase and the infrastructure required for hydrogen fuel has not been fully developed, this technology is identified as being in the research TRL stage for both applications. It should be noted that superconducting/cryogenic electrified powertrains (fuel cells) are also actively being researched to fully electrify aircraft, but that solution could be further out in terms of timing.[23 24]

Hybrid-Electric Propulsion assesses a propulsion system that utilizes a battery-powered motor with conventional gas turbine engines. It is anticipated that the CO_2 emission reduction for hybrid-electric propulsion is 20%.[25] Hybrid-electric propulsion is likely to only be applicable for regional applications in the 2030-2040 time horizon due to the development required to achieve high-density batteries to support commercial aircraft missions, as well as the additional weight of the battery.[26] The expected aircraft range for this technology is less than 1,000 kilometers (mild hybrid).[27] However, although not part of this assessment, it should be noted that turbo-electric propulsion is being explored for larger aircraft applications.[28] When applied to narrow-body or wide-body aircraft, the anticipated benefit is substantially less (current expectations are up to low single-digit percentage benefits, assuming aircraft integration issues do not totally eliminate the net benefit). Since research institutions and industry are actively pursuing hybrid-electric propulsion, this was identified as being in the development TRL stage for regional applications and in the research TRL stage for narrow-body applications.

Open Rotor is an engine technology that uses an unducted fan or propfan that increases engine bypass ratios and fuel efficiency. To achieve this emission reduction, aircraft will require a high-wing or truss-braced wing configuration to support a larger engine.[29] Technology improvements could address cruise speed and noise levels concerns.[30] The industry has made significant advancements in open-fan engine design, making the engine architecture simpler and lighter.

Significant investments in open rotor technology—including fan blades, direct air flow at speeds consistent with conventional turbofan architectures, improvements in acoustics and the utilization of carbon fiber composites—could further optimize propulsive and thermal efficiencies.[31] This technology is expected to be applicable for regional, narrow-body and wide-body applications in the 2030-2040 time frame.[32] The open rotor technology has been in the development TRL stage for several years and has yet to progress outside of an aircraft test bed. This concept-engine architecture is on track for a full demonstrator-engine ground test and flight tests by around the middle of the decade and is expected to be tested on advanced, new-generation single-aisle aircraft with a noise level that meets anticipated future regulations.[33]

Geared Turbofan Engine is an engine technology that utilizes a gearbox between the fan and the compressor, each rotating at the most efficient speed, which improves the propulsive efficiency of the engine. Based on industry public data, it is anticipated that the CO_2 emission reduction for geared turbofan engine is 20%-25%.[34] Further advancements to the core and other components will enable additional generations of this technology to be more efficient than its predecessor. Since this technology is currently available for regional and narrow-body applications (e.g., PW1000G), this assessment looks at scaling to wide-body applications in the 2030-2040 time horizon.[35] Geared turbofans have been identified as being in the development TRL stage for wide-body applications and in the adoption TRL stage for regional and narrow-body applications. Although this report only focuses on wide-body applications for this technology, it should be noted that the adoption of geared turbofan engine on narrow-body applications can make a significant impact on carbon emission reduction in the nearer future.

High-Pressure Ratio Core Engine is an engine technology with an enhanced efficiency compressor that operates at higher pressure, reducing engine weight and improving thermal efficiency, which delivers more power and increases fuel efficiency. It is anticipated that the CO_2 emission reduction for high-pressure ratio core engine is 5%-10% with respect to current-generation wide-body engine (e.g., GE90) technology.[36] To achieve this emission reduction, the new generation of high-pressure ratio core engine reduce fuel consumption, increase the bypass ratio and increase the pressure ratio. The limitation of this technology is related to the mission profile: Wide-body applications have fewer flight cycles per day (approximately one/day) when compared to narrow-body applications (which can have up to 12 cycles/day). Since fewer cycles result in less engine stress, this technology is currently only available for wide-body applications (e.g., GE9X). Potentially scaling to regional and narrow-body applications in the 2030-2040 time horizon will depend on the mission profiles of those aircraft and the related engine performance.

Fuel Cells for Onboard Power is a power generation technology that utilizes fuel cells instead of engine-driven generators, which creates more-efficient onboard electrical power generation. This technology doesn't emit CO_2,[37] and it only accounts for 1%-5% of the carbon emissions contributed by onboard power in comparison to aircraft that use energy from a gas turbine.[38] To achieve this emission reduction, the hydrogen fuel must be produced with renewable energy. This technology is applicable for regional and narrow-body applications in the 2040-and-beyond time horizon since it will rely on other hydrogen-based technologies.[39] Both applications are in the development TRL stage.

Laminar Flow Control is an aerodynamic technology that maintains the airflow over the aircraft surface and nacelles turbulence-free. This can be achieved by shaping the aircraft surface (natural) or boundary layer suction (hybrid). For this study, both types of laminar flow control are assessed together. It is anticipated that the CO_2 emission reduction for laminar flow control (natural and hybrid) is 5%-15% in comparison to aircraft that don't utilize aircraft laminar flow technology.[40] To achieve this emission reduction, aircraft will need to make use of both natural and hybrid laminar flow control as well as incorporate new aerodynamic designs, including changing the material composition of the wing and control surfaces. This improves the airflow over the wings and control surfaces, which would reduce the drag on the aircraft. Both laminar flow control types would be applicable for regional and narrow-body aircraft in the 2030-2040 time horizon.[41] This technology would not be available for wide-body aircraft due to the difficulty in maintaining laminar flow control for larger aircraft.[42] Due to the new aerodynamic designs and materials being researched for this, it has been identified as being in the research TRL stage.

Blended-Wing Body (BWB) is an aerodynamic technology for a fixed-wing aircraft without clear differentiation between wings and fuselage. The airfoil-shaped bodies and high-lift wings significantly improve lift-to-weight drag ratio. It is anticipated that the CO_2 emission reduction for blended-wing bodies is approximately 20% in comparison to a conventional tube-and-wing design.[43] This emission reduction is an assessment of the wing/fuselage design for wide-body aircraft for ranges over 7,000 nautical miles. This technology is assessed for wide-body aircraft in the 2040-and-beyond time horizon.[44] Due to configuration complexity and research being conducted on full-scale commercial applications, this technology was identified as being in the research TRL stage. These assessments are further substantiated by executive interviews and Accenture research.[45]

Transonic Truss-Braced Wing (TTBW) is an aerodynamic technology that utilizes a structural wing support to allow for larger wing spans without increases in structural weight. Increasing the span reduces drag, and the higher wing position can enable larger engines. The CO_2 emission reduction for transonic truss-braced wing is anticipated to be 8%-10% in comparison to conventional aircraft design.[46, 47] To integrate aircraft with this technology into existing airport infrastructure, the larger wingspan—supported by a truss or strut—would require folding wing tip technology.[48] This technology is applicable for regional and narrow-body aircraft in the 2030-2040 time horizon and wide-body aircraft in the 2040-and-beyond time horizon.[49] Since this technology is in the conceptual phase and still being researched as part of several studies, it was identified as being in the research TRL stage for wide-body applications and in the development TRL stage for regional and narrow-body applications.

Advanced Composites are a new class of materials that decrease aircraft weight and provide improved environmental performance for aircraft. This technology is also inclusive of thermoplastics and thermosets. It is anticipated that the emission reduction for advanced composites is 1%-3%.[50] To further enable this technology, lightweight and high-strength materials would need to be developed at rates that meet aircraft production demand.[51] This technology is applicable for all segments and large-scale applications in the 2030-2040 time horizon.[52] While some applications of this technology are available on current aircraft, the full potential may not be realized until new applications of the technology enter the market. Since increasing the rate of production of the materials is currently being researched and developed, this technology was identified as being in the development TRL stage.

Example Calculation

Maximum Addressable Emission-Reduction Potential Calculation for Open Rotor Engines

Open rotor engines with an applicability to regional and narrow-body aircraft have a range of up to 2,000 kilometers. The technology-specific emission reduction is estimated at 15%-20% when compared to current engine offerings.

Using the historical 2019 emissions data shown in Figure 19 below, the amount of CO_2 emitted by regional and narrow-body aircraft flying ranges of up to 2,000 kilometers is 39%. Since this technology will only be applied to aircraft flying these ranges, this is the only portion of the market that the technology will impact in terms of carbon emission levels.

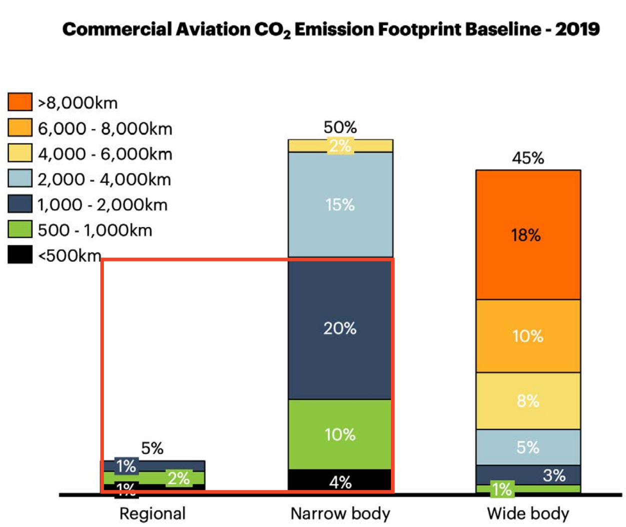


Figure 19 – 2019 Emissions and Flight Ranges Used for Calculations

Once the percentage of the total CO_2 emissions produced by these market segments is captured and the range limitation is taken into consideration, this number is multiplied by the technology-specific emission-reduction percentage. This can be seen in Figure 20.

	Total CO_2 Emissions	Technology-Specific Emission Reduction	Maximum Addressable Emission-Reduction Potential
Low	39%	15%	**6%**
High	39%	20%	**8%**

Figure 20 – Open Rotor Calculation for Maximum Addressable Emission-Reduction Potential

Since open rotor engines have a technology-specific emission reduction ranging from 15% to 20%, the maximum addressable emission-reduction potential was calculated for both, giving a final range of 6%-8% for the applicable market segments.

PART TWO

FEASABILITY ASSESSMENT

A. SECTION OVERVIEW

This Feasibility Assessment takes a closer look at the technologies identified in the Technology Report (part one) and provides a deeper understanding of the likely viability trends for market entry by 2050.

Where applicable, we assessed the technologies separately for feasibility in the following market segments: regional (R), narrow-body (NB) and wide-body (WB) aircraft. These distinctions are important: Regional aircraft account for just 5% of global aircraft emissions, while narrow-body aircraft account for 50% and wide-body aircraft account for 45%.

The following technologies offer high addressable emission-reduction potential and feasibility for market entry in the 2030-2040 time frame:

- Geared turbofan engine (WB)
- Laminar flow control (NB)
- High-pressure ratio core engine (NB)
- Open rotor (NB)

Hybrid-electric propulsion findings indicate a low technical feasibility on a global aviation fleet basis in this time horizon, mostly due to higher complexity and lower maturity technology status.

When it comes to the technologies anticipated for market entry after 2040, feasibility was mainly impacted by technical maturity or infrastructure requirements to support the technology, especially for hydrogen and all-electric propulsion.

These findings aim to provide a deeper understanding of decarbonization technologies and should be taken in the context of the industry environment at the time of this report. While the feasibility results provide a view of where these technologies stand in terms of maturity and pace to enter the market, the collective industry stakeholders ultimately have to decide which technologies to incorporate and advance in their programs and platforms. Embracing this challenge is essential in navigating the journey to net zero by 2050.

B. FOCUSED TECHNOLOGY LIST

The Technology Report identified 11 technologies, found in Figure 21 below, that could be positioned to enter the market and deliver on decarbonization goals. The technologies are broadly grouped into the following categories: new energy pathways, engine technology, airframe configuration, structures, and systems.

Determining the feasibility of these technologies requires a deeper assessment to fully understand the technical and operational implications as well as the capital investment that could be required. A technology that promises significant reductions may ultimately be hindered by infrastructure needs or public perception, both of which impact feasibility.

Each of the 11 technologies were evaluated on an individual basis, and further detail is provided in the technology assessments.

Focused List of Technologies		
Group	**Technology**	**Market Segment**
New Energy Pathways	All-Electric Propulsion	R
	Hydrogen Propulsion	R, NB
	Hybrid-Electric Propulsion	R
Engine Technology	Open Rotor	R, NB, WB
	Geared Turbofan Engine	WB
	High-Pressure Ratio Core Engine	R, NB
Airframe Configuration	Blended-Wing Body (BWB)	WB
	Transonic Truss-Braced Wing (TTBW)	R, NB, WB
Structures	Laminar Flow Control Technology (Natural and Hybrid)	R, NB
	Advanced Composites	R, NB, WB
Systems	Fuel Cells for Onboard Power	R, NB

Figure 21 – Focused List of Technologies

C. FEASIBILITY ASSESSMENT CRITERIA

We used the Feasibility Assessment to evaluate the 11 technologies individually based on parameters and criteria drawn from our interviews with industry stakeholders and industry research. The sets of criteria and sub-criteria, shown in Figure 22, were used to further understand each technology's ability to enter the market and be scaled.

Criteria	Sub-Criteria
Technical Complexity	Systems Integration Technical Readiness Level[53] Certification Manufacturing/Material Availability Technology Insertion Point
Operational Viability	Training Requirements Maintainability Infrastructure Passenger Acceptance[54] Noise[55]
Cost Impact[56]	OEM Research Airline MRO Regulator Supplier Other Industries Infrastructure

Figure 22 – Interview Assessment Criteria and Sub-Criteria

We evaluated each technology based on technical complexity, operational viability and cost impact, and we structured the stakeholder interviews around these criteria. The resulting data gathered allowed us to assess each technology by taking a life cycle view.

For example, the sub-criteria for technical complexity included systems integration complexity, material and manufacturing tooling availability, and certification complexity. Factors for operational viability included training requirements, infrastructure readiness and passenger acceptance. Cost impact focused on capital investment for manufacturers, operators, infrastructure, and maintenance providers.

D. ASSESSMENT

After gathering the data, we individually assessed each technology by market segment. We used the average maximum addressable emission-reduction potential methodology for each applicant market segment, representing the average overall industry reduction these technologies could individually provide—assuming full adoption by the respective market segment.

This analysis does not look at the combined system efficiency when applied to an aircraft. Wide-body and narrow-body applications, for example, hold a greater market share and contribute to more carbon emissions, which produces a greater average addressable emission-reduction potential. Regional applications have relatively smaller addressable emission-reduction potential due to the relative smaller market share.

The assessment is based on information shared by industry stakeholders, research and public data pertaining to where the technologies stand at the time of this report. Along with the maximum addressable emission-reduction potential, we used the assessment criteria to assess technology feasibility to indicate the relative complexity/maturity of the technology and its impact on market feasibility. For example, a technology with more complexity could indicate a lower maturity state, while a technology with less complexity could indicate a higher maturity state.

Time Horizon: 2030-2040

Technology	Average Maximum Addressable Emission-Reduction Potential	Market Segment
New Energy Pathways		
Hybrid-Electric Propulsion	1%	Regional
Engine Technology		
Open Rotor	1%	Regional
Open Rotor	10%	Narrow Body
Open Rotor	9%	Wide Body
Geared Turbofan Engine	8%	Wide Body
High-Pressure Ratio Core Engine	4%	Narrow Body
High-Pressure Ratio Core Engine	1%	Regional
Airframe Configuration		
Transonic Truss-Braced Wing	6%	Narrow Body
Transonic Truss-Braced Wing	1%	Regional
Structures		
Laminar Flow Control	5%	Narrow Body
Laminar Flow Control	1%	Regional
Advanced Composites	1%	Wide Body
Advanced Composites	1%	Narrow Body
Advanced Composites	1%	Regional

Figure 23 – Technology Feasibility for Technologies With Estimated Market Entry for the Applicable Aircraft Programs in the 2030-2040 Time Horizon

Among the technologies in the 2030-2040 time horizon, narrow-body and wide-body applications have the highest average addressable emission-reduction level when compared to the regional applications (as expected, due to the larger market share for wide- and narrow-body applications when compared to regional).

The feasibility of transonic truss-braced wing (NB/R) and open rotor (WB/NB/R) was affected by the level of investment required for this technology to be adopted on larger applications. Advanced composites (WB/NB/R), laminar flow control (NB/R), geared turbofan (WB) and high-pressure ratio core engine (NB/R) have a higher maturity status and thus greater feasibility. Hybrid-electric propulsion (R) has higher complexity and lower maturity when compared to other technologies anticipated to enter the market in this time horizon.

Time Horizon: 2040 and Beyond

Technology	Average Maximum Addressable Emission-Reduction Potential	Market Segment
New Energy Pathways		
Hydrogen Propulsion	41%	Narrow Body
Hydrogen Propulsion	5%	Regional
All-Electric Propulsion	1%	Regional
Airframe Configuration		
Blended-Wing Body Fuselage	8%	Wide Body
Transonic Truss-Braced Wing	7%	Wide Body
Systems		
Fuel Cells for Onboard Power	2%	Narrow Body
Fuel Cells for Onboard Power	1%	Regional

Figure 24 – Technology Feasibility for Technologies With an Estimated Market Entry for the Applicable Aircraft Programs in the 2040-and-Beyond Time Horizon

The feasibility of technologies with an estimated market entry beyond 2040, such as hydrogen propulsion (NB/R), all-electric propulsion (R) and blended-wing body fuselage (WB) was mostly impacted by high technical complexity and greater investment required to scale. Although most technologies in the 2040-and-beyond time horizon face more technical barriers, some have the same feasibility as those estimated for market entry between 2030 and 2040. This similarity is due to the infrastructure requirements that a technology requires to be a feasible option prior to 2040. Assessment of the requirements at the individual technology level will provide a better understanding of the improvements required to attain feasibility. For example, testing these technologies on smaller applications can improve the feasibility, which may result in faster adoption and scale to larger applications.

Engine propulsion and wing technologies have the highest addressable emission-reduction potential. However, these results are inconclusive and will need to be revisited when sufficient data on the emission impact of well-to-wake is available and taken into consideration. Less-complex technologies—such as surface treatments, advanced composites and engines—are likely to require fewer operational changes and capital investment, making them more feasible technologies. Further assessment of these individual technologies is found in the technology results section below.

Technology Results

The technology results provide a summary of the findings for each of the 11 technologies. Each summary contains the average maximum addressable emission-reduction potential for the applicable market segments, the anticipated time horizon it will enter the market and an assessment for the technology.

1. Hybrid-Electric Propulsion

Description: Propulsion system that utilizes a battery-powered motor and a gas turbine engine.

Emissions Reduction

The average maximum addressable emission-reduction potential for hybrid-electric propulsion is only applicable to regional aircraft with a market entry estimation in the 2030-2040 time horizon. Since the technology is limited to regional aircraft and short ranges of less than 1,000 kilometers (mild hybrid), it will have a minimal impact on carbon emission levels, even when assumed to be fully deployed across the global regional aircraft fleet.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2030-2040

Technology Feasibility

When assessed on the technology feasibility assessment criteria, hybrid-electric propulsion for regional applications is relatively complex compared to other technologies that are anticipated to enter the market in the 2030-2040 time horizon. Hybrid-electric gas turbines can add substantial weight and complexity, potentially negating the efficiency benefits provided by the hybrid-electric component. Since the energy density of current batteries would need significant development to support larger airplane application, this technology is restricted to regional aircraft. The benefits of hybrid electric would not scale well with its platform size, and the potential benefits for NB and WB aircraft will be substantially less, at equivalent mission lengths for non-hybrid platforms.

Since hybrid-electric propulsion is being actively pursued by industry stakeholders, such as VoltAero and Collins Aerospace,[57, 58] it is placed in the development stage of maturity in this assessment. With the proper investment in R&D, regional applications can be incorporated into current aircraft production; however, this will still present significant challenges. It will also require additional certification efforts, new manufacturing tools and processes, operational training for aircraft crew and infrastructure changes (such as charging stations) at airports.[59] Significantly more new maintenance tooling and repair parts will also be needed due to the entry of new aircraft into the market.

Hybrid-electric propulsion would not significantly impact the passenger experience or perceived safety. This technology has a higher cost burden for manufacturing companies such as original equipment manufacturers (OEMs) and suppliers when compared to costs associated with current-generation aircraft. In addition, airlines and maintenance, repair, overhaul (MRO) companies will need capital investment to acquire, operate and maintain hybrid-electric aircraft. Integrating the hybrid-electric aircraft into airports and airspaces will also bring additional infrastructure and regulatory costs. Furthermore, the cost of frequently replacing batteries during the life of the aircraft remains a significant variable.

Assessment

Increasing feasibility will require additional investment in research and development to bring this technology to market, along with high-voltage distribution and scaling of lightweight power electronics. Additional investment in infrastructure will be necessary to accommodate the charging of batteries onboard hybrid-electric aircraft. It would be beneficial for OEMs to explore partnerships with airports to understand how to accommodate different voltages. Industry partnerships that leverage expertise in electrification from other industries, like automotive and urban air mobility, would accelerate the development and adoption of electric-powered aircraft. Although this assessment covers a combination of gas turbine engines and energy storage for hybrid-electric propulsion, it should be noted that the industry is also actively pursuing other hybrid-electric solutions for larger-scale applications, such as turbo electric.[60]

2. Open Rotor

Description: Engine technology that uses an unducted fan or propfan that increases engine bypass ratios and fuel efficiency.

Emissions Reduction
The average maximum addressable emission-reduction potential is evaluated for wide-body, narrow-body and regional applications separately to evaluate the impact on each market segment. The technology is likely to be available for all applications in the 2030-2040 time horizon.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2030-2040
Narrow Body	10%	2030-2040
Wide Body	9%	2030-2040

Technology Feasibility
Wide-body and narrow-body applications are more complex compared to regional applications, mainly because regional applications require less-complex integration across aircraft systems and can be incorporated into current aircraft production. For wide-body and narrow-body applications, the technology will require complex integration across numerous aircraft systems—particularly around installation—and will need to be incorporated on a new aircraft program. Open rotor technology is actively being pursued by industry stakeholders and is therefore considered to be in the development stage for regional, narrow-body and wide-body applications.[61, 62]

All applications can utilize existing manufacturing tools and processes. The technology will require moderate additional certification effort, additional operational training for aircraft crew and additional maintenance, tooling and repair parts. Technology improvements could address cruise speed and noise levels concerns. Passenger acceptance may also be negatively impacted for wide-body applications due to the slower aircraft speeds.

Besides the acquisition cost of open rotor, airlines must consider maintenance costs. These costs primarily result from fatigue properties of the open rotor, which requires adequate maintenance procedures (including inspections, surface refurbishment and overhaul), as well as the complex gear assembly and its relatively low-reliable components, resulting in higher inventory costs for parts. Regulatory costs associated with the certification and integration of the new open rotor engine technology into the existing system are also a factor.[63]

Assessment
Improving the feasibility of this technology requires additional investment to mature and scale to a demonstrator level. Additional partnerships between OEMs and research institutions can help accelerate maturity through increased testing and research.

Although this technology can be applied to both narrow-body and regional applications, it would be beneficial to begin with regional applications. If it could be proven on regional applications and then scaled to narrow-body and wide-body applications, it could address a significant portion of emissions generated by aircraft. Since open rotor engines will need a new aircraft architecture to accommodate the size of the engine, combining the technology with transonic truss-braced wings, for example, could serve as a solution for addressing this issue.

3. Hydrogen Propulsion

Description: Hybrid-electric propulsion powered by hydrogen combustion and fuel cells through modified gas turbine engines; liquid hydrogen is used as fuel for combustion with oxygen.

Emissions Reduction

We evaluated the average maximum addressable emission-reduction potential for hydrogen propulsion separately for narrow-body and regional applications, and both applications are likely to be available in the 2040-and-beyond time horizon. The addressable emission-reduction potential only considers CO_2 emissions and assumes the use of green hydrogen, which is not presently available in significant volumes. The impacts of greenhouse gases and other technical factors need to be explored.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	5%	2040 and Beyond
Narrow Body	41%	2040 and Beyond

Technology Feasibility

Hydrogen propulsion will have complex integration for both regional and narrow-body applications. Regional applications will require complex integration across numerous aircraft systems and are in the development stage, while narrow-body applications will require complex integration across most all aircraft systems and are still in the research stage. However, hydrogen technology is being actively pursued by multiple industry partners, such as Airbus,[64] Universal Hydrogen[65] and ZeroAvia.[66]

This technology will require certification and all-new manufacturing tools, processes and aftermarket parts. Incorporating this technology will also require new aircraft programs due to its complex system-integration requirements.

Like most of the other technologies, hydrogen propulsion would need operational training for aircraft crew. Airports will need to implement infrastructure changes such as airport fueling and transportation systems to provide a continuous supply of hydrogen at large volumes. The industry will also need to address the challenges of converting hydrogen into a cryogenic state and transporting it to the aircraft.[67] Successfully implementing this technology also will depend on overcoming its negative connotations among the public as a viable and safe fuel source.

Manufacturing companies will face higher cost burdens, and supporting hydrogen aircraft will require infrastructure changes. Airlines will have to make significant additional capital investments to operate and support hydrogen aircraft. MROs will face higher maintenance costs, and regulators will need to integrate this new technology into the market. Other industries, such as energy and transportation, will incur additional costs to develop, scale, transport and store clean hydrogen.

Assessment

Making hydrogen propulsion a reality requires significant investment for research and development and for infrastructure upgrades to accommodate and refuel hydrogen aircraft in airports—not to mention investment in green hydrogen production and the renewable energy scale necessary to create the green hydrogen.
As of today, green hydrogen production does not exist at scale and will require significant investment and development.

Although hydrogen propulsion has great promise when it comes to carbon emission reduction in commercial aviation, a lack of investment will further delay its entry into the market. It should also be noted that hydrogen could impact other non-CO_2 greenhouse gases, such as nitrogen oxides (NO_x) and contrails.

Additional partnerships between OEMs could help accelerate the maturity and integration of this technology. Once proven on regional applications, hydrogen propulsion can potentially be scaled to narrow-body applications. Addressing global infrastructure and technical challenges could create an opportunity for hydrogen propulsion to be applied to wide-body applications, especially if other configurations (such as blended-wing body) are introduced to accommodate fuel volume. Hydrogen fuel has a low volumetric energy density and fuel cells have limited power density;[68] however, hydrogen combustion paired with using hydrogen to power fuel cells could be the most ideal approach[69] until fuel cell technology improves.

4. All-Electric Propulsion

Description: Engine technology that utilizes electric motors to drive conventional propellers or a set of small fans; power is stored in batteries.

Emissions Reduction

The average maximum addressable emission-reduction potential for all-electric propulsion is only evaluated for short-range regional applications and is likely to be available in the 2040-and-beyond time horizon. All-electric propulsion is heavily dependent on how quickly high-energy-density batteries are matured and fielded. The emission-reduction potential assumes the use of renewable energy as the source for the energy stored in the batteries.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2040 and Beyond

Technology Feasibility

All-electric propulsion for regional applications has a high technical complexity due to multiple factors. Regional applications are still in the research stage, and there is currently no precedent set for certification of all-electric propulsion. It's anticipated that it will also require all-new manufacturing tools and processes to bring it to market. Incorporating all-electric propulsion will also require a new aircraft program due to the complex configuration; however, proof of hybrid electric could potentially help push this concept along and reduce the technical barriers this technology currently faces.[70]

Integrating all-electric propulsion will require significant new operational training for aircraft crew, as well as new infrastructure changes to accommodate the all-electric aircraft at airports. New maintenance tooling and repair parts will also be necessary.

The higher cost burden for all-electric propulsion will impact manufacturing companies as well as airlines and MROs, which will incur additional costs to acquire, operate and maintain all-electric aircraft. Similarly, regulators will incur additional costs to integrate the all-electric aircraft into the market—this would require the involvement of other entities, such as the Department of Energy, to make improvements to the energy grid.

Assessment

Improving the feasibility of this technology will require investment in research and development toward improving and certifying this technology. Additional investment in infrastructure development will be necessary to accommodate and charge all-electric aircraft. There will need to be standardization in the charging infrastructure developed to ensure these regional aircraft can charge at all airports, regardless of destination. It would also be prudent to partner with airports to understand how to accommodate different voltages. To make this possible, it will be essential to utilize industry partnerships, such as leveraging experts in electrification from the automotive and urban air mobility industries, to accelerate the development and adoption of all-electric aircraft. This will also require a shift in technical focus for propulsion companies.

It is unlikely that this technology will scale to any applications larger than short-range regional aircraft unless significant advancements are made in battery energy density and weight reduction.

5. Laminar Flow Control

Description: Aerodynamic technology that maintains the airflow over the aircraft surface and nacelles turbulence-free; this can be achieved through shaping of the aircraft surface (natural) and/or boundary layer suction (hybrid). This assessment looks at the combinatory effects of hybrid and natural.

Emissions Reduction
The average maximum addressable emission-reduction potential for laminar flow control is evaluated for narrow-body and regional applications, both of which are anticipated to be available in the 2030-2040 time horizon. This emission-reduction percentage is the combinatory effect of natural and hybrid.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2030-2040
Narrow Body	5%	2030-2040

Technology Feasibility
For both narrow-body and regional applications, the integration of laminar flow control will require minimal system integration across the aircraft systems since the technology is part of the aerodynamic design and material composition of the wings and control surfaces.

Although both applications of laminar flow control are still in the development stage, it will require minimal additional certification effort because it doesn't change the flight controls or handling of the aircraft. The technology can largely use existing manufacturing tools and processes, but because of how the technology is incorporated—either by designing a surface to have laminar flow control or using materials to achieve laminar flow control—it will have to be incorporated into a new aircraft program.

This technology should not necessitate new aircraft crew training, changes to existing infrastructure or new maintenance tooling and repair parts to bring it to market. It is expected that some additional capital investment may be required to further improve the technology maturity and to scale the technology to get the maximum benefit for regional and narrow-body applications. However, surface contamination (e.g., insects) can hinder the efficiency of this technology regardless of application.

Assessment
Laminar flow control could be unlocked either through the design of a new wing or surface to achieve natural laminar flow control. Hybrid laminar flow control can be achieved using materials and boundary layer suction. For both options, we determined that this technology should be incorporated on a new aircraft as part of a portfolio of technologies where it could deliver results in terms of carbon emission reduction in commercial aviation on a system level.

Although this technology can be applied to both narrow-body and regional applications, it would be the most beneficial to apply it to narrow-body applications first since that has a higher maximum addressable emission-reduction potential. Unfortunately, this technology would be challenging to scale to wide-body application due to the difficult nature of maintaining laminar flow control over a greater surface area. The challenges of surface contamination and boundary layer separation largely increase.[71]

6. Transonic Truss-Braced Wing

Description: Aerodynamic technology that utilizes a structural wing support to allow for larger wing spans without increases in structural weight; increasing the span reduces drag, and the higher wing position can enable larger engines, like open rotors.

Emissions Reduction
The average maximum addressable emission-reduction potential for transonic truss-braced wings is evaluated

separately for wide-body, narrow-body and regional applications since the technology is estimated to be available for narrow-body and regional applications in the 2030-2040 time horizon and for wide-body applications in the 2040-and-beyond time horizon.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2030-2040
Narrow Body	6%	2030-2040
Wide Body	7%	2040 and Beyond

Technology Feasibility

According to industry experts, implementing transonic truss-braced wings on wide-body, narrow-body and regional applications is anticipated to have relatively the same level of technical complexity; however, the scaling of the technology to larger applications requires additional capital investments to bring this technology to market.

The technology is in the research stage for all applications and will require additional certification efforts as well as advancements in existing manufacturing and materials to come to market. The system integration for the technology is complex due to the required integration across numerous systems within the aircraft. In addition, the design complexity of the technology will require incorporating a new aircraft program.

Like other novel wing configurations, the higher cost burden for transonic truss-braced wings will impact manufacturing companies—particularly when it comes to narrow-body and wide-body applications—and there will also be additional maintenance, infrastructure and regulatory costs.

It is expected that the aerodynamic change to the aircraft will necessitate significant operational training; however, it shouldn't require infrastructure changes to accommodate the increased wingspan since it could utilize folding wing tip technology. The new configuration will require moderately new maintenance tooling and repair processes, and passenger acceptance could potentially be negative due to the significant differences in aerodynamic design compared to current generation aircraft.

Assessment

Improving feasibility will require ecosystem partners to work together to advance the maturity of the transonic truss-braced wing from the research phase and scale it to a demonstrator level. It will take additional research investment to further advance the technology by reducing emissions and noise while enhancing performance. It should also be noted that this technology can be enabled by folding wing tip technology to accommodate the increased wingspan in airports.

7. Blended-Wing Body Fuselage

Description: Blended-wing body (BWB) aerodynamic technology for a fixed-wing aircraft without clear differentiation between wings and fuselage; airfoil-shaped bodies and high-lift wings significantly improve lift-to-weight drag ratio.

Emissions Reduction

The average maximum addressable emission-reduction potential for blended-wing body is evaluated for wide-body applications and anticipated to be available in the 2040-and-beyond time horizon.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Wide Body	8%	2040 and Beyond

Technology Feasibility
Implementing the blended-wing body onto wide-body aircraft is operationally and technically complex. This technology will require integration across most systems within the aircraft. Currently in the research stage, BWB technology will need new manufacturing tools and processes to bring it to market. Due to the design complexity of BWB, this technology will require a new aircraft program to be incorporated and currently has no precedent set for certification.

It is expected that all-new operational training will be required due to the aerodynamic change of the aircraft. It will also need new maintenance tooling and repair parts, as well as new infrastructure changes, to ensure the aircraft can be accommodated at airports.

Achieving passenger acceptance for this technology could potentially be a difficult task. It does shield engine noise, but it also involves major changes to aerodynamic design, including the complete removal of windows from the cabin.

The blended-wing body has a unique size, shape and potential weight, which brings a higher cost burden across the board—for OEMs, airlines, airports, suppliers, MROs, regulators and research institutions alike.

Assessment
Improving the market feasibility of the blended-wing body will require additional investment to further research and advance the technology to a full-scale demonstrator level. Industry partnerships could accelerate this process. It will also be crucial to understand the size and weight requirements for the aircraft in development, as well as the infrastructure changes required to accommodate these aircraft, regardless of the routes they travel.

8. Fuel Cells for Onboard Power

Description: Power generation technology that utilizes fuel cells instead of engine-driven generators; this creates more-efficient onboard electrical power generation.

Emissions Reduction
The average maximum addressable emission-reduction potential for fuel cells for onboard power is evaluated for narrow-body and regional applications, both estimated to be available in the 2040-and-beyond time horizon.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2040 and Beyond
Narrow Body	2%	2040 and Beyond

Technology Feasibility
It is anticipated that integrating fuel cells for onboard power for narrow-body and regional applications will face less technical barriers since the fuel cell technology is relatively mature. Regional applications are in the

development stage since the technology is actively being pursued by industry stakeholders (e.g., Safran[72]), while narrow-body applications are in the research stage. Due to the lack of similar existing technologies, it will require new maintenance tooling and repair parts, new manufacturing tools and parts, and additional training for aircraft crew to operate this new technology. Minimal integration across aircraft systems is required, which could expedite the incorporation into current aircraft production; however, a new certification process will be required.

Like hydrogen propulsion, this technology is not expected to be available before 2040 due to the changes in infrastructure needed to accommodate the fuel cells at airports.[73] It also faces the same challenges as hydrogen propulsion around passenger perception.

There are no additional costs anticipated for regulators, but OEMs, research institutions, airlines, MROs, suppliers and airports will see costs associated with the complexity of integrating this technology.

Assessment
Additional partnerships between OEMs and research institutions would help accelerate technology maturity through increased testing and research. The technology itself has few feasibility limitations compared to other technologies falling into the same time horizon, but the infrastructure barriers and supply of hydrogen as a fuel hinder this technology from being brought to market sooner.

Although the technology can replace conventional subsystems for onboard power, it brings minimal emission-reduction potential on its own. Therefore, this technology would especially benefit from potential opportunities to be included as part of a portfolio of technologies on a new aircraft. Fielding this technology could drive more-advanced traditional APUs as well as potentially advance the maturity of fuel cells for hydrogen propulsion.

9. Advanced Composites

Description: New class of materials that decrease aircraft weight and provide improved environmental performance for aircraft; the raw materials for advanced composites can be derived from natural renewable resources.

Emissions Reduction
The average maximum addressable emission-reduction potential for advanced composites is evaluated for wide-body, narrow-body and regional applications. The technology will need additional advancements to be further incorporated on these applications. The technology is estimated to be available at a wider scale for all applications in the 2030-2040 time horizon.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2030-2040
Narrow Body	1%	2030-2040
Wide Body	1%	2030-2040

Technology Feasibility
Advanced composites technology was assessed to be relatively feasible since it does not involve complex integration or major advancements in manufacturing tools and materials. Findings indicate that the challenge is the application of composites to narrow-body and regional aircraft—because of the rate at which materials are needed, manufacturing processes are not currently available to meet demand. The manufacturing process would need to increase by four to six times its current rate. It is expected that this technology will scale to wide-body applications before narrow body and regional. The technology is in the deployment phase, with a clear precedent set for certification. Only minimal additional certification effort is needed for incorporation into current aircraft programs.

There are no evident requirements that this technology would need additional operational training for aircraft crew, changes to existing infrastructure or any significant new maintenance tooling and repair parts. It is anticipated that noise levels would not change from current aircraft, and no change to passenger experience or perceived safety is expected.

The higher cost for advanced composites will be mostly incurred by manufacturing companies and research institutions, which must further develop, increase the rate of and mature the technology. Airlines, MROs, regulators and other industries would not incur additional costs to operate or certify aircraft with this technology.

Assessment
Additional partnerships between OEMs and research institutions, as well as research and development investment, can help accelerate the technology maturity and production rate of the material for all applications through additional testing and research.

Although the technology reduces structural weight, it brings minimal emission-reduction potential by itself and would especially benefit from potential opportunities to be included as part of a portfolio of technologies utilized on new aircraft.

10. Geared Turbofan Engine

Description: Engine technology that utilizes a gearbox between the fan and the compressor; each rotates at the most efficient speed, improving the propulsive efficiency of the engine.

Emissions Reduction
The average maximum addressable emission-reduction potential for a geared turbofan engine is evaluated only for wide-body applications because the technology is already incorporated in narrow-body and regional applications.[74] Despite the fact that the geared turbofan engine has not been adopted by all OEMs for narrow-body and regional applications,[75] this technology is estimated to be available for wide-body applications in the 2030-2040 time horizon.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Wide Body	8%	2030-2040

Technology Feasibility
Since geared turbofan engine for wide-body applications are currently in the development stage and require minimal additional certification efforts, the technology is considered to be a relatively feasible option for the industry within the 2030-2040 time horizon. Although the geared turbofan will require complex integration across numerous aircraft systems, it can utilize existing manufacturing tools and processes. Further, it does not require additional operational training for aircraft crew, changes to existing infrastructure or any significant new maintenance tooling or repair parts.

For manufacturing companies, there will be a lower cost burden for the geared turbofan engine since it requires half the number of airfoils and results in replacing intricate airfoils with gear steel.[76] Research institutions, airlines, MROs, regulators, other industries and infrastructure would see little to no change in the capital investment required.

Assessment
This technology requires additional investment to scale it to fly on a demonstrator level. Additional partnerships between OEMs and research institutions could also help accelerate technology maturity through increased testing and research. There are little to no technical barriers existing today—only the lack of a viable

business case. Although this technology is already in use on narrow-body and regional aircraft, pursuing wide-body applications could address a significant portion of the emissions generated in the wide-body market segment.

11. High-Pressure Ratio Core Engine

Description: Engine technology with an enhanced efficiency compressor that operates at higher pressure, reducing engine weight and improving thermal efficiency, which delivers more power and increases fuel efficiency.

Emissions Reduction

The average maximum addressable emission-reduction potential for high-pressure ratio core engine is evaluated for narrow-body and regional applications. The technology is estimated to be available for both applications in the 2030-2040 time horizon. Since the technology has already been certified for current wide-body applications and is available for incorporation, this assessment does not focus on wide-body technology in the 2030-2040 time horizon.

Market Segment	Average Maximum Addressable Emission-Reduction Potential	Time Horizon
Regional	1%	2030-2040
Narrow Body	4%	2030-2040

Technology Feasibility

Aside from a few technical barriers for both narrow-body and regional jet applications, this technology was assessed to be a feasible technology for the 2030-2040 time horizon. While still in the development stage, a complex system integration across numerous aircraft systems is expected, although existing manufacturing tools and processes can be used. Due to the small core design, manufacturing and cost challenges are high. No major changes to existing infrastructure or significant new maintenance tooling and repair parts are expected.

Higher costs are expected for manufacturing companies to apply the high-pressure ratio core engine in narrow-body and regional applications. Airlines, MROs, regulators, and other industries are expected to incur additional costs.

Assessment

This technology also requires additional investment to fly on a demonstrator level. Partnerships between OEMs and research institutions can help mature the technology through increased testing and research.

Although this technology is already applied on wide-body applications, broadening the application to narrow-body and regional applications would be beneficial. It would unlock new propulsion emission-reducing technologies for narrow-body and regional aircraft and could address a significant portion of emissions generated for this market segment. However, a downside to bear in mind is that the high-pressure ratio core engine could impact other non-CO_2 greenhouse gases, such as NO_x.[77]

E. CONCLUSION

The feasibility assessment divides the 11 technologies into two different time horizons: technologies that would see incorporation on aircraft entering into service in the 2030-2040 time horizon and technologies that would see incorporation on aircraft entering into service in the 2040-and-beyond time horizon. A summary of the technologies in these time horizons is found below.

Market Feasibility for Technologies: 2030-2040

- The assessment identified these technologies:
- Geared turbofan engine (WB)
- High-pressure ratio core engine (R/NB)
- Laminar flow control (R/NB)
- Hybrid-electric propulsion (R)
- Open rotor (R/NB/WB)
- Advanced composites (R/NB/WB)
- Transonic truss-braced wing (R/NB)

The average maximum addressable emission-reduction potential ranges from 1% to 8%. The smaller scale of regional aircraft has less of an impact on overall aircraft emissions. These technologies may have a lower addressable emission reduction but can offer emission-reduction improvement benefits sooner than the larger applications.

Technologies in this time horizon are primarily regional applications. While several of these technologies are applicable for narrow-body and/or wide-body applications as well, it will require additional time and investment for these technologies to mature and scale.

Geared turbofan engine (WB), laminar flow (NB/R), high-pressure ratio core engine (NB/R) and advanced composites (WB) are the most feasible in this time horizon due to higher maturity status, including certification status. Hybrid-electric (R) was observed to be less feasible because of its technical complexity and advancements required for high-energy-density batteries.

Market Feasibility for Technologies: 2040 and Beyond

From our calculations, technologies that are in this time horizon are:

- All-electric propulsion (R)
- Hydrogen propulsion (R/NB)
- Transonic truss-braced wing (WB)
- Blended-wing body fuselage (WB)
- Fuel cells for onboard power (R/NB)

The maximum addressable emission-reduction potential for the technologies in this segment ranges from 1% to 41%. The upper limit is driven by the new energy pathways, and although the emission reduction is high, so is the uncertainty for these novel technologies.

The larger market segment of the narrow-body fleet also contributes to the greater impact on reducing overall aircraft emissions. These technologies show significant potential to reduce emissions, but due to their low technology feasibility, it will be difficult for aircraft to incorporate and field them.

Due to the addressable emission market share that these technologies cover, companies should consider accelerating them and incorporating them on aircraft sooner. Additionally, scaling these technologies further to apply to wide-body applications, since this segment makes up 45% of aircraft emissions, would significantly decrease aircraft emissions, but this would take place post 2050.

Transonic truss-braced wing (WB) and fuel cells for onboard power (NB/R) have the greatest feasibility in this time horizon. Hydrogen propulsion (NB/R) has the lowest feasibility due to the technical complexity and infrastructure requirements to enable it.

Portfolio of Technologies

The Technology Report and the Feasibility Assessment demonstrated the maximum addressable emission-reduction potential of 11 focused technologies independently. The potential is even greater when multiple technologies are integrated as part of a portfolio on an aircraft.

Technologies such as laminar flow control, transonic truss-braced wing, fuel cells for onboard power and advanced composites can all be incorporated on multiple aircraft types. While the maximum addressable emission-reduction level for their respective addressable markets is not high individually (1%-8%), when combined, a greater emission reduction through synergies can be generated. In the longer term, the combination of technologies like blended-wing body with advanced composites can generate greater benefits, particularly when applied to the next wide-body aircraft generation.

Other examples of portfolios of technology include a blended-wing body fuselage and advanced composites for a wide-body aircraft, and a combination of hydrogen propulsion with a transonic truss-braced wing for a narrow-body aircraft. Although portfolios of technologies would require additional up-front investment to identify the optimal combination, the potential for unlocking the greatest emission reduction will be worth the effort.

Policy Roadmap

The insights gathered from stakeholder interviews for the acceleration of decarbonization technologies as documented in this Feasibility Assessment are further explored in the Policy Roadmap. These interviews were instrumental in shaping AIA's recommendations on how global harmonization, a one-government approach and a deeper understanding of gaps within the industry can help achieve the 2050 sustainability goals.

PART THREE:

AIA POLICY ROADMAP

A. SECTION OVERVIEW

There is no single solution—no “magic bullet”—that will help the aviation industry reduce its carbon footprint. Instead, reaching decarbonization targets will depend on a combination of technological solutions, policies, regulations and incentives. Different solutions will be available for different aircraft on different time horizons. And it will take time to propagate the technologies that do ultimately arrive “on wing” in the commercial aviation sector. Government and industry can be more effective in advancing the sustainability agenda by working together to develop policies, regulations and standards. It’s crucial that all parties understand the design requirements to meet both safety and sustainability goals.

The public sector does have an opportunity—and a responsibility—to facilitate change and ensure that policies and regulations are instituted in a timely manner. This goes well beyond addressing individual laws, product certification rules or policy enhancements. It will require a cohesive, flexible system that functions across multiple agencies and evolves as circumstances change. If the commercial aerospace sector can successfully coordinate across industry and governmental stakeholders, then true aviation sustainability leadership can be attained.

While fleet renewal, offsetting and operational efficiency benefits have yielded emission-reduction results in recent years, meeting net-zero goals for 2050 will take additional steps and the industry should work to minimize the long-term need for offsets. OEMs, airplane platform technologies and associated ecosystem partners each have an instrumental role to play in reducing CO_2 emissions.

SAFs (Sustainable Aviation Fuels), and the associated government support, will also be critical to achieving our collective ambition for emissions reduction, but they are not the primary focus here.

This study has confirmed that airplane and engine technologies and associated ecosystem partners will be instrumental in reducing CO_2 emissions and meeting net-zero goals.

B. AVIATION AND SUSTAINABILITY: WHERE THINGS STAND

Despite public perception, the aviation industry has been committed to sustainability for some time. Today’s modern aircraft are 80% more fuel efficient than the first airliners and produce 50% less CO_2 than the same flights did in 1990. Data show that each new aircraft generation improves fuel efficiency by 15% to 25% on a per-passenger-mile basis.

According to a recent analysis by the International Council of Clean Transportation (ICCT), the average block fuel intensity—the amount of fuel in grams burned per passenger-kilometer flown, as measured from the departure gate to arrival gate—of new aircraft decreased 41% from 1970 to 2019, with an annual average reduction of 1.3%. Additionally, the engine fuel consumption from the 1960s to 2010 has decreased 49%, and the average aircraft “burn per seat” has decreased 82% compared to the commercial jetliner the Comet 4. In the last 10 years, the introduction of fuel-efficient aircraft models such as the A320neo, A350, Boeing 787 and 737 MAX have further reduced the amount of fuel required. Figure 25 shows this decrease in fuel burn and compares the trip fuel consumption and the fuel/seat-kilometer from 1960 to 2010.

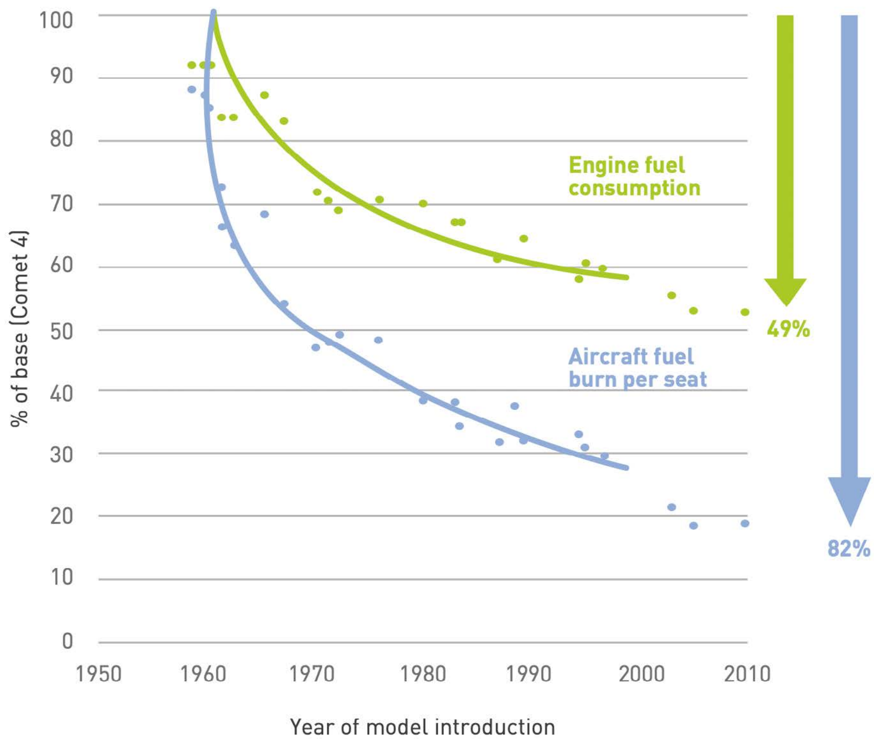


Figure 25 – Fuel Efficiency Through Technology Since the Early Jet Age[78]

Decarbonization efforts continue across the sector, driven largely by industry, governments and other experts working together through the ICAO, which has responsibility for international aviation emissions and publishes Standards and Recommended Practices (SARPs) to harmonize global aviation regulations. For example, ICAO adopted the industry's first aircraft CO_2 standard in 2016, with an initial effective date of January 1, 2020, for aircraft applying for a new type certificate.

This kind of international collaboration is essential in aviation, which by its very nature requires cross-border solutions. Domestic aviation emissions are covered by the Paris Agreement, and the responsibility for compliance falls on agencies like the FAA and EPA. SARPs, even when they are not adopted by US regulators, are still requirements for export of any US-manufactured aircraft to countries that have adopted SARPs into their own domestic regulations.

Aviation was the first sector to establish global sectoral targets for carbon emissions reduction, agreeing in 2009 through the Air Transport Action Group (ATAG) to short-, medium- and long-term goals, including carbon-neutral growth from 2020 forward and reducing net emissions to 50% of 2005 levels by 2050. The long-term 2050 goal was later amended in 2021 to net-zero emissions by 2050, aligning with the ambitious goals of the Paris Agreement. In the mid-term, technology and operations are not sufficient to curb net CO_2 emissions to carbon-neutral growth levels. For this reason and because the aviation industry is difficult to decarbonize, market-based measures have been adopted as part of the solution.

In 2016, ICAO adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), making the international aviation community the first sector to agree to carbon-neutral growth.

The US has trailed behind other countries in the incorporation of the CO_2 emission standard. The FAA still does not have the ability to certify an aircraft to the ICAO CO_2 standard, which risks putting US manufacturers at a competitive disadvantage. The delays that have occurred could be viewed through the lens of the US not being able to stay aligned with international aviation goals.

There has been some positive progress in the use of SAF, a drop-in hydrocarbon fuel that is compatible with today's fleet of aircraft and meets sustainability requirements. It's derived from renewable or waste feedstocks and is approved for use in aircraft at blends of up to 50% with conventional jet fuel. Efforts are underway to raise blend limits up to 100% SAF; however, blend limits do not pose a practical constraint because it is currently difficult to produce SAF at a cost that is economically viable for operators, and the supply of SAF is not readily available. These issues must be addressed to encourage universal adoption globally.

C. UNITED STATES CONTRASTED WITH EUROPEAN UNION

To appropriately assess how existing policy constructs currently impact the aviation industry, it is essential to understand the different approaches at the international level.

Policy Instruments

The EPA issued a greenhouse gas (GHG) emissions standard for aircraft in 2021 that adopts the CO_2 emissions standards set in 2017 by the ICAO. The FAA still needs to issue regulations so that aircraft can be certified to the new standards.

A voluntary program issued by the FAA's CORSIA Monitoring, Reporting and Verification (MRV) Program requires US air carriers and commercial and general aviation operators to submit airplane CO_2 emissions data to the FAA to establish uniformity with CORSIA's standards and recommended practices.

The EU implemented the EASA (European Union Aviation Safety Agency) Basic Regulation for aircraft CO_2 emissions in 2018 following the global standards adopted by ICAO in 2017. The new standard provides additional requirements to be included in the aircraft design process that focus on fuel efficiency. Under the EU Emissions Trading System (ETS), all airlines are required to monitor, report and verify their emissions and to surrender allowances against those emissions. The EU has committed to implement CORSIA through the Bratislava Declaration.

The EU has also released the Fit for 55 legislative packages aimed at reducing net EU GHG emissions by at least 55% by 2030. Over 20 associations collectively representing the entire European aviation ecosystem have announced a joint commitment—EU Pact for Sustainable Aviation—that complements the Fit for 55 legislation. Through this pact, the EU pledged to work with policy makers on the goal of achieving net-zero CO_2 emissions by 2050.

Similar to the Fit for 55 legislation, the US government launched a Sustainable Aviation Fuel Grand Challenge to increase the production of SAF to 3 billion gallons a year by 2030. This is complemented by a broad set of actions that the US government will be taking to reduce aviation emissions, such as technology advancements, policies and executive actions. Its aim is to reduce the cost of SAF production, enhance the sustainability of SAF production pathways and accelerate the scale-up and demonstration of commercial SAF production. These efforts include the DOE, DOT and USDA in the launch of the government-wide SAF Grand Challenge.

Government-Funded Programs

Several companies have partnered with the FAA under the umbrella of the public-private partnership (PPP) Continuous Lower Energy, Emissions and Noise (CLEEN) program that started in 2010 and is currently in its third phase. The collaboration on research and development projects is focused toward reducing noise, emissions and fuel burn. The CLEEN technologies developed so far in the US have resulted in the creation of enhanced aircraft wings, advanced jet engine combustion systems and flight management system algorithms leading to lower emissions and more flight-efficient routes.

NASA has a long history of supporting and investing in aeronautics and partnering with the industry. Many of the significant improvements on today's aircraft are a direct result of NASA's leadership. From X-planes to major demonstration projects for airspace/operational efficiency to icing research, NASA's continued leadership and partnership is a key component in the future of aviation sustainability. As part of its approach, NASA launched an initiative called the Sustainable Flight National Partnership (SFNP), partnering with the FAA to accomplish aviation's aggressive climate change agenda. Its fiscal year 2022 budget request confirms its plan to develop next-generation, efficient aircraft and to support new academic-led research of zero-emission aviation. NASA has four programs—Airspace Operations and Safety, Advance Air Vehicles, Integrated Aviation Systems, and Transformative Aeronautical Concepts—each with a significant number of projects that have been helping advance sustainable aviation technology and systems for over a decade.

For its part, the EU has announced a clean aviation program, the European Partnership for Clean Aviation. The program is intended to accelerate the development of disruptive technologies, including hybrid-electric and all-electric concepts, ultra-efficient aircraft architectures, and hydrogen-powered aircraft—which will aim to deliver a new breed of regional, short-haul and medium-haul airliners for entry into service by 2035.

The European Partnership for Clean Aviation will build on the work done to date by the Clean Sky and Clean Sky 2 Joint Undertakings, which is the EU's flagship public-private partnership program to develop innovative technologies to reduce fuel burn, CO2 and NO_x emissions, and external noise levels. The EU Clean Sky's projects have developed more than 30 demonstrators that have helped to dramatically slash CO2 emissions and noise footprints. Improvements include lighter composite structures, fuel-efficient engines, better wing aerodynamics, smarter trajectories and more electrical architectures.

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a unique public-private partnership supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. The second generation of the FCH JU aims to accelerate the commercial deployment of hydrogen-based energy and transport solutions across the region.

The United Kingdom, Germany, France, Spain and others have their own government-funded programs. Specifically, for the United Kingdom, the Aerospace Technology Institute's technology program invests half of its funding toward technologies that directly reduce aviation emissions. Another partnership between industry and government is the Jet Zero Council (JZC), aimed at bringing together ministers and chief executive officer-level stakeholders with the goal of delivering new zero-emission technologies and innovative ways of reducing aviation emissions. The JZC focuses on accelerating the design, manufacture, testing, certification, infrastructure and commercial operation of zero-emission aircraft and aviation systems.

Industry and Academia

On the academic front, a cooperative aviation research organization called the Aviation Sustainability Center (ASCENT)—funded by the FAA, Transport Canada and other government agencies—focuses on meeting the environmental and energy goals of the Next Generation Air Transportation System (NextGen), including reducing noise, improving air quality, reducing climate impacts and increasing energy efficiency.

Groups of researchers, scientists and engineers from the University of Illinois at Urbana-Champaign formed the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) to represent a multidisciplinary consortium from a variety of universities, laboratories and industry groups.

By developing, maturing and designing disruptive technologies, research themes such as distributed electric propulsion, electrical components, energy storage and systems integration are being advanced for electric aviation.

Similarly, in Europe, several private-sector companies have participated under the umbrella of the Clean Sky program for the development of technology demonstrators that help with noise reduction and lowering emissions. One such example is the Breakthrough Laminar Aircraft Demonstrator in Europe (BLADE), which is led by Airbus and 20 other partners. This demonstrator advances the laminar flow control technology over the wing for both narrow-body and regional applications. Also, several universities and research institutions are core partners and members of the Clean Sky 2 integrated technology demonstrator program. One such example is the University of Nottingham, which has secured 25 projects through Clean Sky 2 and is working on various platforms—including E-Fan X, a step toward electric propulsion, and Ultrafan, an application of geared turbofan engine technology.

Operations and Infrastructure

NextGen is an FAA program developed to reduce air-traffic delays, improve air safety and increase efficiency, leading to fuel savings and lower-carbon emissions. NextGen also focuses on developing capabilities that will guide and track aircraft more precisely and efficiently in the air and on the ground to save fuel, decrease emissions and manage the impact of noise on communities.

For example, performance-based navigation (PBN), enabled by satellite technologies, creates more fuel-efficient routes that reduce emissions. Collaboration between NASA and the FAA has fostered the development and adoption of the technologies and operational concepts that underpin PBN. The FAA's Aviation Environmental Design Tool (AEDT) is used to evaluate the environmental impacts of airspace changes under the National Environmental Policy Act (NEPA). Other examples of sustainable development initiatives include the Noise Compatibility Program and the Voluntary Airport Low Emissions Program, which are focused on airport noise and air quality.

In the EU, the Single European Sky (SES) initiative works to reduce the fragmentation of European airspace and to improve the performance of air-traffic management in terms of safety, capacity, cost-efficiency and the environment. The first SES legislative package (SES I) was adopted in 2004, SES II in 2009 and SES II+ in 2013.

The European Commission upgraded the SES regulatory framework into a Single European Sky ATM Research (SESAR) to establish more sustainable flight paths. SESAR is the operational and technological pillar of the SES initiative; one of the key priorities is to enable the reduction of the environmental impact per flight by 10%. The SESAR Joint Undertaking has also unveiled new solutions specifically addressing the airport environment, including the Advanced Engine Off Navigation (AEON) project to lower CO_2 emissions generated by aircraft taxiing.

Its research and innovation programs are addressing inefficiencies in air-traffic management through digital transformation and developing technological solutions such as i4D for the optimizing of trajectories, leading to fuel savings. The RISE Project (RNP Implementation Synchronization in Europe) aims to improve airport accessibility, enhance safety and reduce environmental impact at airports throughout Europe.

Various incentivization initiatives to facilitate decarbonization are provided by EASA's Sustainable Aviation Program, which supports greener technologies through environmental certification and standards. EUROCONTROL has also accelerated its work on aviation sustainability by developing several tools and models focused on analysis of noise, fuel consumption and emissions. For example, FATHOM, EUROCONTROL's new interactive analysis tool, helps aircraft operators achieve more efficient, sustainable flights.

Results Remain To Be Seen

Both regions are focusing their efforts on identifying new technology pathways toward developing sustainable aviation infrastructure and operations. Overall, the EU has been leading the way in efforts at both regulatory and industry levels when compared to the US. Additionally, investments in the development of sustainable aircraft technologies by both the EU government and the European private sector have far exceeded those in the US.

However, data of actual emission-reduction results has yet to demonstrate a variance resulting from the investment and efforts expended by both the EU and US regions. Therefore, while we can determine that sustainability investments, efforts and funding are greater and more numerous on the EU side, the results remain to be seen.

As more data is gathered around impact, emissions reduction and metrics for aviation sustainability, we will be able to determine with more certainty that the return on investment is indeed achieved.

D. LIMITATIONS AND CHALLENGES

The challenges identified by stakeholders for the US to improve and accelerate the adoption of sustainability-focused technology can be broken into three categories:

1. Cohesiveness of governmental effort
2. Infrastructure investment
3. International harmonization

Cohesiveness of Governmental Effort
To achieve net zero, stakeholders must not only align on goals, but also on strategy.

Unity of Purpose

This is a complex issue, requiring a strategic, multipronged response. In the US, the national aeronautics R&D policy (2006) and a subsequent plan (2008-2010) were developed, but both documents are now outdated.

The FAA recently published its Aviation Climate Plan, which does include NASA. But at present, the absence of a documented, integrated multiyear plan that outlines its long-term goals and the roles and responsibilities of various stakeholders presents a challenge for the industry to achieve sustainability goals. Greater public-private collaboration could further refocus and reenergize the industry in meeting sustainability goals: This is not only good for the environment, but also good for business. And there is an opportunity for the US to build a multidecade foundational plan that all parties—governmental, non-governmental, industry and academia—can support. The national R&D policy and plan must be updated in the very near future so all have a clear understanding of what we are trying to achieve.

Unity of Effort

A plan is only as good as the ability and willingness to execute it. Sustainability goals will require significant integration across multiple agencies, as well as OEMs, academia, suppliers, infrastructure, airlines, regulators, MRO and other industries. That integration requires leadership, but it is not clear which agency or ecosystem partner should lead the effort.

The Department of Transportation might seem like a natural choice to play the role of leader and integrator, but the solutions require investment in energy and power sources, so perhaps that falls under the purview of the Department of Energy, and so on and so forth.

What is clear? Without an integrated plan, stakeholders run the risk of redundancies of effort within multiple organizations and misaligned strategies or timelines, resulting in increased overall costs to government and industry and a delayed adoption of potential solutions.

Infrastructure

Infrastructure is often cited as one of the biggest obstacles to overcome in the adoption of any new technology, and this holds when it comes to sustainable technologies in the aviation industry. Infrastructure is expensive, and investing in the incorrect solution set could delay a positive result for years. For that reason, it's crucial for the US government to understand the full picture before picking a final approach.

When trying to understand the full picture for technologies like novel propulsion and new aircraft designs, infrastructure stakeholders will need to build their plans accordingly. That includes considering how to reequip aircraft; the supply, storage and transportation of fuel; battery charging and storage infrastructure; new passenger terminals and gates; stronger runways to deal with an increase in aircraft weight; and ensuring interoperability between airports.

While the ability to operate an aircraft is important, it is also important to keep these new aircraft flying. Maintaining these aircraft will also require MRO infrastructure as well as parts and tools to repair them. This needs to be considered from a global view as well.

International Harmonization

A US plan can't be developed in a vacuum. Aviation is a global industry, and products that are designed and manufactured in the US are delivered around the world. It is critical to work closely with international organizations such as the ICAO to ensure that the Standards and Regulatory Practices (SARPs) are shaped in such a way that they are achievable in a cost-effective manner without compromising safety, and that they are part of a cohesive international strategy.

ICAO is the appropriate place to work on these standards to ensure that governments acting as states of design or manufacture stay harmonized in achieving positive climate outcomes. As US regulators continue to develop standards for aviation decarbonization, it is important to ensure that there are policies in place for the continuation of operations of today's aircraft, and subsequently transition the US fleet toward the lower-emission technologies over time.

Where Do Stakeholders Stand?

The team conducted over 30 interviews with industry stakeholders and identified a clear consensus on the type of government interventions needed to support the industry in decarbonization efforts. The following themes emerged:

- Standards and regulations for electrification and alternative fuels (hydrogen and renewable energy) require clearer definitions for the industry to make the required investment.
- Incentives to promote R&D in advanced technologies (engines, airframes, aerostructures, fuel, monitoring systems, autonomous systems, etc.) need to start big and narrow down over time.
- Government support including tax breaks, reduction of leasing rates and cost gaps (e.g., buy electric credits), and lower regulatory barriers/penalties will encourage companies to invest now.
- Investment in infrastructure (production, distribution and storage) is considered essential for achieving the long-term goals; this requires the prioritization of government funding.
- Unified global certification with the principle of safety first will streamline the process for new technologies, resulting in an accelerated pathway for decarbonization technologies to enter the market.
- A recurring theme throughout the interviews was the belief that government needs to provide continuity on decarbonization initiatives for the targeted results to be achieved.

Lack of clarity around the definition of decarbonization standards and lower-emission regulations is also a concern, particularly for aircraft manufacturing companies with long planning cycles for aircraft-related technologies. Last, but certainly not least, interoperability and harmonization are also top of mind for executives at OEMs and suppliers as they strive to serve a global industry with localized products.

E. RECOMMENDATIONS

One Plan

It is critical that the US proactively addresses the challenges around unity of purpose and unity of effort. Merely setting long-term goals and hoping for the best is not enough. There must be a multiyear plan tied to funding that the industry can count on.

This roadmap should be broken into distinct time horizons: now-2030, 2030-2040 and 2040-and-beyond, with flexibility to adjust as the situation warrants. As Figure 26 shows, there is a significant difference between the CO_2 technology path we are following today and what results are achievable if aggressive action is taken.

Practically speaking, aviation advances are made at a systems level, and industry and government should continue the practice of researching configurations, engines or other technologies for each time horizon, aiming to develop a portfolio approach with technologies at different levels of feasibility.

Policies and industry standards are tools that provide guidance as well as overarching requirements that link the technologies together in a portfolio. They provide standard operating procedures, a step-by-step process and a roadmap for synergistic technologies to be combined on an aircraft platform.

For example, for technologies that have a lower feasibility but a higher emission-reduction potential, such as novel propulsion technologies like hydrogen propulsion, a roadmap must be put in place to direct the technology development to manage investments more efficiently. Since implementing individual technologies does not result in significant decarbonization, this roadmap should also direct companies to look at what additional technologies, like advanced composites, fuel cells for onboard power and/or laminar flow control, should be paired with these propulsion technologies when fielding a new aircraft. These portfolios of technologies will require additional up-front investment but will help to achieve overall industry decarbonization goals.

Stakeholders must work together to assess all sustainability solutions through this holistic lens. Bringing the technologies addressed in this study to market requires ensuring that tomorrow's aircraft and airspace systems are equipped to monitor and integrate these systems into today's operating environment while still having the flexibility for air traffic management (ATM) itself to evolve over time.

In the now-2030 time horizon, it appears reasonable to continue focusing on improvements of engine performance and efficiency gained through evolving solutions for propulsion, aircraft weight, flight optimization, control surfaces and aerodynamic efficiency while identifying other technologies that can be incorporated into this time horizon. Continually pursuing technologies like high-pressure ratio core engine and geared turbofan engine for existing market segments will help to decrease aircraft emissions, but significant changes are still a ways off. Combined with SAF and new industry standards, these technologies will help aviation move forward in achieving its targets.

In the 2030-2040 time horizon, because of the higher feasibility of the technology, new market segments for high-pressure ratio core engine and geared turbofan engine and increased usage of advanced composites, laminar flow control and open rotor (regional) are additional steps toward net-zero targets—but only if they can scale to larger applications. The industry stakeholders, including manufacturers, regulators, government agencies, operators, infrastructure service providers and academia, all have critical roles to play in the timely development and deployment of these systems and for the enablement of future aircraft that use these technologies.

For entry into service dates of aircraft programs in the 2030s, the technology needs to be at a Technology Readiness Level (TRL) of six within the next couple of years, because even after the technology enters the market, it takes years to propagate across the market to achieve its full emission-reduction potential.

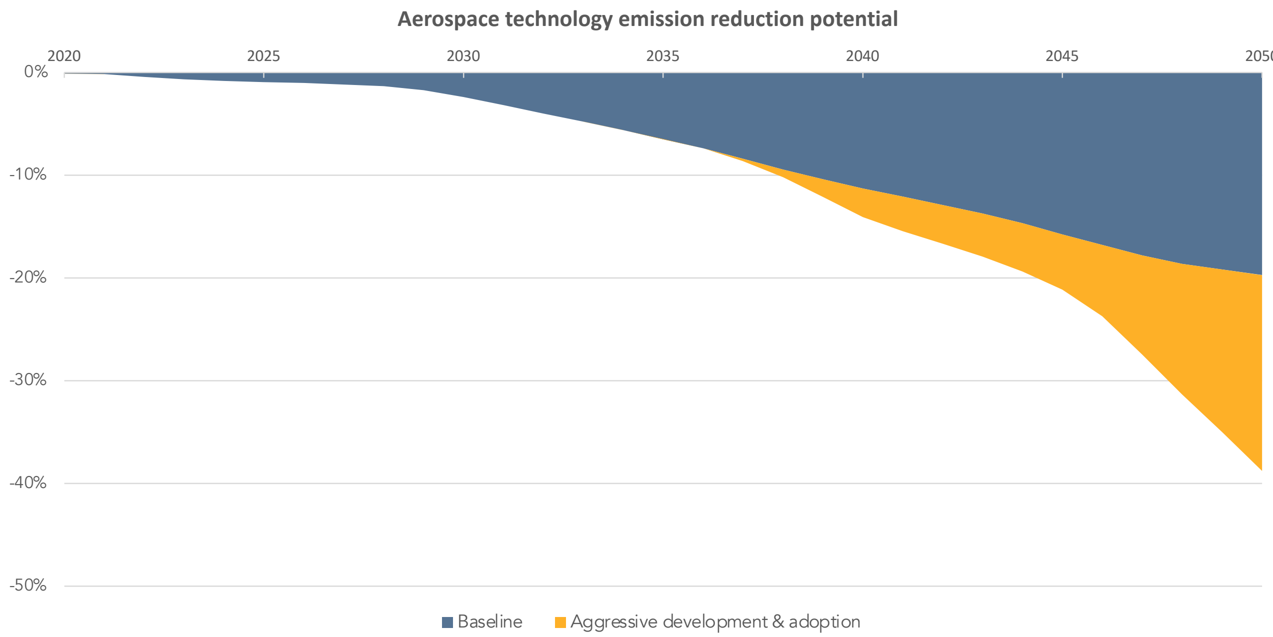


Figure 26 – Aerospace Technology Emission-Reduction Potential Between 2020-2050[79]

In the 2040-and-beyond time horizon, technologies like hydrogen propulsion, blended-wing body and transonic truss-braced wing will act as a step-change in reducing emissions produced in aviation because of their high emission-reduction potential. Currently, NASA and the industry are aiming to demonstrate several of these capabilities in the mid- to late 2020s, enabling the possibility that they may enter service on an aircraft sooner. However, they will need additional time to mature due to their lower feasibility. For this reason, we call on the US to create a roadmap for how we get there as soon as possible. We also strongly encourage integrating this plan across multiple organizations at the outset to ensure alignment of effort and maximize the benefits gained. This effort will likely require a lead agency while allowing for other agencies to focus on what they do best and materially contribute to the bigger plan.

Therefore, to achieve the aviation and US ambitions for net-zero CO_2 emissions by 2050, the balance of emission reduction from what can be achieved by SAFs, supplemented by carbon offsetting mechanisms, needs to be paired with technology. Vice versa, this study also reaffirms that airplane technology alone cannot be the only industry solution, even under aggressive development and adoption scenarios. A holistic approach is indeed required.

The Regulatory System

Today's certification system is not positioned to move sustainability products to market quickly, but opportunities do exist to improve the process without sacrificing the critical element of safety. By moving toward a performance-based, internationally recognized set of standards, the industry can utilize science-based data to produce solutions that are available in realistic time frames and allow continuous improvements for the aviation system. Because of safety considerations, aviation is evolutionary, not revolutionary. The industry needs to approach sustainability in the same way.

For new technologies, standards can define the requirements for design up front, which will help speed these new technologies to market while still maintaining safety. Existing certification requirements could be leveraged for new products so the process is not hindered with unnecessary new requirements.

Finally, as mentioned previously, the need to work across geographical regions is imperative. US products are certified internationally through the practice of validation and focusing on the following two paths will accomplish results globally:

1. Harmonization: Where manufacturers and regulatory bodies for states of design work with each other to ensure that any rulemaking that may be required is coordinated in such a manner that their rules are aligned. An example of this would be for all-electric propulsion in the standardization of charging infrastructure, voltage and required current, batteries, and connectors.

2. Acceptance: Where bilateral agreements exist, states of design should look to accept one another's certifications to the maximum extent possible without placing additional roadblocks or requirements that add no safety value. An example of this would be for reciprocal certification of new wing, fuselage or airframe designs.

Tools for Government Support

As the aviation industry emerges from the COVID-19 pandemic, there are several tools and mechanisms that government can leverage to provide industry the support it needs to move ahead with the sustainability agenda.

The phrase "green recovery" has been used by the European Union and other governments, and they are putting a significant amount of financial capital behind the problem. Stakeholder interviews revealed concerns that if the US fails to act in a similar manner, the potential for a significant competitive advantage for Europe exists. Funding for next-generation aircraft sets a competitive trajectory that lasts a long time, and the competitive nature of commercial aviation is expanding beyond just the US and the EU.

There are several tools and mechanisms to achieve the universally held net-zero goals, such as direct public funding, the use of public-private partnerships and industry incentives. As such, a roadmap for centralized integration will ensure that the funding gets to the place where it can be most effectively used in an optimal time frame for the sustainability benefits to be realized. Technologies such as novel propulsion for narrow-body applications, new airframes and new wing designs, which are in the 2040-and-beyond time horizon, will benefit from public-private partnerships that ensure that investments made today enable aircraft with these technologies to enter the market.

Long-Term Planning

NASA provides a good example of what more can be done. The budgeting process for divisions such as NASA Aeronautics Research Mission Directorate (ARMD) can be significantly enhanced for high-priority items such as sustainability. Most government agencies work on a five-year cycle; with year-to-year budgets subject to oscillations, they are always working toward longer-term outcomes.

For the aviation industry to hit its 2050 goals, public funding could be optimized by working to develop an ongoing plan and keeping the technology research pipeline full. This change could significantly enhance the opportunity for industry to accelerate technology development.

As the stakeholders explore different programs, focusing first on the systems with the most emission-reduction potential will result in a more immediate impact.

Long-term funding is required for technologies in the 2030-2040 and 2040-and-beyond time horizons. These technologies will focus on evolutions of current propulsion technology, novel propulsion technology, new airframe options and new wing/control surface options and will need to have funding secured to ensure that they continue being a priority. Bringing together public and private resources to invest in high-risk, high-reward technologies at scale can accelerate these promising technologies.

By determining the true feasibility of each of these technologies, the industry can also benefit from a portfolio approach to exploring promising technologies at a systems level, hence assessing the obstacles or challenges that must be overcome to maximize benefits.

Public-Private Partnerships

There is consensus from stakeholder interviews that further exploration of public-private partnerships and collaboration can be very effective in advancing mutual goals. Initiatives like SFNP and CLEEN should be enhanced to make further use of partnership opportunities. There are also opportunities for similar aviation programs to be put in place.

One component of these public-private partnerships that can also be enhanced is the expansion of technology demonstrators. Whether it's Boeing's Eco Demonstrator or NASA's X-planes, these platforms allow industry and government to incorporate multiple technologies on a single integrated aircraft and validate technologies in flight, which enables further investment in technology advancement and commercialization to maximize sustainability benefit.

Technologies that would benefit from being flown on a demonstrator include those that are the most feasible in the 2030-2040 time horizon, such as hybrid electric, transonic truss-braced wing, advanced composites, open rotor, high-pressure ratio core and others. Testing these technologies on a demonstrator or X-plane level could help to mature and scale them to narrow-body and even wide-body applications.

In the 2030-2040 time horizon, the industry anticipates increased electrification, such as hybrid-electric propulsion (for regional aircraft), new aerodynamics (like TTBW for regional and narrow-body aircraft), advanced composites (for all types), new propulsion (such as open rotor and high-pressure ratio core for narrow-body and regional aircraft), and geared turbofan engine (for wide-body aircraft). In the mid term we expect laminar flow control technologies to be available for regional and narrow-body aircraft. These technologies are making steady advancements, and additional funding to accelerate readiness for entry-into-service aircraft opportunities will ensure that emission-reduction potential is realized in the 2030-2040 time horizon.

There are many other opportunities for the private and public sector to work together. A side benefit from this collaboration is that data gathered in a systemic environment can help accelerate the certification process, bringing more solutions to market. Furthermore, it is believed that there are opportunities to include more of the industrial base, not only OEMs, as the supply chain drives the market. So, while wing, engine and fuselage design advancements are the more visible technologies, many subsystem technologies can benefit from this partnership as well.

F. CONCLUSION

This roadmap has shown that there are many available potential technologies on the horizon that have the potential to reduce aircraft emissions. These technologies are at various TRL levels and maturity states. However, the private sector alone is not sufficient for these technologies to be accelerated into the market. Inaction by government or a failure to collaborate sector-wide will be detrimental to the strides that the industry has achieved in the realm of decarbonization technologies.

This Policy Roadmap is not advocating for the creation of a brand-new policy construct, nor is it calling for the restructuring of the current system. But a deliberate and cohesive action is necessary to accelerate the development and market launch of the decarbonization technologies. In addition to an optimal prioritization based on technology-specific facts and data and the use of the various tools and mechanisms as outlined in this document, government is instrumental in advancing these technologies.

Recommendations include:

- Updating industry standards, policy and planning to a single plan with associated time horizons. Specifically, the National Climate Aviation Strategy should be required to be updated every five years.
- Ensuring the long-term plan provides the opportunity to align five-year budgets in the meantime.
- Creating a singular integrating office to align goals and schedules.

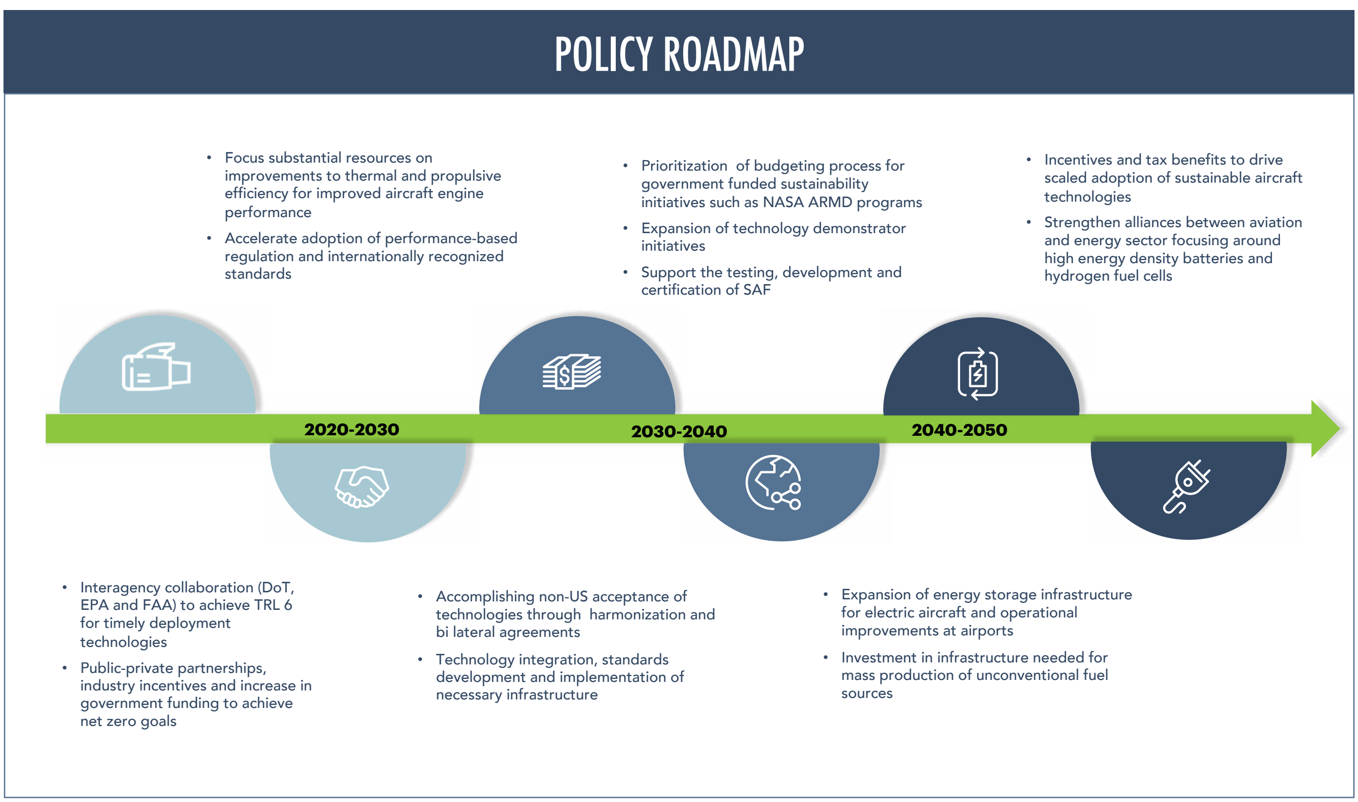
- Maintaining and enhancing the current technology portfolio approach.
- Working to shape ICAO SARPs into achievable goals.
- Ensuring that the system is positioned to incorporate these new technologies as quickly as possible while maintaining safety as the number-one priority.

It will take the right level of public and private-sector collaboration, combined with data-driven, deliberate prioritization of technologies, to accelerate the development and market launch of decarbonization technologies and advance the industry along its journey toward net-zero emissions by 2050. ■

G. APPENDIX

	US	EU
Policy instruments	**EPA GHG emission standards for airplanes** **FAA CORSIA Monitoring, Reporting and Verification (MRV) Program** **SAF Grand Challenge**	**EASA Basic Regulation for aircraft CO2 emissions** **ECAC Bratislava Declaration for CORSIA implementation** **Fit for 55 legislation** **EU Pact for Sustainable Aviation** **EU Emissions Trading System (ETS)**
Government-funded programs	**Continuous Lower Energy, Emissions & Noise (CLEEN) program, FAA** » Budget Phase 1: ~$125M (2010-2015) » Budget Phase 2: ~$100M (2016-2020) » Budget Phase 3: ~$100M (2021-2025) **Sustainable Flight National Partnership (SFNP) program, NASA** » Integrated aviation systems program: $302M for development of sustainable flight demonstrator (2021). Note this is the Year 1 level of funding; the 5-year-level budget is not included here. » Advanced air vehicles program: $244M for advanced engine technology development, composite structures and advanced transonic truss-braced wing (2021). Note this is the Year 1 level of funding; the 5-year-level budget is not included here. » Additional budget for AOSP and TACP related to sustainability » Note: There are several other programs. The above are a few examples collected at the time this study was written.	**European partnership for clean aviation** » €10B for research partnerships between the EU, member states and industry **Clean Sky Initiative, European Commission** » Clean Sky 1: €1.6B (2008-2017) » Clean Sky 2: €4B (2014-2014) » Clean Sky 3: TBD (2025+) **Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU 2)** » €5.1M for fuel cell hydrogen system for aircraft emergency operation (2020) **Aerospace Technology Institute Program, UK** » £84.6M to develop green technologies (2021) » £42.3M matched by industry » £685m to develop green technologies (2022-2024) with industry match will exceed £1 Billion **Jet Zero Council, UK** » £3M to develop an emission-free flight infrastructure
Industry collaboration	**CLEEN Phase 3:** General Electric, Honeywell Aerospace, Pratt & Whitney, Boeing, Delta TechOps, GKN Aerospace, MDS Coating, America's Phenix, Rohr Inc. **CLEEN Phase 2:** Aurora Flight Sciences, Boeing, Delta Tech Ops / MDS Coating Technologies / America's Phenix. It also includes Rohr Inc., General Electric, Honeywell, Pratt & Whitney, Rolls-Royce **CLEEN Phase 1:** Boeing, GE Aviation, Honeywell, Pratt & Whitney, Rolls Royce	» **Clean Sky 1:** BLADE project: Airbus, Dassault Aviation, SAAB, Safran and others (not an exhaustive list) » **Clean Sky 2:** More Electrical Large Aircraft project: Airbus, Safran, Thales, Liebherr, Zodiac » **Clean Sky 2:** Integrated Technology Demonstrators (Airframe, Engines, Systems): Dassault, Airbus, SAAB, Safran, Rolls Royce, MTU, Thales, Liebherr

Academia collaboration	**Partner universities:** ASCENT Program; Boston University, Georgia Tech, MIT, Missouri S&T, Oregon State, Penn State, Purdue, Stanford, Dayton, University of Hawaii, University of Illinois, University of North Carolina, University of Pennsylvania, University of Tennessee, University of Washington, Washington State University (not an exhaustive list)	» **Partner universities:** Nottingham, Stuttgart, Bradford, Imperial College (not an exhaustive list)
Operations/ infrastructure	Next-generation air transportation system (**NextGen**) » Airport environmental programs	» Single European Sky (SES 1, SES 2, SES2+) » **SESAR project** » RNP Implementation Synchronization in Europe (RISE)



The policy recommendations included in this report are those of AIA and do not reflect the opinions or views of Accenture".

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Silver also served as the 787-8 Deputy Fleet Chief for the introduction of aircraft into commercial operations. Silver worked with airline customers, regulators, and airplane program chief engineers on model-specific technical and safety issues affecting the in-service fleet to increase reliability and ensure smooth operations for the airlines. Silver also has vast experience working Airplane Systems for airplane programs such as the 777 and 767.
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