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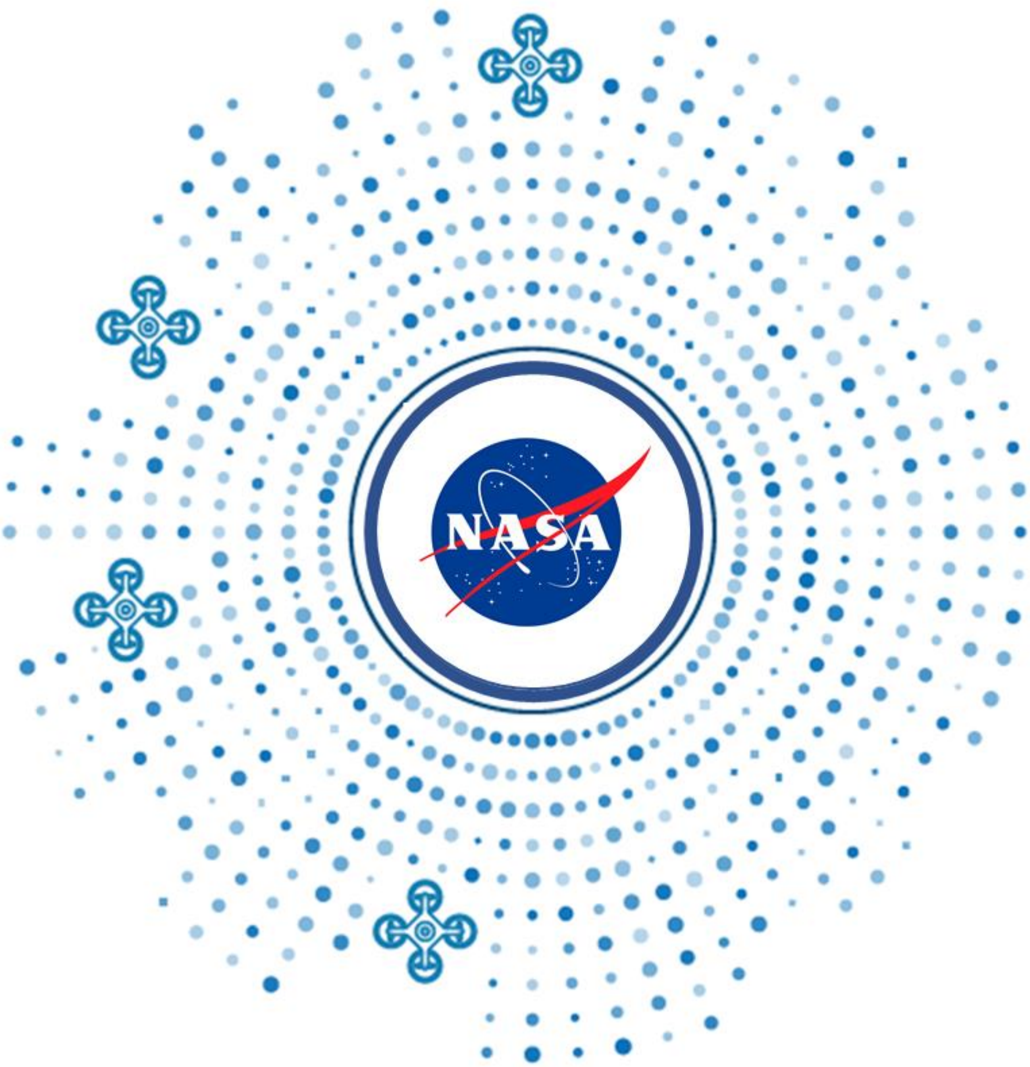

Additional Aviation Sustainability Strategies

Assessment, Evaluation, & Analysis

National Aeronautics and Space Administration (NASA)

Aeronautics Research Mission Directorate (ARMD)

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I. Introduction

I.I Background & Goal

Emissions from the aviation sector are expected to grow significantly in the next few decades due to growing demand for aviation.[1] The U.S. fleet size has increased significantly in the past 20 years, growing from 2,132 aircraft to 5,485 aircraft.[i] Similarly from 1990 to 2019, aviation emissions more than doubled, growing faster than any other transportation mode.[2] These emissions include carbon dioxide (CO2), as well as non-CO2 sources including nitrogen oxides (NOx), sulfur dioxide (SO2), water (H2O), and particulate matter (soot).[2] However, this report focuses specifically on CO2 emissions because the impacts from CO2 are well-understood and long-lived. There are also many climate goals tied to CO2 emissions, including the US Aviation Climate Action Plan which is pushing for net-zero in 2050.

CO2 is a greenhouse, or heat-trapping, gas that comes from the extraction and burning of fossil fuels, from wildfires, and natural processes like volcanoes.[3] Greenhouse gases absorb heat radiating from the Earth's surface and release it in all directions, including back toward Earth's surface. By adding more CO2 to the atmosphere, humans amplify the natural greenhouse effect, causing global temperature to rise.[4] Since the onset of industrial times in 1750, human activities have raised atmospheric CO2 by 50%.

Considering this challenge, the United States has set a climate goal to achieve net-zero CO2 emissions in the U.S. aviation sector by 2050 to reduce the environmental impact of aviation. Net-zero emissions refers to the amount of greenhouse gases (GHGs), such as CO2, methane or SO2, that are removed from the atmosphere being equal to those emitted by human activity. This contrasts with carbon-neutrality, which refers to no net release of carbon dioxide to the atmosphere, especially through offsetting emissions, that could be accomplished through a series of actions.[5]

As of 2022, the goal of net-zero has been adopted by much of the aviation industry including multiple airlines and countries.[6]

To reach net-zero by 2050, sustainable aviation fuels (SAFs) are identified as the technology that could provide the greatest impact within this timeframe. However, certain challenges may limit the production and/or adoption of SAFs in the marketplace, such as competition for feedstocks, production capacity, and high cost. In this case, SAFs would be insufficient to meet the net-zero CO2 emission goals. Therefore, in addition to SAFs, other strategies will be needed to close the gap on emissions produced as a result of SAF shortfalls or to enhance the impact of SAFs on reducing emissions.[7]

NASA's Aeronautics Research Mission Directorate (ARMD) aims to examine these additional pathways to explore how its research may best contribute to the realization of net-zero emissions by 2050. Specifically, this effort considers strategies that can reduce emissions in the aviation sector in combination with the use of SAFs and carbon offsets while still meeting

[i] This was calculated using information from the 10-Ks of Delta Air Lines, American Airlines, United Airlines, Hawaiian Airlines, Alaska Airlines, Southwest, and JetBlue

projected passenger demand. The strategies considered are not only feasible but also could be operationally scalable by 2050. The goal of this report is to investigate additional strategies such as alternative flight and ground operations, providing insight into the CO2 emission reduction potential and feasibility of strategy implementation by 2050.

I.II Aviation Emissions Landscape

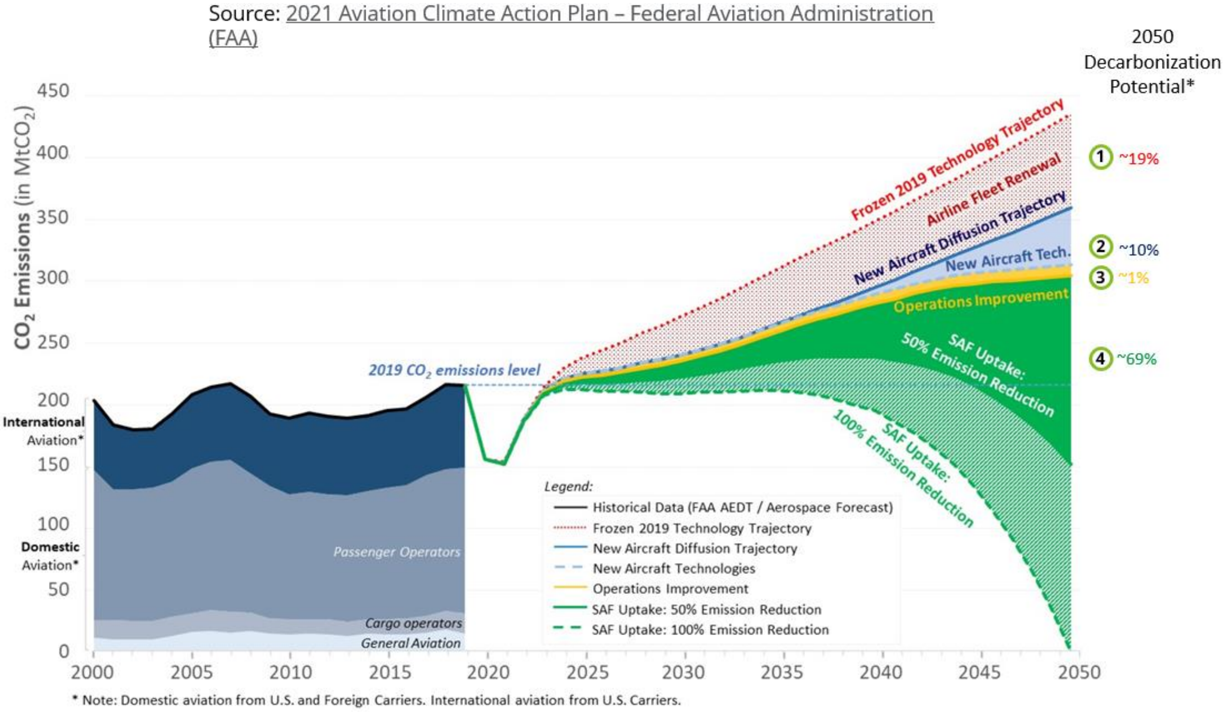
Without intervention, CO2 emissions in 2050 are expected to more than double from 2019 baseline emissions.[8] Therefore, multiple decarbonization pathways, in addition to SAF adoption, will be needed to decarbonize aviation by 2050. Some of these pathways are categorized in the Federal Aviation Administration (FAA)'s U.S. Aviation Climate Action Plan, which outlines 4 key aviation emission opportunities:

1. Airline fleet renewal emissions reductions resulting from the retirement of legacy aircraft in favor of newer, more fuel-efficient aircraft that are currently in production.
2. New aircraft technology emissions reductions result from the adoption of new, more efficient aircraft that are not yet developed.
3. Operations improvements reduce fuel burn, providing incremental cost savings and emissions reductions.
4. SAF is the primary driver to achieve emissions reductions by 2050; its adoption is limited by supply and its associated green premium over standard jet fuel.

The Figure below provides a visualization of the potential decarbonization impacts of the four key factors according to the U.S. Aviation Climate Action Plan.

Figure 1: Overview of Aviation Climate Action Plan[8]

Source: 2021 Aviation Climate Action Plan – Federal Aviation Administration (FAA)



The vision demonstrated in the U.S. Climate Action Plan also aligns with additional research that verifies comparable forecasts. In specific, Jensen et al. reviewed the four key points examined in the U.S. Aviation Climate Action Plan and found similar decarbonization reduction percentages.[9] The paper found that airline fleet renewal could achieve 17% of the 2050 emissions reduction goal, compared to 19% in the Climate Action Plan.[8] [9] Airline fleet renewal accounts for the acquisition of new aircraft with improved fuel efficiency such as the Boeing 737 MAX and Airbus A320neo.[8] Advanced aircraft technologies, which are a result of research and development investments in aircraft and engines, were found to contribute 17% of the 2050 emissions reduction goal, compared to 10% in the Climate Action Plan.[8] **Error! Bookmark not defined.** Operational improvements were found to contribute 2% of the 2050 emissions reduction goal, compared to 1% in the Climate Action Plan.[8] [9] Finally, SAF was found to contribute 70% of the 2050 emissions reduction goal, compared to 69% in the Climate Action Plan.[8] [9]

In the early stages, this report also leveraged Boeing's Cascade Climate Impact Model (Cascade) to gain an initial understanding of the different areas within the aviation industry that may be Opportunity Areas for emission reduction.[10] The model demonstrates emissions reduction potential and impacts of what reaching decarbonization by 2050 could include. From the Cascade model, this effort identified fleet renewal, future aircraft, operational efficiency, and renewable energy as key areas with potential for future research and emission reduction.[10] Building off the U.S. Climate Action Plan and the Boeing Cascade model, this report examines 100+ additional sources, including Deloitte research, to inform analysis and findings to shape the Opportunity Areas in this report.

I.IV Key Emissions Drivers

To conceptualize the full picture of potential aviation-related associated CO2 emissions, NASA's research first examined aviation emissions across ground transportation to and from the airport, non-flight related airport operations, and in-flight related operations. The analysis examined the CO2 emissions associated with an individual passenger's entire transportation journey for a flight.

This analysis uses a combination of Scope 1, 2, and 3 emissions as currently defined and outlined by the FAA.[11] Scope 1 emissions refer to emissions that are owned and controlled by the airport operator, such as energy generation and airport vehicles.[11] Scope 2 emissions refers to emissions from the off-site generation of energy purchased by the airport operator.[11] Scope 3 emissions are those owned and controlled by airport tenants and other stakeholders such as airline vehicles, ground service equipment (GSE) and energy usage, or ground vehicles including buses and trains.[11]

A passenger's associated CO2 emissions begin with ground transportation to the airport, such as in a car or bus. These emissions per passenger resulting from roundtrip ground transportation to the airport are estimated at 21.3 kg CO2e (carbon dioxide equivalent).[12] [ii] CO2e is the number of metric tons of CO2 emissions with the same global warming potential as one metric ton of another greenhouse gas.[13] Once arriving at the airport, associated CO2 emissions can include utilizing non-flight related airport operations, such as heating and cooling in the airports, which are estimated to produce 5.2 kg CO2e emissions per passenger.[iii] This was calculated using JFK's Terminal 4 emissions from 2019 of 56,545,000 kg CO2e, which includes Scope 1, 2, and 3 emissions.[14] Also produced pre-flight are ground operations, such as ground support vehicles to carry luggage. Ground related operations emissions related to this phase of the traveler's journey are estimated at .6 kg CO2e, calculated using Delta's "other" Scope 1 emissions from 2021 of 168,140,000 kg CO2e .[15iv]

The next phase of the passenger's journey is the emissions produced by the flight itself. Associated CO2 emissions are generated from jet fuel consumption, which is used in-flight, and jet fuel production, which are the emissions generated from the production of jet fuel. Jet fuel consumption, or "tank to wake" emissions per passenger are estimated at 66.3 kg CO2e.[v] This was calculated using the United Kingdom (UK) government's emission conversion factors for 2021 and the average U.S. flight length.[16] [17]Note, the UK conversion factors were used since the U.S. does not have conversion factors and the U.S. EPA references the UK conversion factors in describing Scope 3 emissions factors.

In addition, Jet fuel production, or "well to tank" emissions per passenger are estimated at 13.6 kg CO2e. This was calculated using the UK government's emission conversion factors for 2021 and the average U.S. flight length.[16] [17] [vi] The average flight length of 511 miles was converted to km (822.4) and then multiplied by the "well to tank" short-haul conversion factor to estimate emissions on a per passenger basis of 13.6 kg CO2e.[16] [17], this is for demonstration purposes to maintain commonality between categories on a gross per passenger mile basis (i.e. well-to-tank emissions are based on amount of fuel consumed, which is related to but not the same as average aircraft passengers and distance).

[ii] This was calculated by multiplying the average roundtrip distance to an airport in the U.S. of 52 miles, and the EPA estimate of 0.41 kg of CO2e per mile for a passenger vehicle, to estimate emissions per passenger of 21.3 kg CO2e.

[iii] During 2019, JFK Terminal 4's annual passenger count was 21,859,054.**Error! Bookmark not defined.** JFK's Terminal 4 emissions were then doubled to account for the destination airport and divided by the number of passengers in 2019 to estimate emissions per passenger of 5.2 kg CO2e.

[iv] This was calculated using Delta's "other" Scope 1 emissions from 2021 of 168,140,000 kg CO2e, Delta's revenue passenger miles (RPM) from 2021 of 134,692,000, and the average U.S. flight length. The amount of "other" scope 1 emissions was divided by RPM, and the result was then multiplied by the average U.S. flight length of 511 miles to estimate emissions per passenger of .6 kg CO2e.

[v] The U.S. average flight length was used to keep the flight length consistent across all five categories. The UK states that the short-haul emissions conversion factor for business travel by air in the economy class without radiative forcing (RF), and including CH4 and N2O, is 0.08059 kg CO2e per passenger km. The average flight length of 511 miles was converted to km (822.4) and then multiplied by the short-haul conversion factor to estimate emissions on a per passenger basis of 66.3 kg CO2e.

[vi] The UK states that the well to tank short-haul emissions conversion factor for business travel by air in the economy class without RF is 0.01654 kg CO2e per passenger km.

The following Table 1 shows the breakdown of the analysis including the kg CO2e and corresponding percent for each phase of the traveler's journey.

Table 1: One Way U.S. Domestic Economy Average Emissions Per Passenger Again (CO2e)

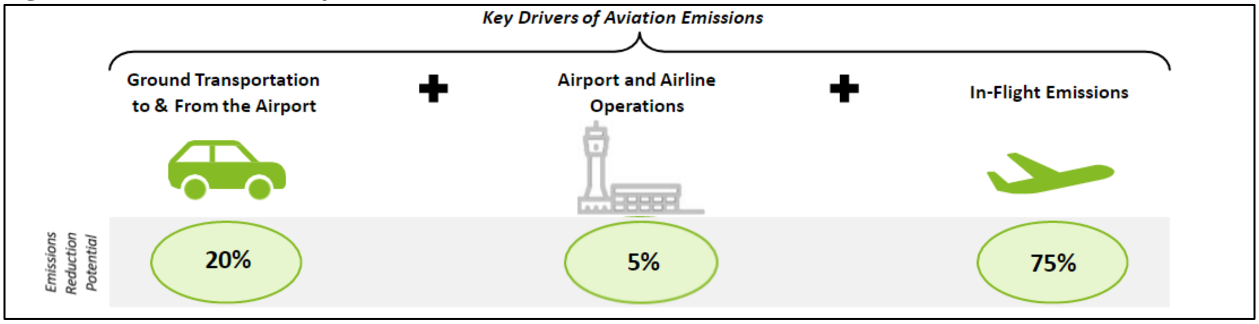
Category	kg CO2e	Percent
Ground Transportation to/from Airport	21.3	19.9%
Airport Operations (Non-Flight Related)	5.2	4.9%
Ground and Flight Related Operations	0.6	0.6%
Jet Fuel Consumption ("Tank to Wake")	66.3	61.9%
Jet Fuel Production ("Well to Tank")	13.6	12.8%
Total	**107.0**	**100%**

The total one-way U.S. domestic average emissions per passenger totals to 107 kg CO2e, as shown in the table above. Ground transportation accounts for about 20% of an individual traveler's emissions, while in-flight emissions, which includes jet fuel consumption (62%) and production (13%), accounts for about 75% of an individual traveler's emissions. Finally, non-flight related airport operations and ground and flight related operations account for about 5% of a traveler's emissions.

This analysis indicates three key emissions drivers: ground transportation, airport and airline operations, and in-flight emissions. The main source of aviation emissions is in-flight emissions, and most efforts to decarbonize aviation focus on reducing in-flight emissions.

The Figure 2 below shows the three main categories of Key Emission Drivers that will be important to reduce the emissions related to air travel.

Figure 2: Overview of Key Emission Drivers



II. Approach

II.I Development of Sustainability Strategies Methodology

The emission drivers identified in the examination of the aviation landscape then guided the creation of strategies to reach net zero emissions in the aviation sector by 2050. A wide range of research into opportunities for reducing CO2 emissions was conducted that included over 100 total sources. From this research, a total of 27 initial potential strategies were created.

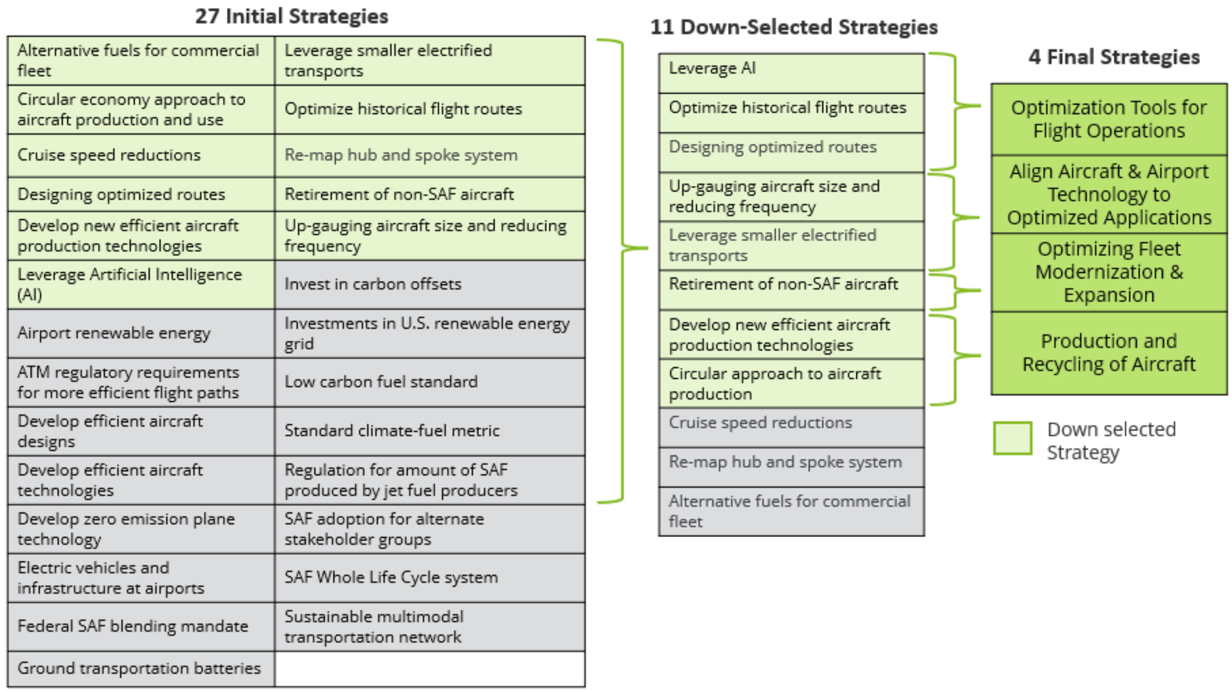
These 27 strategies spanned topics ranging from SAF, ground transportation, flight operations, the production of aircraft and more. This research was presented to NASA's ARMD Strategic Leadership Team (SLT) for feedback and areas of interest. The SLT gave guidance to identify more transformational strategies that may not have been widely explored yet, as well as areas where ARMD research could assist, ultimately down-selecting to 11 strategies. With this direction, strategies relating to SAF and ground transportation were eliminated from the scope of this study to prioritize emerging transformational strategies.

Following the first down-selection, the 11 strategies were refined further into four final strategies through numerous review sessions with relevant NASA stakeholders. By consolidating and grouping areas of interest, four distinct strategies were finalized. Informed by previous research, certain "Opportunity Areas" were highlighted within each strategy. The Opportunity Areas aim to provide more tangible or actionable steps to understand and realize the strategy.

To note, this report does not include strategies related to business decisions that increase CO2 emissions in the short-term, since these do not impact the long-term strategy of aviation decarbonization by 2050. For example, the literature review revealed instances of relatively efficient wide-body aircraft, which sat in storage since the onset of the COVID-19 pandemic in 2020, that were just 14-15 years old prior to being retired. While this business decision makes financial sense due to rapidly declining passenger demand and streamlining maintenance operations, it has a negative impact on CO2 emissions. These individual instances may not have been planned prior to the COVID-19 pandemic and therefore represent one-off responses to rapidly changing passenger demand. There will always be an interplay between the economics of airlines (and aircraft OEMs) and reducing emissions/reaching net zero by 2050. Therefore, this report does not include analysis of individual airline business case decisions due to unique events and circumstances.

The following Figure 3 provides an overview of each phase of strategy down-selection and refinement.

Figure 3: Down Selection Process from Initial to Final Strategies



The effort began with an initial list of 27 strategies that were drafted from research and collaboration with NASA. A list of the 27 original strategies and a brief description are located in Appendix C. After the initial list of 27 strategies, 11 were then down-selected as strategies that were more "transformational", not heavily researched, and NASA could play a role in. From the 11, four strategies were created that could encompass several earlier strategies. For example, Optimization Tools for Flight Operations would encompass AI, optimizing historical flight routes, and designing optimal routes.

The following Table 2 provides an overview of the four final strategies and the corresponding Opportunity Areas.

Table 2: Overview of Developed Strategies

Strategy	Strategy Name	Opportunity Areas
Strategy 1	Optimization Tools for Flight Operations	• AI for Taxiing • AI for Flight Path Optimizations • AI For Reducing Contrails
Strategy 2	Align Aircraft & Airport Technology to Optimized Applications	• Electrification of Regional Air Carrier Aircraft • All-Electric Short-Range Regional Routes • Up-Gauging and Route Frequency • Renewable Energy and Optimizing Airport Emissions
Strategy 3	Optimizing Fleet Modernization & Expansion	• Accelerated Replacement of Inefficient Aircraft • Aircraft Re-Purpose for U.S. Secondary Market
Strategy 4	Production and Recycling of Aircraft	• Additive Manufacturing • Recycled Composite Manufacturing

The final four strategies represent the four key areas of interest for further research, assessment, and evaluation to determine the feasibility of supporting aviation decarbonization by 2050.

II.II Assessment Methodology

Once the strategies and corresponding Opportunity Areas were selected, an analysis was performed that assessed each Opportunity Area in more detail. Additional research narrowed focus to gain a more in-depth understanding of each Opportunity Area. The analysis aimed to provide more detail on the proposed strategies and determine the potential for emission reduction by 2050.

Every in-depth assessment for each Opportunity Area includes:

- A higher-level broad introduction of the area, definitions, and descriptions of how the Opportunity Area exists today.
- An identified challenge within the Opportunity Area that a new technology, capability, or process may address and could help reduce emissions.
- Proposed potential methods to address the challenge.
- A use case to demonstrate potential solutions to the challenge described in detail.
- A per flight estimate of CO2 impact based on each use case.
- A recommendation for potential next steps of implementation for ARMD.

These assessments are detailed in Sections 1.0, 2.0, 3.0, and 4.0 of this report. Within these, the unique use case included describes the potential of implementation of the Opportunity

Area. This use case can be replicated by other entities to achieve CO2 reductions; however, these impacts may vary by implementation circumstance.

II.III Impact Evaluation Methodology

After the assessment of each Opportunity Area, an evaluation was performed leveraging the research and data in the previous section. For example, in the report, 1.1 is the **Assessment of Strategy 1** and 1.2 is the **Impact Evaluation of Strategy 1**. This structure is applied for each of the four strategies.

The evaluation examined the viability of implementing each Opportunity Area and assessed the potential impact towards reaching net-zero emissions by 2050. The overarching goal being to produce a rough order ranking of the four strategies that recommends key areas of focus for future research.

Four factors were selected to determine the viability of implementation and impact of a proposed strategy. These factors were used as indicators to provide a scoring rubric of the Opportunity Areas to demonstrate the practicality and success of a certain strategy at reducing emissions by 2050.

The following Table 3 provides an overview of these four factors and their corresponding definitions to provide a common understanding of each term.

Table 3: Definitions of Four Key Impact Evaluation Factors

Evaluation Factor	Definition
Carbon Impact	The change in CO2 emissions as a result of selected use case implementation on an average per flight basis
Scalability Timeline	The timeline in which scaling of the strategy can be achieved
Implementation Cost	The change in cost associated with strategy implementation
Accessibility	Opportunity to the public for air travel, such as increased frequency, seats, or routes

II.IV Impact Evaluation Factor Scoring Rubrics

After defining each Evaluation Factor, a method to measure and score each on a standard basis was developed. The first step was the development of Four Impact Evaluation Factors:

1. CO2 Emission Reduction Potential
2. Scalability Timeline
3. Implementation Cost
4. Accessibility

The CO2 emissions reduction potential impact is measured on a per flight basis in kg CO2, while due to uncertainty of future technologies, Scalability Timeline, Implementation Cost, and Accessibility were determined to be qualitative metrics.

Then, rubrics were developed that matched aspects of the Impact Evaluation Factors with associated scores to standardize evaluation across all strategies. Each evaluation factor was then put on a 1, 3, 6, 9 scale so that Opportunity Areas that cover different parts of aviation emissions, for example comparing airport emissions to in-flight optimization, could be compared on a more standard basis. It is important to note that the scoring scales developed were dependent on the strategies assessed. Therefore, the broader applicability of these scoring scales to other strategies not assessed may not apply as they may have distinctly different ranges of CO2 emissions that consider specific ranges based on the scores within this report.

II.IV.I Carbon Emission Reduction Potential Scoring Rubric

The first Impact Evaluation Factor examines CO2 emission reduction potential to measure the impact of each Opportunity Area on CO2 emissions. This is a quantitative metric that measures CO2 emission reduction potential by kilograms of CO2 reduced or created because of each Opportunity Area.

To produce these metrics, each use case for each Opportunity Area was considered. From available information, reports, and calculations, the total CO2 saved from each use case was calculated. The CO2 emissions number for each Opportunity Area is inherently connected to the individual use case. For example, there may be use cases that produce greater or less CO2 impact. Then, to compare the CO2 on a standard basis, these numbers were distilled into the change in kilograms (kg) of CO2 per flight. The CO2 per flight calculation represents the CO2 increase or reduction based on the average number of flights for the use case, not a marginal rate.

After the CO2 calculation was performed for each use case, all the resulting CO2 savings per flight were considered and ranges of the kg of CO2 saved per flight were matched with scores of 1, 3, 6, or 9. Then a series of ranges for kg of CO2 saved per flight were matched with corresponding scores. The specific ranges were selected so that the strategies evaluated would include each of the scores.

The following Table 4 provides a standardized scoring rubric for the CO2 emissions reduction potential calculations. The full step-by-step calculations can be found in **Appendix A: Carbon Impact Calculations.**

Table 4: Carbon Emissions Reduction Potential per Flight Scoring Rubric

Carbon Emissions Reduced by Use Case, per Flight Scoring Definition	Corresponding Final Score
1000+ kg Co2	9
100- 999 kg CO2	6
0 kg CO2 – 99 kg CO2	3
kg CO2 Added > 0	1

II.IV.II Scalability Timeline Scoring Rubric

Reaching decarbonization by 2050 is an underlying core tenant of the aviation ecosystem, and the sooner that decarbonization occurs, the better the result will be for the environment. Therefore, the timeline of implementation is a key factor in determining the effectiveness and potential impact of a CO2 reduction strategy.

The scalability timeline Evaluation Factor was developed to examine the time-phased feasibility of each strategy. This aimed to capture more nuance in combination with CO2 emission reduction metrics. For example, even if a strategy has a high CO2 reduction potential, it could be limited by the time it takes to scale and achieve the predicted CO2 emission savings. For example, a small increase in the near term, that has decades to accumulate impact, may be more impactful than a larger decrease in a year closer to 2050. Therefore, this metric took a practical look at the timelines on which each strategy could have an impact on emissions.

Scalability timeline scoring considered not only the initial implementation timeline, but also the point at which the technology or strategy could reach a scale that substantially impacts CO2 emissions. This section defines scalability as the capability or technology being more likely than not to be implemented beyond early adopters. This definition of scalability assumes that once a technology is implemented and scales beyond early adopters, it will continue to grow and be scaled.

The following Table 5 provides a standardized scoring rubric for the time-phased feasibility of scaling each strategy.

Table 5: Scalability Timeline Scoring Rubric

Scalability Timeline Scoring Definition	Corresponding Final Score
Strategy is scaled in the immediate future, by 2030	**9**
Strategy is scaled in the short-term, by 2035	**6**
Strategy is scaled in the medium-term, by 2040	**3**
Scaling of the strategy can be achieved in the long-term, by 2050	**1**

II.IV.III Implementation Cost Scoring Rubric

Another factor considered to play a significant role in the feasibility of the Opportunity Areas was the cost of implementation. Independent of the amount of CO2 emissions that could be saved, cost could be a significant enabler or hinderance to strategy implementation. While there are many different measures for costs, such as cost of resulting externalities or opportunity costs, this analysis only captures the cost of implementing the strategy.

This effort defines cost as the cost of implementing an Opportunity Area including the total expenses associated with implementing the project. This is the amalgamation of costs to bring an Opportunity Area into the marketplace. For example, operational changes were generally considered to be lower cost compared to R&T efforts for aircraft innovations or ubiquitous changes in infrastructure. Because the cost of implementing a project would vary significantly based on location and a variety of circumstance-dependent factors, the costs could not be quantified, but rather evaluated relative to current state. In other words, while the exact total implementation cost of a future technology is unknown, based on informed estimates and current research the general magnitude and increase or decrease compared to current cost was captured. Note, this assumes that if implementation of a strategy is costly for the producer and supplier, this may be passed along to the consumer.

The following Table 6 provides a standardized scoring rubric for the implementation cost of each strategy.

Table 6: Implementation Cost Scoring Rubric

Implementation Cost Scoring Definition	Final Score
Implementation is less expensive than current operations	**9**
Implementation costs approximately the same as current operations	**6**
Implementation is more expensive than current operations	**3**
Implementation is significantly more expensive than current operations	**1**

II.IV.IV Accessibility Scoring Rubric

When an Opportunity Area is implemented, it is desirable that accessibility to the public is preserved or increased, so that no group faces less access to aviation than before. For this evaluation, accessibility is defined as the opportunities for the public to access aviation service, such as flight frequency, the number of available seats, or the number of available routes. Accessibility was analyzed to ensure that equity of access for the public was not infringed by any of these strategies or Opportunity Areas. For example, increasing accessibility may include adding frequency of flights at an underutilized airport, while decreasing accessibility may include cutting service at airports.

While an Opportunity Area does not necessarily have to improve accessibility to provide emission reduction benefits, accessibility does play a key part in strategy implementation. For example, an Opportunity Area that increases the number of routes served could draw more passengers to utilizing more sustainable travel. Similarly, an Opportunity Area that reduces service would draw less passengers and therefore may not be feasible from a demand or business case perspective and may not be implemented. As a result, the public will have some level of impact in the success of these Opportunity Areas based on their perspective, making it crucial to analyze accessibility as a key factor in evaluating a Strategy.

Accessibility examined the end state of Opportunity Area implementation. The short-term rollout of these technologies, such as construction time, may have an impact on accessibility, but the time the use case reaches its "scaled" point is when the accessibility was captured.

The following Table 7 provides a standardized scoring rubric for the changes to accessibility due to strategy implementation.

Table 7: Accessibility Scoring Rubric

Accessibility Scoring Impact	Final Score
Implementation will result in increased public accessibility	**9**
Implementation will result in no change to public accessibility	**6**
Implementation will result in a slight decrease to public accessibility	**3**
Implementation will significantly hinder public accessibility	**1**

II.IV Scenario Analysis Methodology

After scoring each Evaluation Factor, three scenarios were developed to aggregate the results of the evaluation. A scenario is defined in this document as a set of weightings developed and applied to raw score results to convey relevance and importance of each Evaluation Factor.

The three scenarios developed aimed to highlight strategies that are more robust to varying viewpoints based on the weightings of each Impact Evaluation Factor. The scenarios chosen are representative of various viewpoints on how to evaluate the strategies. For example, some viewpoints may want to place greater weight on CO2 emission reduction potential, while some may want a more balanced and holistic view. Therefore, the strategies that score the highest across all scenarios are likely to be more consistently favored.

This section provides an overview of the three scenarios developed and the weights that correspond to each Evaluation Factor that will be used in a later scenario analysis section and conclusion.

II.IV.I Scenario 1: Equal Weightings

Scenario 1, "Equal Weightings", was developed to provide a base scenario that considered each Evaluation Factor equally. While this is not considered to be the most realistic prioritization scenario, it ensures that each Evaluation Factor is considered and can be used as a basis to compare to shifting Evaluation Factor weightings as indicated in Figure 4 below.

Figure 4: Scenario 1—Equal Weightings Percentages

Scenario 1	Carbon Impact	Scalability Timeline	Cost	Accessibility
Equal Weightings	25%	25%	25%	25%
	Carbon impact is weighed the same as all other factors.	Scalability Timeline is weighed the same as all other factors.	Cost is weighed the same as all other factors.	Accessibility is weighed the same as all other factors.

II.IV.II Scenario 2: Preferred Scenario

Scenario 2 is the "preferred" scenario because it takes a holistic approach towards weighing each of the Evaluation Factors. This scenario was agreed upon through NASA guidance considering which strategies may make the most sense to examine further from a NASA research perspective. This scenario prioritizes Carbon Impact and Scalability, as they are viewed the most important Impact Evaluation Factors towards reaching net-zero CO2 emissions by 2050. Cost receives a slightly lower but still significant weighting because it is a realistic variable that could have major impact on strategy implementation. Accessibility was weighted the lowest, because while important, it is not the primary consideration in reaching decarbonization by 2050.

This scenario represents the anticipated weightings assigned to each Evaluation Factor in a decision-making circumstance, based on hierarchy of importance to aviation decarbonization as demonstrated in the Figure 5 below.

Figure 5: Scenario 2—Preferred Scenario

Scenario 2	Carbon Impact	Scalability Timeline	Cost	Accessibility
Preferred Weightings	40%	30%	20%	10%
	Carbon impact is prioritized.	Scalability Timeline is almost as important as carbon impact to reach goal by 2050.	Cost is a vital consideration, but many will require implementation costs, so it is not the main factor.	Accessibility should be considered but is not a determining factor.

II.IV.III Scenario 3: Carbon Reduction First

Scenario 3, "Carbon Reduction First", prioritizes reaching decarbonization by 2050 over all other factors. This scenario prioritizes decarbonization and weights carbon impact as the most important factor. This scenario also considers scalability timeline because the sooner a strategy can be implemented, the sooner it may begin to realize CO2 reductions. For example, a strategy that has modest CO2 reduction, but can be implemented sooner has more years to realize potential reductions, and therefore may reach a more significant aggregate CO2 reduction by 2050.

This scenario does not consider cost and accessibility and takes more-or-less a single variable optimization approach to reach decarbonization by 2050, as indicted in Figure 6 below.

Figure 6: Scenario 3— Carbon Reduction First

Scenario 3	Carbon Impact	Scalability Timeline	Cost	Accessibility
Sustainability First Weightings	60%	40%	0%	0%
	Carbon impact has the largest prioritization.	Scalability Timeline is also prioritized, though not as heavily as carbon impact.	Cost is not considered in this model.	Accessibility is not considered in this model.

1.0 Strategy 1: Optimization Tools for Flight Operations

The largest contributor towards aviation sector emissions are in-flight emissions, which account for approximately 75% of a traveler's total emissions.[vii] The technology used in flight is especially important because it can impact the efficiency of operations. The more efficient the operations during stages of flight, the less fuel burn and therefore less emissions may be produced.[18] Today there remain inefficiencies that lie in certain stages of flight that emerging technologies, such as Artificial Intelligence (AI), may offer potential in decreasing CO2 emissions to reach net zero emissions by 2050.[18]

The first strategy examines emerging in-flight technologies and advancements beginning to be applied to aviation. Specifically, this section takes a core focus on AI and its capabilities to address previously intractable data collection, aggregation, and analysis tasks. However, initial AI programs have only been tested in pilot programs, and not yet implemented on a wide scale. This strategy examines several applications for AI, including for taxiing, flight optimization, and contrail avoidance and considers their potential impact if scaled. By improving and scaling these emerging technologies to make flight operations more efficient, fuel reduction and emissions reduction may be realized.

1.1 Assessment of Strategy 1

1.1.1 AI for Taxiing

Taxiing is an essential part of flight that connects the aircraft to their assigned gates by moving the aircraft on the runway or taxiway before an aircraft takes off and after an aircraft has landed. Today, taxiing is performed by a pilot under the guidance of Air Traffic Control (ATC) at towered controlled airports.[19] Taxiing takes into consideration factors such as the gate used, the runway used, and how many other planes are taking off and landing at the same time. However, with increasing traffic, taxiing has become increasingly inefficient at major airports.

In recent years, taxi times have increased at the U.S.'s busiest airports due to major runway construction projects, schedule changes that increase the number of flights at peak hours, and new distant runways that relieve congestion but require more time to reach. In addition, airlines are measured against their on-time departures, meaning aircraft must push-back on time to achieve an on-time departure, even though the plane will spend more time and fuel taxiing in queue. This has resulted in recent studies that cite anywhere between 2% and 17% of fuel burn goes to taxiing in and out, with shorter flights having a proportionately higher fuel burn.[20] For example, JFK airport in New York has the longest average taxi out time in the U.S. of 27.1 minutes.[21] One of the key factors that can contribute to long taxiing wait times, is difficulty assigning nearby gates and high levels of manual ATC decision making at a busy

[vii] Refer to Figure 2: One Way U.S. Domestic Economy Average Emissions Per Passenger (CO2e)

airport. In specific, taxiing decisions consider a wide range of dynamic variables, such as distance to gate, size of the airline schedule, airport geography, availability of gates, ramp traffic, and inbound and outbound flight delays, which can be cumbersome for air traffic controllers to manually evaluate changing data sets in a short amount of time.[22]

Rising taxing times and associated CO2 emissions could be addressed by using AI to optimize time to gate. AI has the capability to draw from, aggregate, and analyze large data sets to provide recommendations to ATC and airline dispatchers. This enables AI to provide a more dynamic evaluation of the many variables that are considered when assigning gates and runaways during taxi. If these variables, such as distance or changes due to delays can be optimized, then coordination of arrival and departure schedules could be enhanced and therefore lower taxiing wait time. In turn, lower taxiing time could reduce the amount of fuel burned and lessen emissions.

NASA has previously studied how programs could be used to optimize taxiing times through their Airspace Technology Demonstration 2 (ATD-2) Integrated Arrival, Departure and Surface (IADS) Operations program. This program allows aircraft to depart the gate later and then move directly from the tarmac to the runway for takeoff without long wait time.[23] Since initial implementation at Charlotte Douglas International Airport, NC, the FAA continues to support ATD-2 operational use at Charlotte to facilitate transition to Terminal Flight Data Manager program. In addition, the program has also been demonstrated at Dallas/Ft. Worth International and nearby Dallas Love Field, TX.[23]

In addition to NASA's work, various AI-based pilot programs have also emerged that aim to reduce taxiing wait and idle times. American Airlines implemented their Intelligent Gating Program with the goal of reducing the amount of jet fuel used for arriving aircraft. The Intelligent Gating Program provided real-time analysis of data points such as routing and runway information to automatically assign the nearest available gate to arriving aircraft, reducing the need for manual involvement from gate planners.[23] This program was deployed at American Airlines' Dallas Fort Worth (DFW) hub and reduced taxi time by about 10 hours per day total and saved more than a minute of taxi time per flight by reducing the taxiing distance from runway to gate.[24] In specific, 870,000 gallons of fuel were saved the year that American Airlines conducted the pilot program at DFW, which through this report's calculation, equates to on average decrease of 51 kg CO2 per flight (0.34 kg CO2 per passenger).[25]

While the American Airlines Intelligent Gating Program demonstrates the feasibility to reduce fuel burn through AI for taxiing, it has only been implemented in limited pilot programs. Although a single application of an AI program for taxiing may seem like a relatively small reduction in emissions, if implemented on a wider scale, more benefits could be demonstrated. Therefore, to produce significant emissions reduction, AI for taxiing programs could be adopted across the country, for every airport, and every airline by 2050 to further reduce CO2 emissions. Further NASA efforts could support this goal by conducting a study to determine how multiple AI programs, such as one for departing aircraft like NASA's ATD-2 program, and one for arriving aircraft, like the Intelligent Gating Program, could be used in tandem for maximum CO2 reduction. While every U.S. airport is different and faces different levels of congestion, taxiing delays, construction projects, and logistics, scaling AI-enabled taxiing tools could provide CO2 emissions savings.

1.1.2 AI for Flight Path Optimizations

Prior to departure, all Part 121 flights must have a flight plan filed with the Federal Aviation Administration (FAA) that includes the route, altitudes, speeds, amount of fuel the aircraft plans to use, and additional fuel needed for safety requirements.[26] Today, flight plans are created by an airline flight planner that takes into account a range of factors at departure/arrival airports and on the route.[27] For example, these factors can include forecast upper air winds, temperatures, atmospheric convective activity, National Airspace System (NAS) traffic and closures, aircraft payload, value of the payload, and the schedule and operational constraints for the crew and aircraft.[27] Many of these factors are dynamic and can constantly change on the route from the original flight plan. However, existing airline systems may not have predictive capabilities that are able to compile large amounts of historical and current data from multiple sources.

During flight, there is an abundance of dynamic flight data that needs to be processed in a time-sensitive and rapidly changing environment. As a result, the original flight path may not be the most efficient due to changing flight conditions and factors. For example, a flight from Daniel K. Inouye International Airport Honolulu, HI to Soekarno-Hatta International Airport, Jakarta, Indonesia can take a wind-optimal route that is 11% longer in distance than the direct great circle route but results in 2% faster flight time and 3% reduction in fuel burned.[28] This example demonstrates the importance of considering changing and dynamic variables to create an optimal flight route. To assist human operators in weighing the changing variables for flight planning, AI could be used to provide recommendations to quickly assess multiple data sets in a highly dynamic environment.

AI has the capability to aggregate and evaluate both historic and current data to predict and create optimized flight paths. This capability is important because flight plans that rely solely on past data can lead to inefficient flight routes. For example, a study conducted with Boeing subsidiary Jeppesen examined an airline's flight planning system that only used fixed company routes developed from historical wind data and ATC requirements.[26] The study determined that using current wind conditions and forecasts could have provided significant fuel savings, up to about 1 million gallons per year, for the airline.[26] Since the airline had 60 single-aisle airplanes, this would equate to 16,667 gallons per aircraft per year. A short-range narrow-body aircraft typically has 50,000 flight cycles or about five flight cycles per day, resulting in about 9 gallons saved per flight.[viii] [29] This study demonstrates the gaps in existing flight planning that AI could help to fill and optimize, such as atmospheric data & winds (contrail avoidance, weather, sonic-boom for future supersonic, etc.).[26]

[viii] This was calculated from five flight cycles per day * 365 days per year = 1,825 flight cycles per year. 16,667 gallons / 1825 flight cycles = 9.13 gallons per flight

The Flyways program implemented by Alaska Airlines demonstrates how AI could be used to enhance flight planning and reduce emissions. Flyways is a platform that uses both AI and machine learning (ML) to assist operators in optimizing flight routes and improving the flow and predictability of aircraft traffic.[30] Flyways used ML models of the NAS to predict future scenarios and to manage dynamic factors by processing millions of data inputs both quickly and accurately.[30] By combining both original route data with changing current dynamic conditions, Flyways was able to provide optimization recommendations for both pre-flight and in-flight path adjustments. These recommendations were then provided to flight dispatchers who had the option to accept and implement. During a 6-month pilot program in 2020, Flyways AI found recommendations to optimize 64% of mainline flights. Of these flights, dispatchers accepted 32% of the recommendations.[30] It is estimated that the pilot program saved about 480,000 gallons of jet fuel.[30] Based on this report's calculations, this equates to roughly an average savings of about 68 kg CO2 per flight. However, the pilot program was conducted during the COVID-19 pandemic when flight volumes were lower than usual levels. Therefore, it should be considered that at regular air traffic levels, benefit per flight may be reduced because there may be more constraints over where aircraft can safely fly.

By adopting AI technology to optimize flight paths, U.S. airlines could realize fuel and emission savings. To realize these CO2 and fuel emissions savings by 2050, AI technology already developed and tested should be scaled quickly across airlines. Further NASA research may consider how AI in-flight programs work together if implemented by multiple airlines including the implications on Air Traffic Management (ATM) and safe separation.

1.1.3 AI for Reducing Contrails

A significant byproduct of in-flight jet fuel combustion is the formation of contrails.[31] Contrails are line-shaped clouds or "condensation trails," that form behind jet engine aircraft.[32] These clouds form when exhaust gases cool and mix with surrounding air, humidity becomes high enough, and the air temperature is low enough for liquid water condensation.[32] Generally, contrails are most persistent in high-humidity areas and can last for hours, grow to several kilometers in width, and 200 to 400 meters in height.[32] Due to the predictability of these formation conditions, contrail formation for a given aircraft flight can be accurately predicted if atmospheric temperature and humidity conditions are known. Based on predictions of contrail forming conditions, avoiding the formation of contrails may reduce aviation's net warming impact.

Contrails consist of water vapor and form at appropriately humid air conditions using soot and other aerosol emissions as nucleation cites.[33] Water vapor from engine combustion enhances this, low soot from SAFs decreases it. They contribute to increased cloud coverage that correlates with the earth's temperature.[34] Contrails may contribute up to an estimated 57% of aviation's effective radiative forcing (ERF), a measure of the impact of anthropogenic actions that lead to a net surface warming.[35] [ix] In practice, some studies even cite that contrails could change the earth's net surface temperature between 1.8ºC and 3ºC.[36] However, there is an ongoing discussion of the true climate impact of contrails because there are wide ranges in estimated results and studies include large confidence intervals. While documentation of contrail impacts has varying results, there is general agreement that contrails contribute to increased warming and can be classified as an impact of aviation. Although the conditions that create contrails are well known, there are only few early-stage efforts to mitigate their formation.

The creation of contrails could be reduced by avoiding the conditions in which they form. To mitigate contrails, knowledge of formation conditions could be combined with emerging technologies, such as Digital Twins or AI, to inform pilots on how to avoid environments that support contrail formation.

A NASA study on Transonic Truss-Braced Wing (TTBW) Contrail Assessment & National Airspace System (NAS) Impacts from Contrail Avoidance examines how a NAS Digital Twin simulation tool could be used to investigate persistent contrail formation avoidance.[37] The NAS Digital Twin tool works with an Autoresolver that develops coordinated closed-form trajectory-based resolutions that maneuvers a flight from its original plan to avoid the contrail and then returns it back. With this technology, a study was conducted that analyzed and compared persistent contrail formation length between current Boeing 737-800 and potential TTBW substitution flights. The study found that for 7.6% of the flights simulated, a change in altitude could prevent the formation of a persistent contrail. Therefore, further examination of technologies that can reduce contrail formation by instructing a change of altitude could help to reduce the number of contrails created.

Another potential technology that could be transformational for contrail avoidance is the use of AI. In 2023, Google Research partnered with American Airlines and Breakthrough Energy to combine large data sets that included satellite imagery, weather, and flight paths.[38] The resulting program used AI-based predictions that were cross-referenced with Breakthrough Energy's open-source contrail models to provide pilots with altitudes that could avoid the formation of contrails.[38] American Airlines then ran 70 test flights over six months testing this AI-based approach, and found that according to satellite imagery, the pilots were able to reduce contrails by 54%.[38] However, this reduction of contrails was also accompanied by an increase of fuel burn needed to avoid the formation regions. Google Research estimates that a fuel impact of 0.3% across an airline's flights would be needed, and that contrails could be avoided at scale for around $5-25/ton CO2e.[38] Based on this pilot program, this report calculated an approximate 107 kg CO2 increase of CO2 per flight to avoid contrails. Although this opportunity increases CO2, it should be considered in the context of the significant amount of ERF that contrails are estimated to generate.

[ix] This number comes from a study that looked at the ERF of a range of different contributors. Note, this number on contrails is highly uncertain and often debated. According to a 2021 study, for the 1940 to 2018 period, the net aviation ERF is +100.9 mW m − 2 (5–95% likelihood range of (55, 145)) with major contributions from contrail cirrus (57.4 mW − 2), CO2 (34.3 mW − 2), and NOx (17.5 mW − 2).

AI could be an effective technology to avoid contrail formation but has only been tested in small pilot programs and may produce marginal benefits. Therefore, to realize the potential warming reduction benefits of emerging technologies, both Digital Twin and AI solutions could be scaled across U.S. airlines. However, this solution should also consider the tradeoff between the warming effect achieved by mitigating a contrail in tandem with the amount of additional CO_2 created from fuel burn to avoid the contrail creation. The balance of these two factors should be optimized to a point where the ERF saved from reducing contrails outweighs the additional CO_2 used to avoid a contrail-producing environment. Future NASA research could examine how to balance reducing contrails with the additional CO_2 that may be released to avoid them. Better understanding the tradeoff between savings in net surface warming from reducing contrails and increased CO_2 released could help form an optimal plan for reducing CO_2 emissions and mitigating climate change. In addition, the ATM impacts of avoiding contrails could be examined to ensure safe separation.

1.2 Impact Evaluation of Strategy 1

This section evaluates Strategy 1, as well as the Opportunity Areas within the strategy.

1.2.1 Carbon Emissions Reduction Potential

This section provides a quantitative assessment of the potential impact on CO_2 emissions of each Opportunity Area on a per flight basis for each use case. The following Table 8 provides the change in CO_2 emissions per use case on a per flight basis to enable comparison across Opportunity Areas of CO_2 emissions.

Table 8: Carbon Reduction Potential Scoring Rubric for Strategy 1

Opportunity Area	Use Case	Δkg CO_2 Per Flight	Carbon Impact	Score based on per Flight
O.A. #1: AI for Taxiing	American Airlines at DFW Intelligent Gating Program	-51	0 kg CO_2 – 99 kg CO_2	3
O.A. #2: AI for Flight Path Optimizations	Flyways AI for Alaska Airlines	-68	0 kg CO_2 – 99 kg CO_2	3
O.A. #3: AI for Contrails	Google Research, Breakthrough Energy, & American Airlines	+107	kg CO_2 Added >0	1

1.2.2 Scalability Timeline

Strategy 1 is anticipated to have a more immediate implementation timeframe because initial pilot programs have already begun. While these AI programs have yet to scale, the initial technology development has been completed and potential CO_2 reductions have been recorded. For example, the Intelligent Gating Program has been operational since 2023, the

Flyways program was introduced in 2021, and Google conducted its contrails project in 2023. [22 30 38]

In addition to the demonstrated roll-out of AI programs, there is also envisioned to be an acceleration in the adoption of AI over the coming decade across aviation.[39] As existing programs are rolled out, other airlines may follow this precedent with comparable AI based programs or optimizations to remain competitive in the marketplace.

The following Table 9 provides an overview of the scalability timeline scores for each Opportunity Area in Strategy 1.

Table 9: Scalability Timeline Scoring Rubric for Strategy 1

Opportunity Area	Use Case	Estimated Scaled Timeline	Score
O.A. #1: AI for Taxiing	American Airlines at DFW Intelligent Gating Program	Could be scaled in the immediate future, by 2030	9
O.A. #2: AI for Flight Path Optimizations	Flyways AI for Alaska Airlines	Could be scaled in the immediate future, by 2030	9
O.A. #3: AI for Contrails	Google Research, Breakthrough Energy, & American Airlines	Could be scaled in the immediate future, by 2030	9

1.2.3 Implementation Cost

While the implementation of AI systems for aviation optimization will incur a cost, this cost is not envisioned to be a significant change to existing expenses and will cost approximately the same as current operations.

The initial costs associated with AI include research, development, testing, training, and refinement of the system. Because AI relies on historical data, this phase can also include costs associated with acquiring, cleaning, and validating AI system data.[40] In addition, AI deployment may require additional training, Central Processing Unit (CPU), compatibility, security, and monitoring costs.[40] While these may represent significant costs, implementation does not require purchase of significant new energy infrastructure, airport infrastructure, or new aircraft. Therefore, even if initial investment is made by airlines and stakeholder partners to develop and deploy the system, this solution is envisioned to be adaptable to airline systems and platforms already in existence and would not require substantial brick and mortar investment and associated build time.

While all Opportunity Areas in Strategy 1 are anticipated to follow the development and deployment process of an AI system, there remain some additional slight differences and impacts on costs for each. One unique Opportunity Area is AI for contrails because implementation requires additional fuel cost. However, this increase in cost is reported to be minimal, requiring a fuel increase of 0.3%, and would therefore keep this Opportunity Area in the slight increase of cost range.[38]

The Opportunity Areas in Strategy 1 are envisioned to generate a small increase in cost but remain approximately the same as current operations. While it is not considered in the scope of this analysis, it should also be noted that the initial cost for airline stakeholders to implement an AI system may be offset in the long run if the efficiency gains of the AI program minimize future costs. This is not captured in the scoring but may represent an opportunity for future research.

The following Table 10 provides an overview of the implementation cost scores for each Opportunity Area in Strategy 1.

Table 10: Implementation Cost Scoring Rubric for Strategy 1

Opportunity Area	Change in Cost Description	Change in Cost Categorization	Final Score
O.A. #1: AI for Taxiing	• Cost of technology development • Cost testing, simulations, validation • Costs of training • Implementation	Implementation costs approximately the same as current operations	6
O.A. #2: AI for Flight Path Optimizations	• Cost of technology development • Cost testing, simulations, validation • Costs of training • Implementation	Implementation costs approximately the same as current operations	6
O.A. #3: AI for Contrails	• Cost of technology development • Cost testing, simulations, validation • Costs of training • Implementation • Increase cost of fuel	Implementation costs approximately the same as current operations	6

1.2.4 Accessibility

The Opportunity Areas within Strategy 1 are envisioned to have a neutral impact on the accessibility of aviation services based on minimal impacts to overall flight time.

While each of the AI programs were reported to have an impact on flight time, the change is minimal and is not envisioned to change flight frequency, service, or opportunity for air travel to the public. For example, American Airline's Intelligent Gating Program estimates that they were able to reduce taxiing time by 20%, which based on DFW's average taxiing time of approximately 19 minutes, would represent a 4-minute savings in taxiing time.[41] Similarly, Alaska's Flyways AI program was able to save 5.3 minutes of flying time per flight.[42] While these results scaled could impact CO2 emissions reductions, the time savings is unlikely to contribute to an increased frequency or service of flights. The NASA TTBW Contrail Assessment & National Airspace System (NAS) Impacts from Contrail Avoidance also shows a minimal increase, citing that altitude change maneuvers in simulation reduced persistent contrail formation length by 69.8% for an only 1.2% increase in flight duration.[37]

In contrast to taxiing and flight path optimization AI Opportunity Areas, AI for contrails is envisioned to add to in-flight time. Google, American Airlines, and Breakthrough Energy estimate that total additional fuel impact of avoiding contrails could be as low as 0.3% across an airline's flights, which may contribute to a small increase in flight time.[38] This additional fuel is likely due to increasing flight path length to avoid contrail formation. However, this added flight length is likely small enough that flight frequency and service would not be impacted.

While AI programs may result in changes to overall flight length, the differences are envisioned to be minimal enough that the overall accessibility of flights would not be impacted.

The following Table 11 provides an overview of the accessibility scores for each Opportunity Area in Strategy 1.

Table 11: Accessibility Scoring Rubric for Strategy 1

Opportunity Area	Change in Accessibility Description	Change in Accessibility Categorization	Final Score
O.A. #1: AI for Taxiing	• May impact efficiency and lower taxing times, but unlikely to change the service, frequency, and opportunity for air travel.	Implementation will result in no change to public accessibility	6
O.A. #2: AI for Flight Path Optimizations	• Unlikely to change the service, frequency, and opportunity for air travel.	Implementation will result in no change to public accessibility	6
O.A. #3: AI for Contrails	• Unlikely to change the service, frequency, and opportunity for air travel.	Implementation will result in no change to public accessibility	6

1.2.5 Overall Strategy Score

The following Table 12 provides a summary table containing the final scores for each Opportunity Area and each Evaluation Factor.

Table 12: Total Strategy 1 Score Summary

Opportunity Area	Carbon Impact Score	Scalability Timeline Score	Cost Score	Accessibility Score
O.A. #1: AI for Taxiing	3	9	6	6
O.A. #2: AI for Flight Path Optimizations	3	9	6	6
O.A. #3: AI for Contrails	1	9	6	6

2.0 Strategy 2: Align Aircraft & Airport Technology to Optimized Applications

To reach zero emissions in the aviation sector, certain strategies, such as SAF, are envisioned to be scaled throughout the industry. However, this section aims to examine strategies that have potential to reduce CO2 emissions but are not a "one-size-fits-all" solution across the aviation sector. Various overarching factors considered include electrification technologies, route type, the hub-and-spoke model, passenger demand, and airport geography and size, each of which can influence the feasibility and effectiveness of the implementation of CO2 reduction measures.

The second strategy takes these nuances into account and identifies a range of technologies and capabilities and matches them to specialized applications where there may be potential for CO2 emission reduction. These Opportunity Areas include leveraging emerging electrified propulsion and aircraft designs for regional routes, up-gauging from narrow-body (single-aisle) to wide-body (twin-aisle) aircraft on appropriate routes and optimizing airport operations through renewable energy implementation. Through focusing technologies and capabilities on the areas in which they could best reduce emissions, this section captures a range of solutions that, although they may not be feasible on every route, could help close gaps in emissions by 2050.

2.1 Assessment of Strategy 2

2.1.1 Electrification of Regional Air Carrier Aircraft Replacements

A "regional air carrier" is a general classification that refers to scheduled passenger air service that operates as a subsidiary or partner under major U.S. airlines and connects communities lacking sufficient demand or infrastructure to a hub in the aviation network.[43] Examples of regional air carriers include American Eagle, a subsidiary of American Airlines and Sky West, which partners with American Airlines, Delta Air Lines, United Airlines, and Alaska Airlines. Through a scope clause agreed upon in 2012 by some major airlines and the pilot trade union, the number of seats that a regional air carrier can fly for American Airlines, Delta Air Lines, or United Airlines is capped at 76 seats and a maximum takeoff weight of 86,000 pounds.[44] These regional air carriers generally fly distances of approximately 500 miles on average, with the purpose of connecting passengers to the hub-and-spoke system.[45]

As of 2022, there are ~1,672 total aircraft that carry between 40 and 76 passengers flown by regional air carriers. While the aircraft flown by regional air carriers play an important role in the aviation hub-and-spoke model, they are generally less fuel efficient than the fleets that service mainline operations. Compared to narrow-body or wide-body aircraft, the regional air carriers produce relatively higher CO2 emissions per passenger.[46] Specifically, it is estimated that these aircraft are 40–60% less fuel efficient than their larger narrow-body and wide-body counterparts.[47] This efficiency gap is primarily due to the relatively large amount of fuel used for departure and takeoff compared to fuel used during the cruise segment of the flight. In addition, the engines for regional carrier aircraft are generally less fuel efficient (higher thrust specific fuel consumption (TSFC)) than larger engines on bigger aircraft.[48] In addition, as of 2021, none of the aircraft flown by regional air carriers in operation could support 100% SAF.[x] Since relatively inefficient aircraft are being used on relatively short distances, the aircraft flown by regional carriers demonstrates a need for a transformational aircraft strategy.

An emerging technology that could help to reduce CO2 emissions from regional air carriers is hybrid-electrification. In a hybrid-electric configuration, an aircraft uses a fuel source, such as jet fuel, SAF, or hydrogen, with electricity from batteries either in tandem or alternately.[49] A hybrid-electric configuration aims to optimize overall energy efficiency and reduce fuel consumption.[49] This report examines specifically hybrid-electric technology for regional air carriers because current battery technology needed for regional air carrier's aircraft sizes and distances needs further advancements to enable a fully electric configuration. Specifically, the specific energy (i.e., energy per unit mass) of Jet A fuel, the standard used for commercial aviation, and the reported energy density of alternative fuels such as hydrogen combustion or fuel cells, are significantly higher than the capabilities of current aviation electric battery technology.[50] [51] [52] [53]

Today, NASA is working on several hybridization projects that aim to reduce regional air carrier emissions. In specific, NASA has focused on megawatt-scale electric propulsion technology through its Electrified Powertrain Flight Demonstration Project (EPFD), which conducts ground and flight tests of electrified aircraft propulsion technologies to enable a new generation of hybrid electric-powered aircraft.[54] One segment of this effort aims to test these technologies for future use in smaller, regional aircraft with less than 100 passengers, fitting this Opportunity Area's focus on regional aircraft.[54] [xi] A NASA research effort has developed a concept aircraft called the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS), which is a novel hybrid-electric regional aircraft that could reduce the amount of energy required to complete a given mission.[55] The concept examines how utilizing the size and placement flexibility of electric motors in the design of an electric or hybrid-electric aircraft could yield substantial energy cost savings.[55]

Building on NASA's efforts, this report examines the potential impact on emissions of introducing similar hybrid-electric turboprop aircraft into the regional air carrier fleet. To make transformational change to the current regional air carrier fleet, this report envisions that by the time these aircraft are developed, tested, and begin to be introduced into fleets, they could leverage a form of carbon neutral fuel, such as SAF or hydrogen. Introducing hybrid-electric turboprop aircraft into regional air carriers could produce significantly less

[x] Obtained from the 10-Ks of Delta Air Lines, American Airlines, United Airlines, Hawaiian Airlines, Alaska Airlines, Southwest, and JetBlue

[xi] In specific, a NASA study on Short-Haul Revitalization identified a seat capacity selection of 48 passengers and a design range of up to 690 miles a favorable candidate for a hybrid-electric propulsion system being chosen as the primary enabling technology.

emissions than the current regional fleet and could help to make hybridization a transformational strategy for regional air carriers.[xii] [56] [57]

This report analyzes the CO2 emissions from a flight utilizing the Embraer 175, which is the most abundant jet among the top 7 U.S. regional air carrier providers, compared to an electric-hybrid aircraft based on the PEGASUS concept using 60% electric power and 40% carbon neutral fuel.[55] Based on the average regional air carrier flight distance of 500 miles, a representative 494-mile flight on an Embraer 175 was chosen from Salt Lake City, UT (SLC) to Albuquerque, NM (ABQ).[58] This flight is estimated to produce 13,148 CO2e.[59] This is in comparison to a hybrid-electric aircraft fueled with 100% SAF operating the same route and distance with no CO2e produced. Therefore, the hybrid-electric aircraft would result in a 13,148 kg CO2e savings. Note, in the conservative case that the fuel is traditional Jet-A fuel and not 100% SAF or hydrogen, the savings would be 60% of the previous calculation at 7889 kg CO2 per flight, still significant.

While actualized hybridization concepts and aircraft models may vary, a shift towards hybrid propulsion for regional air carriers could mark a transformational step towards reducing regional airline emissions. However, because the current fleet does not support SAF and hybrid models are still in development, this strategy may see a later introduction timeframe and therefore later concept scaling. Further NASA research could continue to develop component technologies for these aircraft, which could include more demonstrator aircraft. In addition, NASA could study airspace and operational concepts that can enable higher capacity at large hub airports (which may get strained if demand goes up for these electrified aircraft if operating costs are reduced as predicted). Finally, NASA could develop aircraft concepts (similar to PEGASUS) that consider both updated component technologies in aircraft and operational concepts to maximize benefits of hybrid-electric aircraft.

2.1.2 All-Electric Short-Range Regional Routes

In addition to the “regional air carriers” discussed in the previous Opportunity Area, the term regional air carriers also includes relatively smaller aircraft that service relatively shorter routes. A “short-range regional air carrier” can be generally classified as an airline that operates passenger air service using piston or small turboprop aircraft that carry up to 9 passengers between communities lacking sufficient demand or infrastructure to attract legacy air carriers, their partners, or subsidiaries.[60] These types of shorter-range regional carriers, such as Cape Air, Boutique Air, and Mokulele Airlines, connect point-to-point end destinations and cover distances up to 250 miles.[61] For example, Cape Air has flights from Boston (BOS) to several locations in New England, including Martha’s Vineyard (MVY), Nantucket (ACK), and Provincetown (PVC).[62] Cape Air also has several flights in the Caribbean, connecting destinations in Puerto Rico such as San Juan (SJU) to Culebra (CPX) and

[xii] NASA’s Short-Haul Revitalization Study identifies 48 passengers as a basis for future research on hybridization of commercial aircraft. This was the basis for the PEGASUS concept, which is envisioned with 48 passengers. As of 2023 regional jets have average capacities of 69.2 pax for American Airlines, 72.1 pax for Delta Air Lines, and 55.7 pax for United Airlines. This may mean that potential for increased service for short-haul flights that operate out of regional and community airports.

destinations in the Virgin Islands such as St. Thomas (STT) to Saint Croix (STX).[63] While shorter-range regional travel can connect passengers more directly to destinations, it also can result in relatively high CO2 emissions per passenger compared to mainline routes.

Shorter-range regional routes are generally the least fuel efficient per mile type of air travel compared to longer routes. One factor that can contribute to this inefficiency is the large amount of fuel used for takeoff, compared to the cruise segment of the flight. In specific, fuel is burned in the departure stages (including taxi, take off, and climb) at a higher consumption rate per distance travelled than the cruise stage.[20] In addition, the fuel for takeoff is being expended carrying significantly fewer passengers than wide-body, narrow-body, and even aircraft used by regional carriers, leading to a relatively higher emissions per passenger per mile travelled. The fuel efficiency challenges in small regional travel underscore a need for transformational technology to reduce CO2 emissions.

The adoption of electrified aircraft for regional routes could help reduce operational regional flight emissions.[64] Electrification can refer to all electric, hybrid electric or turboelectric.[65] Electric propulsion is envisioned to be used initially in retrofits of existing certified aircraft and could represent a viable step towards reducing emissions as they do not produce in-flight emissions.[64] Specifically, it is estimated that all electric aircraft could provide a 49% to 88% reduction in CO2e emissions relative to fossil-fueled aircraft, depending on how the energy used to charge the battery is obtained.[66] The lower end of this range represents charging from traditional grid electricity (49-57% CO2 reduction) and the upper end of this reduction range represents charging from renewable energy (82-88% CO2 reduction).[66][64] In addition, electric aircraft are estimated to be 2.1 to 3.2 times more energy efficient as they convert electricity into propulsive force more efficiently than combusting fossil fuels in an aircraft engine.[66]

While electrification could offer transformative emission reduction, there also remain challenges. First, electric propulsion does not yet have the energy density to power more than relatively light aircraft across distances greater than a few hundred miles. Therefore, electric propulsion is envisioned to be implemented on relatively small aircraft with shorter routes, aligning to current gaps in regional inefficiency. In addition, while electric propulsion is anticipated to produce zero operational emissions, energy is still needed to charge the batteries.**Error! Bookmark not defined.** Therefore, to make electrification truly emission reducing, the energy from the power grid and at airports may need to transition to more sustainable sources. Finally, at the end of their lifecycle, electric batteries are very difficult to recycle, making investment in recycling technologies and incentives also important.[67] Despite these challenges, electric propulsion's capability for zero operational emissions could still make significant reductions in emissions on regional flights.

While electric propulsion has not yet emerged into commercial operations, over 215 types of electric-powered aircraft are being developed worldwide and industry is working towards certification of innovative propulsion systems.[65] [68] [69] Some of the earliest certifications for commercial operations focus specifically on leveraging electric propulsion with existing certified aircraft designs.[70] NASA partnerships with industry and efforts such as the

Electrified Aircraft Propulsion (EAP) research work towards next steps of electric propulsion.[71] While an electric propulsion unit has not yet been certified under 14 CFR Part 33 for aircraft engines, the first special conditions for type certification were issued by the FAA in September 2021.[70] For potential emission reductions through electrification, initial certification of electric propulsion systems or entirely novel all-electric aircraft certification will be needed.

Electric propulsion is envisioned to be first implemented on routes comparable to what is currently served by small regional air carriers. To provide a comparable use case of electrified flight by 2050, a regional Cape Air flight was chosen. Electrified regional flights are generally envisioned to have up to 9 passengers if operating scheduled passenger service out of airports and demonstrate up to a 250-mile range.[72] However, these boundaries are expected to change as technology evolves and matures. Cape Air flight routes have a distance between 44 miles (BOS to PVC) and 212 miles (BOS to Saranac Lake, NY (SLK)).[63] A representative Cape Air regional route has a flight distance of 175 miles between Cyril E. King Airport (STT), St. Thomas to Vance W. Amory International Airport (NEV), Nevis.[63] Assuming a fully electric replacement aircraft with zero operational emissions, an estimated 945 kg CO2 per flight may be saved.

Electric propulsion is envisioned to be the first step towards future expansion and adoption of electrification in aviation within the U.S. In specific, electric propulsion is a contributing factor for the vision and concepts of what is referred to as Regional Air Mobility (RAM), which is envisioned to fundamentally change regional travel in the U.S. by bringing the convenience, speed, and safety of air travel to more of the population, regardless of proximity to a traditional travel hub or urban center.[68] This concept aims to leverage and expand service at underutilized public airports within the U.S., while bringing more sustainable regional travel.[68] Therefore, further NASA research could continue development of electric aircraft, such as advancing modeling tools to handle electrical components or advancing the TRL of electric components. Other analysis could examine how regional aviation concepts could fit into the U.S. transportation system and hub-and-spoke system from a multimodal and demand-based perspective. This analysis could research the impact of regional electrification on ground-based modes of transportation, such as a basic comparison of leveraging RAM versus automobile trips for a given destination. Further analysis could seek to examine the tradeoffs and emissions impacts for electrification considering different elements of current regional travel and demand. For example, analyzing instances where individuals may fly direct to their destination on a regional aircraft, cases where individuals drive long distances to reach their nearest hub and fly to their destination, or instances where flights to the hub are of similar or greater distance than to the final flight leg. By understanding the role of electrification within the broader regional transportation system, this research could help to scale future RAM concepts and reduce in-flight emissions.

2.1.3 Up-Gauging and Route Frequency

Over the past two decades, the average number and density of seats on domestic flights for the 11 largest U.S airlines have increased and wide-body aircraft now fly some historically narrow-body routes.[73] This increase demonstrates an airline industry practice called up-gauging, which enables air carriers to increase capacity by either adding seats to existing aircraft or replacing narrow-body aircraft with wide-body aircraft.[74] This technique aims to maximize capacity on aircraft or fly fewer aircraft, dependent on the flight route. However, because increasing seat density within a fixed aircraft body reaches a limit in the physical aircraft body, up-gauging from a narrow-body to wide-body aircraft, while also reducing frequency, is envisioned to be a more scalable pathway to CO2 reduction. One of the major drivers for up-gauging in the airline industry is increased congestion at major airports, despite many of these busy routes being primarily serviced by narrow-body aircraft. [75]

Many of the busiest air routes in the U.S. leverage narrow-body aircraft instead of wide-body aircraft to provide frequency and continuity of service through major hubs. Because major U.S. airlines rely on a hub-and-spoke model and connecting flights are often needed, airlines aim to provide frequent flights for passenger convenience and logistical traffic flow. However, narrow-body aircraft generally produce more emissions per passenger, per flight than wide-body aircraft.[74] To carry the same number of passengers, narrow-body aircraft also require more flights than larger aircraft, which increases total taxi time, takeoffs, and landings, the most proportionally fuel intensive parts of the flight.[76] Although wide-body aircraft require more fuel and produce more emissions than narrow-body aircraft, wide-body aircraft carry more passengers, and generally produce less emissions per passenger. While flight frequency is primarily considered from a demand, service, or congestion perspective by airlines, there could also exist untapped potential for emission reduction.

Up-gauging from a narrow-body aircraft to a wide-body aircraft on select shorter distance routes paired with decreasing flight frequency could be considered as a potential strategy to decrease CO2 emissions per passenger. In specific, this effort considers the potential of up-gauging on busy and highly trafficked U.S. routes that have relatively inelastic demand and cover shorter distances.

For example, U.S. carriers Delta Air Lines, United Airlines, American Airlines, and Hawaiian Airlines all operate a range of wide-body aircraft on domestic routes.[77] Some of these routes run a couple wide-body flights per day on what can be generally considered shorter distance routes.[77] Some of these short routes with high demand include but are not limited to Delta Air Lines operating Orlando, FL (MCO) to Atlanta, GA (ATL), United Airlines operating Chicago O'Hare Airport (ORD) to Washington Dulles Airport (IAD), and American Airlines operating Miami, FL (MIA) to Charlotte, NC (CLT). By using wide-body aircraft, airlines aim to meet demand for these routes. However, this current strategy to meet demand could also be used to reduce emissions if the use of wide body aircraft was able to reduce the overall frequency of flights.[xiii]

To demonstrate what a commonly adopted wide-body short haul strategy could look like, domestic routes in Japan were analyzed. Historically, Japan's domestic aviation market has been one of the few in the world where multiple airlines deploy multiple wide-body aircraft on a variety of routes.[78] This includes the use of Boeing 747s and 777s adapted for short-haul use, and in recent years, Airbus A350s and Boeing 787 Dreamliners also adapted for shorter routes.[78] For example, All Nippon Airways (ANA) offers around 10 Boeing 787 Dreamliner 510-mile flights between Tokyo, Japan and Sapporo, Japan in a single day.[78] This approach was implemented across the country because ANA and other airlines in Japan found a balance between up-gauging and flight frequency, favoring wide-body aircraft that run more efficiently and reduce total CO2 output given the same passenger volume.

While there are inherent differences between the Japanese and U.S. airline markets, these use cases demonstrate potential emissions solutions for the U.S. market. For example, it is not realistic to assume that most U.S. routes could be converted to wide-body because the same passenger density, volume, geography, and airline market competition differ, and there remains the difficulty of acquiring more wide-body aircraft given current production backlogs. However, there are select examples of routes in the U.S. where Japan's model could be considered. These include U.S. routes that cover shorter distances and have high demand, such as Delta Air Lines operating MCO to ATL, United Airlines operating ORD to IAD, and American Airlines operating MIA to CLT.

Applying similar wide-body aircraft operations to historically narrow-body routes could reduce total CO2 emissions produced while still meeting demand and minimally impacting flight frequency. In specific, the single most trafficked short distance route in the U.S. is between the cities of Orlando, FL and Atlanta, GA, which this effort explores as a candidate for up-gauging. The Delta Air Lines route from MCO to ATL is generally run every hour, and a total of 16 times a day.[79, xiv] Of these 16 flights that are currently being flown, 14 are flown using a narrow-body aircraft (generally Boeing 757s), and 2 are flown using a wide-body aircraft (Boeing 767s).[80] Taking this flight on a narrow-body aircraft emits ~78kg CO2 per passenger and ~64 kg CO2 per passenger using wide-body. To transport the same number of passengers on all wide-body aircraft would require 14, instead of 16 flights per day, reducing CO2 emissions by approximately 2081 kg CO2 on average per flight. While this only provides one use case for one Delta Air Lines route, further NASA research could examine changes in air traffic management needs or changes in the hub-and-spoke system (e.g., reducing # of flights to enable more smaller aircraft to come into capacity constrained airports). NASA could also continue research with JetZero in their effort to develop an ultra-

[xiii] (Note, because certain fleets, such as Southwest Airlines and JetBlue Airways do not have wide-body aircraft in their fleets, this effort only examines the potential of up-gauging for airlines that have wide-body aircraft as a part of their fleet.)

[xiv] Considering data from October 2023. This date was chosen to represent not surge operations such as surrounding Thanksgiving, Memorial Day, Holiday season, etc.

efficient Blended Wing Body aircraft that has the passenger capacity of a small wide-body aircraft that uses the engines of a narrow-body aircraft, resulting in the emissions of a narrow-body aircraft and lower fuel emissions per passenger.[81]

2.1.4 Renewable Energy and Optimizing Airport Emissions

Often overlooked in the discussion of aviation-related decarbonization are the emissions caused by airports, which make up about 5% of total aviation CO2 emissions.[xv] For this effort, airport emissions can be defined as the resulting emissions from both airport terminal (lighting, heating, and cooling and appliances) and airport airside activities (runway lighting, auxiliary power units (APUs), aircraft ground energy systems, and ground vehicles). Today, most ground-based airport operations use gasoline and diesel fuel for airport vehicles and ground support equipment (GSE), fossil fuel for electricity and heating, and jet fuel for APUs that power aircraft at airport gates, as well as other sources.[11] These types of fuels result in greenhouse gas (GHG) emissions that combine to make up approximately 5% of total aviation CO2 emissions.

The challenge lies in that airport systems have a high electrical energy demand, resulting in burning fossil fuels which release CO2 and other GHG.[82] The FAA identifies three key categories of airport GHG emissions. Scope 1 emissions include emissions from airport-owned or controlled sources, such as airport-owned power plants that burn fossil fuel, conventional vehicles that use gasoline, or conventional GSE that use diesel fuel.[11] Scope 2 emissions include indirect emissions from the consumption of purchased energy (electricity, heat, etc.)[11] Finally, Scope 3 emissions include indirect emissions that the airport does not control but can influence such as tenant emissions, emissions from passenger vehicles arriving or departing the airport, and emissions from waste disposal and processing.[11] Because Scope 3 emissions are less directly under the jurisdiction of airports themselves, this assessment will focus on only Scope 1 and Scope 2 emissions. While there are efforts being made across the U.S. to reduce emissions at airports, carbon neutrality without the purchasing of carbon offsets could be considered as the next goal.

Airport carbon neutrality could be an integral part of the broader strategy to decarbonize the aviation industry. Achieving net-zero CO2 emissions may include airports converting their ground fleets to electric vehicles (EVs), electrifying building systems, generating renewable energy on-site, and improving energy and water efficiency.[83] The combination of these actions could lead towards significant reductions. While airports alone cannot decarbonize aviation entirely and represent a small number of overall emissions, their efforts can play a significant role in influencing and contributing to the overall goal.

The first and largest airport in North America to reach CO2 neutrality was Dallas Fort Worth International Airport (DFW).[84xvi] In 2016, DFW also became the first airport certified at the

[xv] One Way U.S. Domestic Economy Average Emissions Per Passenger (CO2e) considers data from October 2023. This date was chosen to represent not surge operations such as surrounding Thanksgiving, Memorial Day, Holiday season, etc.

[xvi] The second, and only other carbon neutral airport in the U.S. as of 2023 is San Diego, CA (SAN).

highest level of Airports Council International's Airport Carbon Accreditation Program Level 4+.[84] [xvii] To reach this reduction, DFW's efforts took a two-pronged approach, where they focused on both upgrading the efficiency of existing processes through utilizing technological advancements in tandem with utilizing sustainable power sources. An example of this two-pronged approach is energy efficiency and renewable energy. As of 2022, 69.3% of all energy used at DFW comes from renewable sources.[84] To shift towards using more renewable energy from Texas wind farms, DFW broke ground on a new electric Central Utility Plant in 2023, fueled by electricity purchased from 100% renewable sources. The new plant will replace the old, outdated one, which was run by natural gas. In addition to using renewable energy, DFW also invested in emerging technology to increase energy usage efficiency.[85] In 2021, DFW created a Building Information Model which integrated digital twin and predictive models of airport interior spaces to improve building energy consumption.[86] This model worked by dynamically controlling ventilation rates based on anticipated area occupancy, solar irradiance, and ambient conditions to optimize energy usage, in addition to heating, ventilation, and air conditioning controls. Through advanced technology for energy efficiency and leveraging renewable energy, DFW was able to reduce emissions; however, there were additional pieces needed to reach carbon neutrality.

Another aspect that DFW focused on was fleet and mobility decarbonization through more sustainable fuels and electrification. To reduce ground vehicle fleet emissions, DFW shifted away from traditional fossil fuels to natural gas, derived from sources including landfill biomass for 77% of the fuel used in ground vehicles.[84] In addition, DFW invested in electrifying ground vehicle technologies in a partnership with the National Renewable Energy Laboratory (NREL), which is the Department of Energy's laboratory for renewable energy and advanced transportation.[84] NREL researchers developed a simulation-based optimization modeling framework to help DFW transportation operators design efficient electric bus deployment strategies.[87] The model analyzed real-world conditions and simulated the existing DFW system to determine optimal battery capacity, charging power, and number of charging stations while minimizing capital cost and emissions. In 2023, DFW acquired new electric busses to begin to implement this strategy, looking towards the future of electrification. While renewable energy and fleet overhaul were only a few of the many steps taken by DFW to reach CO2 neutrality, they demonstrate that renewable sources should also be paired with smart technology. In 2022, the sum of DFW's decarbonization efforts led to an 83% reduction of Scope 1 and Scope 2 emissions from their 2010 baseline.[84] Specifically, this equates to a total of 109,099,000 kg CO2e reduced in 2022.[84] To estimate this on a per flight number, this report averaged the savings over the total number of flights in DFW in 2022, which equates to a CO2 decrease of 356 kg CO2 per flight. Overall, DFW demonstrated how investing in both sustainable fuel and leveraging emerging technology focused on decarbonization can greatly reduce CO2 emissions produced at an airport.

[xvii] Airport Carbon Accreditation is the only institutionally endorsed, global carbon management certification program for airports. It independently assesses and recognizes the efforts of airports to manage and reduce their carbon emissions through 7 levels of certification: 'Mapping', 'Reduction', 'Optimization', 'Neutrality', 'Transformation', 'Transition' and 'Level 5'.

The DFW use case demonstrates that reaching CO2 neutrality at airports is a multifaceted and complex challenge that should include both investment in renewable energy and fuels, and emerging technologies to optimize efficiency and operations. However, airports have a wide variety of factors that could make the approach to CO2 neutrality different for each. One of the challenges is that sources of renewable energy can vary greatly from airport to airport. For example, while DFW relies on primarily wind energy, the Denver International Airport (DEN) has invested in over 40,000 solar panels that cover 56 acres of onsite energy production.[88] The same sheer number of solar panels is not possible at a space-constrained airport such as JFK, which plans to pair solar panels on roofs with fuel cells to optimize energy storage and usage.[89] Based on an airport's geography, terrain, and land constraints, renewable energy is not a "one size fits all solution" and must be considered on a case-by-case basis. Therefore, this document urges a focus on the second part of the strategy that DFW employs, pairing an appropriate renewable energy source with emerging technology that helps efficiency optimization. The types of studies, partnerships, and programs that DFW employed all focused on developing a software, such as a digital twin, that could perform optimization. While this approach to renewable energy may not be as standardized airport-to-airport, NASA could research the implementation feasibility of optimizing systems that could be applied across more airports nationwide.

2.2 Impact Evaluation of Strategy 2

This section evaluates Strategy 2 as well as the Opportunity Areas within the Strategy.

2.2.1 Carbon Emissions Reduction Potential

This section provides a quantitative assessment of the potential impact on CO2 emissions of each Opportunity Area. The following Table 13 provides the change in CO2 emissions per use case on a per flight basis to enable Opportunity Area comparison across CO2 emissions. The full step-by-step calculations can be found in **Appendix A: Carbon Impact Calculations.**

Table 13: Carbon Impact Potential Scoring Rubric for Strategy 2

Opportunity Area	Use Case	Δkg CO2 Per Flight	Carbon Emissions Impact per Flight	Score based on per Flight
O.A. #1: Electrification of Regional Air Carrier Aircraft Replacements	Average Regional Air Carrier Flight with Embraer 175	-13,148	1000+ kg CO2	9
O.A. #2: All-Electric Short-Range Regional Routes	Cape Air Regional Flight	-945	100- 999 kg CO2	6
O.A. #3: Up-Gauging and Route Frequency	Delta Air Lines Narrow-body to Wide-body	-2,081	1000+ kg CO2	9

O.A. #4: Renewable Energy and Optimizing Airport Emissions	DFW Decarbonization	-356	100- 999 kg CO2	6

2.2.2 Scalability Timeline

Each Opportunity Area in strategy 2 requires a significant aircraft or infrastructure investment, which can produce varying estimated timeframes for reaching both initial implementation and scaled operations.

Out of the three Opportunity Areas, up-gauging is envisioned to have the longest estimated timeframe to scaled operations. Up-gauging's scalability timeline is dependent on the time needed to acquire new wide-body aircraft to replace narrow-body aircraft in the fleet. Because the waitlist for Airbus and Boeing is over 12 years, this is not a strategy that could be implemented in the short term.[90] However, if orders are placed in time, this strategy may be more feasible by 2040. In addition, JetZero's Blended Wing Body aircraft is still in development and not in production yet.[81]

Renewable energy and optimizing airport emissions, and electrification of regional routes have the shortest scalability timelines within strategy 2. Many airports across the U.S. have already begun to implement sustainability plans. For example, the FAA identifies seven airports in the U.S. that have already "significantly reduced GHG emissions," and the FAA currently has provided grants to 44 participating airports in its Airport Sustainability Planning Program.[91] Of these airports, DFW and San Diego International (SAN) have achieved CO2 neutrality.[91] However, due to the infrastructure and overhaul timeframe and costs, these measures are envisioned to scale sometime before 2035.

Electrification of regional routes first requires either the certification of innovative propulsion systems, such as hybrid-electric or electric, or the certification of novel airframe aircraft, which are still in the development and testing phase. While an electric propulsion unit has not yet been certified under 14 CFR Part 33 for aircraft engines, the first special conditions for type certification were issued by the FAA in September 2021.[70] Although electrification on novel airframe aircraft is envisioned to have a longer scalability timeline, the certification process for electric propulsion on existing airframes is anticipated to reach initial certification by 2030, and could be scaled by 2035.[92]

While all Opportunity Areas within strategy 2 require some form of physical aircraft or infrastructure development and investment, the time frames vary overall between 2035 and 2040.

The following Table 14 provides an overview of the scalability timeline scores for each Opportunity Area in Strategy 2.

Table 14: Scalability Timeline Scoring Rubric for Strategy 2

Opportunity Area	Use Case	Estimated Scaled Timeline	Score
O.A. #1: Electrification of Regional Air Carrier Aircraft Replacements	Average Regional Air Carrier Flight with Embraer 175	Scaled in by 2050	1
O.A. #2: All-Electric Short-Range Regional Routes	Cape Air Regional Flight	Scaled in the short-term, by 2035	6
O.A. #3: Up-Gauging and Route Frequency	Delta Air Lines MCO→ATL Narrow-body to Wide-body	Scaled in the medium-term, by 2040	3
O.A. #4: Renewable Energy and Optimizing Airport Emissions	DFW Decarbonization	Scaled in the short-term, by 2035	6

2.2.3 Implementation Cost

Each Opportunity Area in strategy 2 requires investment generally associated with higher implementation costs, including the purchase of aircraft or installment of infrastructure.

Both Opportunity Areas of regional electrification and optimizing airport emissions will require purchase and installment of airport infrastructure. For regional electrification, this may include charging stations, and for airport sustainability, a broad range of sustainable energy infrastructure.[xviii] These generally have high implementation costs; for example, the construction of DFW's on-site renewable energy plant cost a total of $234 million.[93]

In addition, the Opportunity Areas of up-gauging and regional electrification may require the purchase or development of aircraft, which can present a significant cost. To implement up-gauging from narrow-body to wide-body aircraft on popular routes, purchase of new wide-body aircraft may be needed, though airlines would first utilize current wide-body aircraft in their fleet before purchasing new aircraft. As of 2023, wide-body aircraft from Boeing cost approximately within the range of $200- $375 million.[94] To implement regional electrification, significant investment will be needed to finish development and manufacturing of the final certified and market-ready electric propulsion units and aircraft. While no market price is currently available, creating these electric fleets will likely be a significant investment.[95]

The follow Table 15 shows the Implementation Cost scores for each Opportunity Area in Strategy 2.

[xviii] Note, the cost of charging infrastructure may differ based on geographical location and climate. For example, cold weather charging may require additional considerations and costs.

Table 15: Implementation Cost Scoring Rubric for Strategy 2

Opportunity Area	Change in Cost Description	Change in Cost Categorization	Final Score
O.A. #1: Electrification of Regional Air Carrier Aircraft Replacements	• Development of hybrid-electric aircraft • Testing, certification, validation of hybrid-electric aircraft • Installation of electric supporting infrastructure at airports	Implementation is more expensive than current operations	3
O.A. #2: All-Electric Short-Range Regional Routes	• Development of electric aircraft • Testing, certification, validation of electric aircraft • Installation of electric supporting infrastructure at airports	Implementation is more expensive than current operations	3
O.A. #3: Up-Gauging and Route Frequency	• Purchase of new wide-body aircraft, lowest $200 million-$375 million, per aircraft[94]	Implementation is more expensive than current operations	3
O.A. #4: Renewable Energy and Optimizing Airport Emissions	• Payment of carbon credits[96] • New on-site renewable energy plant[93] • Electrified fleet vehicles • Replacing aging heating/cooling pipes[97]	Implementation is significantly more expensive than current operations	1

2.2.4 Accessibility

The Opportunity Areas in Strategy 2 each have varying effects on accessibility that can be explained by differing missions and the intents of each use case.

Electrification of regional air carriers aims to replace regional air carrier aircraft with hybrid-electric propulsion. If current regional jets with slightly higher passenger capacity are replaced with regional turbo props there may be a minimal increase in frequency, however this Opportunity Area is not envisioned to shift operating paradigms or specifically increase service. In contrast, one of the goals for all-electric short-range routes is to reduce operational costs, which can lead to increased service to underserved airports and/or increase flight frequency at other airports. These factors would increase accessibility to the public.

The intent of up-gauging is to reduce the frequency of flights by replacing narrow-body aircraft on popular routes with wide-body aircraft. While the same number of passengers is held constant in up-gauging, reduction of flight frequency is the main driver behind reducing emissions. However, this reduction in flight frequency, as demonstrated in the use case, is envisioned to be minimal and not hinder public accessibility.

The final Opportunity Area in Strategy 2, renewable energy and optimizing airport emissions, is not envisioned to have an impact on flight service and frequency. Although renewable energy may have the potential for more frequent power losses, it is not predicted to reduce passenger demand. All airport operations, while more sustainably run, are not envisioned to impact public accessibility.

The following Table 16 shows the Accessibility scores for each Opportunity Area in Strategy 2.

Table 16: Accessibility Scoring Rubric for Strategy 2

Opportunity Area	Change in Accessibility Description	Change in Accessibility Categorization	Final Score
O.A. #1: Electrification of Regional Air Carrier Aircraft Replacements	• No change, the regional service itself is not envisioned to be impacted.	Implementation will result in no change to public accessibility	6
O.A. #2: All-Electric Short-Range Regional Routes	• The goal of this is to increase frequency and service to underserved airports and ultimately add to the network	Implementation will result in increased public accessibility	9
O.A. #3: Up-Gauging and Route Frequency	• Decrease in service, due to decreased frequency. The use case demonstrates a slight, rather than hindering decrease.	Implementation will result in a slight decrease to public accessibility	3
O.A. #4: Renewable Energy and Optimizing Airport Emissions	• No change, the source of energy doesn't directly impact the frequency or service.	Implementation will result in no change to public accessibility	6

2.2.5 Overall Strategy Score

The following Table 17 provides a summary table containing the final scores for each Impact Evaluation Factor and each Opportunity Area in Strategy 2.

Table 17: Total Strategy 2 Scores Summary

Opportunity Area	Carbon Impact Score	Scalability Timeline Score	Cost Score	Accessibility Score
O.A. #1: Electrification of Regional Air Carrier Aircraft Replacements	9	1	3	6
O.A. #2: All-Electric Short-Range Regional Routes	6	6	3	9
O.A. #3: Up-Gauging and Route Frequency	9	3	3	3
O.A. #4: Renewable Energy and Optimizing Airport Emissions	9	6	1	6

3.0 Strategy 3: Optimizing Fleet Modernization and Renewal

The U.S. fleet size has increased significantly in the past 20 years, growing from 2,132 aircraft to 5,485 aircraft while the U.S. population grew from 281 million people to 333 million people.[98] [99] This has led to demand for air travel outpacing population growth and a demand for aircraft that outweighs production and supply capacity. Therefore, to make the growing fleet more sustainable, multiple fleet modernization and renewal options must be leveraged simultaneously.

Two key areas that have potential for optimization that could reduce CO2 emissions include the acceleration of the replacement of inefficient aircraft and examining the secondary decommission journey. Overall, this strategy aims to identify novel ways to drive more rapid fleet modernization.

3.1 Impact Assessment of Strategy 3

3.1.1 Accelerated Replacement of Inefficient Aircraft

Each new generation of aircraft is about 17% more fuel efficient than the previous generation.[10] This means that the newer a fleet is, the more fuel efficient and less emissions are produced in-flight. Therefore, the faster that ageing inefficient aircraft can be replaced with newer more efficient aircraft, the sooner potential emission savings can be realized. However, there are significant challenges facing the acquisition of new aircraft that require a more strategic lens on how to replace aircraft.

One of the key challenges in replacement of inefficient aircraft is an extended supplier backlog. Airbus and Boeing both have over 12+ year backlogs for new aircraft orders. Therefore, airlines must plan and order far in advance before receiving a new aircraft.[90] [xix] In addition, manufacturers also face a lengthy aircraft certification timeframe. For example, a type certificate issued by the FAA for a new aircraft type can typically take between five to nine years or longer, while an amended type certificate can typically take between three to five years or longer.[100] This supplier backlog is also paired with high demand for new aircraft from airlines. For example, airlines used to renew aircraft leases on average of 65% to 75% of the time, but now the average aircraft lease renewal it is at a historic high of 90%.[101] Therefore, while the technology exists to produce more fuel-efficient aircraft, manufacturers cannot keep up with airline demand.

Due to long manufacturing and delivery times for new aircraft, fleet modernization of the least efficient aircraft could be accelerated to realize emissions reductions. In specific, an airline could be strategic when deciding which aircraft within its fleet to replace by targeting first the most inefficient aircraft. U.S. major airline fleets consist of wide-body, narrow-body, and regional

[xix] This paper considers Airbus and Boeing because they provide the overwhelming share of passenger aircraft globally. Through August 2016, Airbus has a 59.4% global market share of the single-aisle aircraft market, while Boeing has 40.6%.

aircraft.[xx] In general, wide-body aircraft tend to be the most fuel efficient per passenger in terms of revenue passenger miles (RPM), followed by narrow-body aircraft. However, regional aircraft release nearly 90% more CO2 per RPM compared to narrow-body aircraft.[102] This significant difference in CO2 emissions per RPM indicates that inefficient narrow-body aircraft may be a first target for replacement. If airlines could accelerate the replacement of their most inefficient aircraft, then overall fleet emissions may be reduced.

A use case that reflects this strategy is United Airlines fleet replacement plan released in 2021. United Airlines announced that they ordered nearly 550 new aircraft pre-COVID. Of these aircraft, 200 will be Boeing 737 MAX and 70 Airbus 321neo will replace outdated narrow-body aircraft.[103] United Airlines estimates these replacements will lead to an expected 11% overall improvement in fuel efficiency and reduce CO2 emissions by an expected 17-20% per seat, compared to older aircraft.[103] Based on United Airlines projections, this report calculated the fleet replacement plan, if applied to 2022 flights, could lead to a reduction of 6670 kg CO2 emitted per flight.

Due to aircraft supplier backlog paired with high demand, the decisions airlines make when accelerating the replacement of aircraft can be important to overall fleet sustainability. When airlines choose to replace their most inefficient aircraft, their fleet becomes more efficient. However, the lifecycle of the decommissioned passenger aircraft does not always stop there, and many can have a second life repurposed. Further NASA research could develop a tool that helps airlines and industry make more holistic decisions that consider the downstream impacts of the entire decommission and repurpose journey. This could help visualize and shape the incentives and factors at play that govern these decommissioning and destination decisions. This topic is explored more in the following Opportunity Area. In addition, NASA could pursue research into replacements for regional aircraft that utilize efficient aircraft designs.

3.1.2 Aircraft Repurpose for U.S. Secondary Market

When new aircraft are purchased in the passenger fleet, other aircraft within this fleet are then retired and move to the secondary market. Around 700 commercial aircraft are retired worldwide each year at an average age of approximately 25.7 years.[104] When a passenger aircraft is retired, it can either be re-sold in the secondary market or sent to an aircraft "boneyard" where it is scrapped and recycled. This Opportunity Area focuses solely on the aircraft decommissioning process and re-sale to the U.S. secondary market.

When a passenger aircraft becomes available on the secondary market, there are two types of aircraft renewal that it may undergo before its secondary life. The first type of renewal is when an aircraft is sold from passenger carrier to passenger carrier and does not undergo a complete configuration change but may undergo cabin layout changes (such as seat layout). The second type of renewal is when a passenger aircraft is sold to a cargo company and undergoes a complete configuration conversion for cargo use. Once an aircraft is

[xx]Note, certain carriers such as Southwest or JetBlue only service narrow-body aircraft.

reconfigured, it continues its lifespan and operations, but also continues aging and is comparatively less efficient than a new aircraft.

As a result of the COVID-19 pandemic and an increase in e-commerce, the demand for new cargo aircraft has far outpaced the supply. Specifically, Airbus and Boeing are still working to fulfill their backlog orders for cargo aircraft that were made prior to COVID-19 when demand was lower. This means that newer, more efficient aircraft are not becoming a part of the cargo fleet. Instead, older cargo aircraft continue to be operated longer and the "new" aircraft introduced into the cargo fleet are actually repurposed passenger aircraft.

Because the cargo fleet is comprised of aging cargo aircraft and older, repurposed passenger aircraft, the cargo fleet is relatively inefficient compared to the U.S. passenger fleet. Therefore, replacement of the cargo fleet's most inefficient and oldest aircraft could result in reduced emissions. For example, 60% of the current cargo fleet are more than 25 years old and do not support 100% SAF.[xxi] Additionally, these aircraft are, on average, 17% less efficient than the aircraft they are replaced with, and do not incorporate the latest advancements in aerodynamics, propulsion, systems, and materials.[10]

While introducing repurposed secondary market aircraft into the cargo fleet may not be as efficient as acquiring new cargo aircraft, due to aircraft supply limitations, newer repurposed aircraft could still provide significant emissions reduction benefit. While the average age of the cargo fleet in total is estimated to be ~21.9 years, there are significantly older outliers within that number. For example, FedEx and UPS still operate wide-body McDonnell Douglas MD11s, which have average ages of ~30 years and ~29 years, respectively.[xxi] With aircraft this old, the cargo fleet could benefit from the downstream impacts of decommissioning passenger aircraft to replace ~30-year-old MD11s currently in use.

Replacing the aging cargo fleet with passenger aircraft from the secondary market could both decrease the average age of fleets and decrease emissions. For example, in 2020, American Airlines decommissioned 93 narrow-body and wide-body aircraft.[105] Of these aircraft, 68 aircraft (73%) were sold, 24 were stored, and 1 was scrapped.[105] Of the 68 aircraft sold, 36 (53%) were then converted into cargo aircraft, 3 were sold to other airlines for passenger operations, and the remaining 29 were sold to consulting companies that provide leasing, sales and acquisitions of aircraft but did not have a final destination – either a passenger airline or a cargo airline – listed yet.[105] Of the 36 aircraft sold to the cargo fleet, six aircraft were sold directly to cargo companies, while the remaining 30 were sold to consulting companies. The consulting companies then converted these aircraft to cargo and sold them. These aircraft were sold at an average age of 18.5 years and purchased in U.S., Canada, Belgium, and China.[105] The companies that purchased repurposed aircraft included Amazon Prime Air, DHL Air, YTO Cargo Airlines, SF Airlines, Cargojet Airways, and Amerijet International.[105] This use case demonstrates the transition lifecycle of passenger aircraft into the cargo fleet through American Airlines' aircraft journey in 2020.

[xxi] This was calculated using information from the 10-Ks of Delta Air Lines, American Airlines, United Airlines, Hawaiian Airlines, Alaska Airlines, Southwest, and JetBlue

From this use case, the strategy of replacing the oldest aircraft in the cargo fleet could be implemented to realize emission savings. Noting that American Airlines sold their passenger aircraft at an average age of 18.5 years, this is younger than the average age of the cargo fleet (21.9 years), and significantly younger than the oldest cargo fleet aircraft at approximately ~30 years. This effort calculates that the average flight could save about 1,910 kg CO2 per flight due to efficiency gains in the newer aircraft, and potentially more if run on SAF in the future.[xxii]

The rate at which passenger aircraft are decommissioned and converted into cargo aircraft should be accelerated to replace the oldest aircraft in the cargo fleet that do not support SAF. By converting older passenger aircraft to the cargo fleet more quickly, older cargo aircraft can be retired, and the average age of the cargo fleet could be decreased. To support this goal, NASA could develop a feasibility study to determine the rate at which fleet renewal across both the U.S. passenger and cargo fleets could be achieved, leveraging CO2 savings as a justification for congressional legislation to federally incentivize fleet renewal. In addition, configuration changes require some level of recertification, and NASA could examine the impacts of retrofits such as re-engine of aircraft.

3.2 Evaluation of Strategy 3

This section evaluates Strategy 3 as well as the Opportunity Areas within the strategy.

3.2.1 Carbon Emissions Reduction Potential

The following Table 18 provides the change in CO2 emissions per use case on a per flight basis to enable Opportunity Area comparison across CO2 emissions. The full step-by-step calculations can be found in **Appendix A: Carbon Impact Calculations.**

Table 18: Carbon Reduction Potential Scoring Rubric for Strategy 3

Opportunity Area	Use Case	Δkg CO2 Per Flight	Carbon Emissions Impact per Flight	Score based on per Flight
O.A. #1: Accelerated Replacement of Inefficient Aircraft	United Airlines Replacing Older Aircraft with New Aircraft	-6,670	1000+ kg Co2	9
O.A. #2: Aircraft Repurpose for U.S. Secondary Market	American Airlines Passenger Fleet Decommissioning	-1910	1000+ kg Co2	9

3.2.2 Scalability Timeline

Both Opportunity Areas could be implemented within the medium-term or short-term and involve extending or optimizing the useful life of aircraft.

[xxii] This was calculated using information from the 10-Ks of Delta Air Lines, American Airlines, United Airlines, Hawaiian Airlines, Alaska Airlines, Southwest, and JetBlue

Aircraft repurpose involves selling the aircraft to another customer, which is a business decision that could be scaled in the short term, by 2030. Instead of a passenger airline selling their used aircraft to another passenger airline, a leasing company, or another party, they would sell their aircraft to the cargo fleet or to an intermediary who would convert the aircraft to cargo and then sell the aircraft to the cargo fleet.

The accelerated replacement of inefficient aircraft requires airlines to purchase new aircraft, placing the order with an original equipment manufacturer (OEM), and receiving the new aircraft. As of September 1, 2023, it would take Boeing and Airbus 12+ years to clear their entire backlogs, assuming the backlog does not continue to grow and must be cleared prior to delivering new orders. In addition to new aircraft delivery delays, it would also take an airline time to determine which aircraft will be decommissioned, and then what aircraft should be ordered to replace it.

The following Table 19 provides an overview of the scalability timeline scores for each Opportunity Area in Strategy 3.

Table 19: Scalability Timeline Scoring Rubric for Strategy 3

Opportunity Area	Use Case	Estimated Scaled Timeline	Score
O.A. #1: Accelerated Replacement of Inefficient Aircraft	United Airlines Replacing Older Aircraft with New Aircraft	Strategy is scaled in the medium-term, by 2040	3
O.A. #2: Aircraft Repurpose for U.S. Secondary Market	American Airlines Passenger Fleet Decommissioning	Strategy is scaled in the short-term, by 2035	6

3.2.3 Implementation Cost

Both Opportunity Areas in Strategy 3 involve the sale of aircraft. Accelerated replacement of less efficient aircraft will lead to the purchase of new aircraft by airlines, resulting in a significant increase in cost. Aircraft repurpose for the secondary market will also involve a configuration change to cargo aircraft when applicable, contributing to additional costs. Although the passenger airline is likely to receive the same amount of money for their used aircraft, increased aircraft conversions will be more expensive than current operations.

The follow Table 20 shows the Implementation Cost scores for each Opportunity Area in Strategy 3.

Table 20: Implementation Cost Scoring Rubric for Strategy 3

Opportunity Area	Change in Cost Description	Change in Cost Categorization	Final Score
O.A. #1: Accelerated Replacement of Inefficient Aircraft	• Purchase of new aircraft, $89 million-$400 million, per aircraft[94]	Implementation is more expensive than current operations	3
O.A. #2: Aircraft Repurpose for U.S. Secondary Market	• Cost for configuration changes, such as when a passenger plane is converted for cargo use	Implementation is more expensive than current operations	3

3.2.4 Accessibility

Both Opportunity Areas in this strategy have no change to public accessibility. Both accelerated replacement of inefficient aircraft and aircraft repurpose for the secondary market are not expected to impact accessibility.

Table 21 shows the Accessibility scores for each Opportunity Area in Strategy 3.

Table 21: Accessibility Scoring Rubric for Strategy 3

Opportunity Area	Change in Accessibility Description	Change in Accessibility Categorization	Final Score
O.A. #1: Accelerated Replacement of Inefficient Aircraft	• No expected change in frequency or service	Implementation will result in no change to public accessibility	6
O.A. #2: Aircraft Repurpose for U.S. Secondary Market	• No expected change in frequency or service	Implementation will result in no change to public accessibility	6

3.2.5 Overall Strategy Score

The following Table 22 provides a summary table containing the final scores for each Opportunity Area and each Evaluation Factor in Strategy 3.

Table 22: Total Strategy 3 Scores Summary

Opportunity Area	Carbon Impact Score	Scalability Timeline Score	Cost Score	Accessibility Score
O.A. #1: Accelerated Replacement of Inefficient Aircraft	9	3	3	6
O.A. #2: Aircraft Repurpose for U.S. Secondary Market	9	6	3	6

4.0 Strategy 4: Production and Recycling of Aircraft

The aviation industry has been at the forefront of manufacturing innovation as improved production efficiencies and capabilities have helped to advance new aviation technologies. In recent years, advanced manufacturing practices have helped to manufacture innovative aircraft and more complex prototypes and production parts. Aviation manufacturers reliance on these technologies will likely increase as new production processes advance and offer cost benefits.

Strategy 4 focuses on the production stage of the aircraft lifecycle, including manufacturing technologies and recycling approaches that could reduce emissions compared to traditional production methods. Not only could new manufacturing technologies reduce emissions associated with production, but they may also enable the manufacturing of more lightweight aircraft parts that may reduce fuel burn in flight. This strategy examines additive manufacturing for light-weighting and recycled composite manufacturing to provide a basis for understanding how scaling specific manufacturing processes could lead to reduced CO2 emissions.

4.1 Impact Assessment of Strategy 4

4.1.1 Additive Manufacturing

Additive Manufacturing (AM) is an emerging production technology that has potential to improve aircraft development. AM is the process of creating an object by building one layer at a time.[106] Today, traditional manufacturing methods often involve subtractive processes, where material is created by cutting away at a solid block of material until the final product is complete.[107] Utilizing AM to produce specific aircraft parts could offer unique light-weighting advantages over traditional subtractive methods.

One of the current challenges in subtractive manufacturing is achieving metal light-weighting. Light-weighting involves the use of advanced materials and engineering methods to enable structural elements to deliver the same, or enhanced, technical performance while using less material. Subtractive manufacturing may require certain design considerations for structural integrity that include extra material to account for stresses and forces during machining, particularly, if the component has complex shapes or features.[108] This approach can result in components that are heavier than may be necessary.[109][xxiii] In addition, subtractive manufacturing often involves steps, such finishing and assembly, that can introduce extra material that slightly increase the overall weight of the final part.[110] While these weight additions per part may be minimal, the final weight of the total aircraft is important because weight is directly correlated to fuel burn. Therefore, this report seeks to examine how AM could be used realistically to result in aircraft weight reduction.

[xxiii] While subtractive manufacturing can contribute to increased weight in certain aspects, it is still widely used in aviation and other industries for its precision and ability to produce high-strength components.

Through leveraging AM, the overall weight of an aircraft could be reduced through light-weighting approaches. First, light-weighting can be achieved through decreasing the number of overall parts.[111] [112] For example, in 2012, GE Aerospace collaborated with Morris Technologies and reduced the number of parts in a jet engine fuel nozzle from 20 to one, leading to a 25% weight reduction and reduced assembly times.[113] Also, in a new advanced turboprop engine, a dozen 3D-printed parts were able to replace 855 components produced by multiple contractors.[113] This simplified design with a lower number of parts could also be manufactured with a lighter material. For example, using lighter composite materials could further result in weight reduction.[114] In addition, less components required during aircraft development could speed production times in a future environment where aircraft rely on significantly less components and fewer third parties for production input.

One study aimed to examine the potential of using lightweight AM parts instead of conventional manufacturing for aircraft weight reduction through examining the impact on aircraft weight and estimating potential fuel savings.[115] The study began by identifying different parts of the aircraft, such as the wing systems or engine, and then scored the feasibility of implementing AM for each. The study deemed certain component systems or parts more “feasible” to be replaced by AM materials than others, such as furnishing and equipment systems, or functional propulsion systems. Notably, structural components that bear aircraft major loads and support geometries were scored the least feasible to be replaced with AM. Then, for the components deemed most “feasible”, the study calculated the metal alloy composition and the extent to which they could be replaced by an AM composite.

The study found that in the near term, 9-17% of total typical aircraft mass may be replaceable with AM components.[115] Findings also stated that average aircraft empty mass could be reduced by 4-7% through the adoption of AM components in the selected systems, with the greatest potential mass reductions attributable to aluminum alloys, furnishing and equipment, and engine system components.[115] The final section of the study estimated that if AM components evaluated in this study are used to their full potential, airplane fuel consumption could be reduced by as much as 6.4%.[115] This study demonstrated that while AM cannot replace all parts of an aircraft feasibly, by strategically choosing which parts to replace with AM, the overall weight and fuel consumption of an aircraft may be reduced. Using this 6.4% fuel savings, the total amount of jet fuel consumed by U.S. airlines in 2022, and the total number of U.S. domestic flights in the U.S. in 2022, this report found an average of a 94 kg CO2 decreased per flight.

Scaling lightweight AM for certain aircraft parts could help to reduce in-flight operational emissions. These savings in aircraft weight are achieved through compounding replacement of traditionally manufactured parts with lightweight AM parts. However, there remain questions about certifying the AM processes and ensuring high quality parts consistently. In addition, while manufacturers like Airbus, Boeing, and GE Aerospace are beginning to develop, test, and deploy AM components, the throughput of AM processes is presently low, which makes AM technologies less suitable for high-volume production. To support scalability, NASA could examine advancing AM processes, enabling higher strength and consistently higher quality parts through AM processes.[116] By scaling AM, fuel savings and emission reductions could be achieved.

4.1.2 Recycled Composite Manufacturing

Composite materials are a combination of two or more materials with different physical and chemical properties.[117] Combining materials can result in increased strength and lighter weight, which has led to increasing adoption in aircraft manufacturing.[118] Lightweight materials offer the benefit of reducing overall aircraft weight and increasing fuel efficiency. Therefore, both Boeing and Airbus are using composite materials more frequently in aircraft manufacturing. However, the use of composite materials has also given rise to the challenge that composites are significantly more difficult to recycle than aluminum.

An increasing number of new aircraft are made of composite carbon fiber. This composite is generally used for the fuselage, wings, tail, doors, and interior of new aircraft.[119] However, it is both carbon intensive to produce and difficult to recycle. For example, at aircraft retirement, most of the waste is comprised of carbon fiber.[120] To address this issue, carbon fiber recycling technologies have been developed, but are not widely used. This poses a growing future challenge because the new aircraft that are utilizing carbon fiber will eventually reach retirement. Although carbon fiber and other composite materials offer efficiencies due to their light weight, their lack of recyclability could increase CO2 emissions.

Early development of carbon fiber recycling technology has emerged that may offer promise in the future sustainability of composites. One carbon fiber company recycles carbon fiber using pyrolysis and says its fibers typically retain at least 90% of its tensile strength with no change in modulus.[121] Another company states its chemical recycling process exhibits the same mechanical properties as virgin carbon fiber.[122] While these practices are not yet widespread, leveraging recycled composites for production of composite intensive aircraft only produces a sixth of the carbon it takes to produce virgin carbon fiber.[123] These results demonstrate the potential of composite recycling to reduce CO2 emissions.

If recycling of carbon fiber can be scaled, then potential CO2 emission reduction during production could be realized. However, this strategy relies on a sufficient quantity of carbon fiber from viable recycling sources to be available. Aircraft require high strength carbon fiber as well, so often cannot use recycled carbon fiber from other industries that have lower strength carbon fiber.[123] Because many aircraft utilizing higher compositions of carbon fiber are new, they are not ready yet to be decommissioned and recycled. While this strategy may hold promise in the long run, it relies on the future availability of recycling technologies and recycled carbon fiber itself.[121] [122] [123]

The following use case examines the current composite make-up and potential recycled composition of a Boeing 787 Dreamliner. This aircraft was designed with 50% carbon fiber reinforced polymer by weight, which is used in the wings, fuselage, and other key structural components.[124] This effort examined the production-related emissions reduction in aircraft that could be achieved by using recycled carbon fiber instead of virgin carbon fiber during production. First, the Boeing 787 Dreamliner is currently made with 23 tons of carbon fiber.[136]

The total CO_2 emissions generated from virgin carbon fiber were calculated and compared with the total CO_2 emissions that could be generated with recycled carbon fiber. This savings was then distributed over the average number of flights the aircraft is anticipated to take in its lifetime, yielding a savings of 12.96 kg CO_2 per flight.

Leveraging recycled composites, such as carbon fiber, for production of composite intensive aircraft could reduce production-related CO_2 emissions. Since carbon fiber is increasingly being used in the manufacturing of aircraft and other vehicles, the availability of recycled carbon fiber will likely increase over time. While this strategy may not have immediate impact, it will become more vital in the future as aircraft with higher composite make-up are decommissioned. Future NASA efforts could explore enhancing processes to extract the carbon fiber with even less carbon emitted. In addition, NASA could examine developing aircraft parts that can more easily be recycled after their useful life.

4.2 Evaluation of Strategy 4

This section evaluates Strategy 4 as well as the Opportunity Areas within the strategy.

4.2.1 Carbon Emissions Reduction Potential

This section will provide a quantitative assessment of the potential impact regarding CO_2 emissions of each Opportunity Area. Table 23 provides the change in CO_2 emissions per use case on a per flight basis to make the numbers comparable for scoring. The full step-by-step calculations can be found in **Appendix A: Carbon Impact Calculations.**

Table 23: Carbon Reduction Potential Scoring Rubric for Strategy 4

Opportunity Area	Use Case	Δkg CO_2 Per Flight	Carbon Emissions Impact per Flight	Score based on per Flight
O.A. #1: Additive Manufacturing	Analysis of lightweight AM parts for aircraft	-94	0 kg CO_2 – 99 kg CO_2	3
O.A. #2: Recycled Composite Manufacturing	Boeing 787 Composites	-13	0 kg CO_2 – 99 kg CO_2	3

4.2.2 Scalability Timeline

Both AM and recycled manufacturing have been developed and tested in pilot efforts. The applications of AM in aviation have seen significant progress in recent years and could be scaled in the short term by 2035. However, scaling recycled composite manufacturing is expected to be achieved in the long-term since it requires recycled composites and may take decades to generate the supply needed.

Table 24 provides an overview of the scalability timeline scores for each Opportunity Area in Strategy 4.

Table 24: Scalability Timeline Scoring Rubric for Strategy 4

Opportunity Area	Use Case	Estimated Scaled Timeline	Score
O.A. #1: Additive Manufacturing	Analysis of lightweight AM parts for aircraft	Strategy is scaled in the short-term, by 2035	6
O.A. #2: Recycled Composite Manufacturing	Boeing 787 Composites	Scaling of the strategy can be achieved in the long-term, by 2050	1

4.2.3 Implementation Cost

Additive manufacturing is expected to incur increased costs through initial investment and machine development. However, leveraging recycled composites are expected to have a cost decrease since recycled carbon fiber costs about 40% less than virgin carbon fiber. [135]

Table 25 shows the Implementation Cost scores for each Opportunity Area in Strategy 4.

Table 25: Implementation Cost Scoring Rubric for Strategy 4

Opportunity Area	Change in Cost Description	Change in Cost Categorization	Final Score
O.A. #1: Additive Manufacturing	• Initial investment cost of setting up AM centers, like Boeing's.[125] • Machine cost	Implementation is more expensive than current operations	3
O.A. #2: Recycled Composite Manufacturing	• Recycled carbon fiber is 40% less expensive than virgin carbon fiber • Manufacturing process related to using recycled carbon fiber is minimal compared to virgin carbon fiber • Cost savings over regular carbon fiber	Implementation is less expensive than current operations	9

4.2.4 Accessibility

Both Opportunity Areas in strategy four are expected to have no change in accessibility. Both involve the development of aircraft, which will not change frequency or service for air travel.

Table 26 shows the Accessibility scores for each Opportunity Area in Strategy 2.

Table 26: Accessibility Scoring Rubric for Strategy 4

Opportunity Area	Change in Accessibility Description	Change in Accessibility Categorization	Final Score
O.A. #1: Additive Manufacturing	• No expected change in frequency or service	Implementation will result in no change to public accessibility	6
O.A. #2: Recycled Composite Manufacturing	• No expected change in frequency or service	Implementation will result in no change to public accessibility	6

4.2.5 Overall Strategy Score

The following Table 27 provides a summary table containing the final scores for each Opportunity Area and each Evaluation Factor for Strategy 4.

Table 27: Total Strategy 4 Scores Summary

Opportunity Area	Carbon Impact Score	Scalability Timeline Score	Cost Score	Accessibility Score
O.A. #1: Additive Manufacturing	3	6	3	6
O.A. #2: Recycled Composite Manufacturing	3	1	9	6

5.0 Scenario Analysis

The previous sections focused on assessing and evaluating each Opportunity Area. This section takes these results and applies the three scenarios developed in section II.IV methodology: Equal Weightings, Preferred Scenario, and Carbon Reduction First. By applying the three scenarios to each of the Opportunity Areas and strategies, results were tested to produce comparative final rankings.

5.1 Scenario 1: Equal Weightings Results

Scenario 1, "Equal Weightings", was developed to provide a base scenario that considered each Evaluation Factor equally at 25%. While this is not considered to be the most realistic prioritization scenario, it ensures that each Evaluation Factor is considered and can be used as a baseline to compare across all 4 Strategies and 11 associated Opportunity Areas.

Table 28 shows the total Weighted Scores for each Strategy for Scenario 1.

Table 28: Scenario 1—Equal Weightings Results for Strategies

Strategy Name	Weighted Total Score
Strategy 1: Optimization Tools for Flight Operations	**5.83**
Strategy 3: Optimizing Fleet Modernization & Expansion	**5.63**
Strategy 2: Align Aircraft & Airport Technology to Optimized Applications	**5.0**
Strategy 4: Production and Recycling of Aircraft	**4.63**

More specifically, the following Table 29 shows the total Weighted Scores for each Opportunity Area for Scenario 1.

Table 29: Scenario 1—Equal Weightings Results for Opportunity Areas

Strategy #	Opportunity Area	Weighted Total Score
1.1	AI for Taxiing	**6**
1.2	AI for Flight Path Optimizations	**6**
3.2	Aircraft Repurpose for U.S. Secondary Market	**6**
2.2	All-Electric Short-Range Regional Routes	**6**
1.3	AI for Reducing Contrails	**5.5**
3.1	Accelerated Replacement of Inefficient Aircraft	**5.25**

2.1	Electrification of Regional Air Carrier Aircraft Replacements	**4.75**
4.2	Recycled Composite Manufacturing	**4.75**
2.4	Renewable Energy and Optimizing Airport Emissions	**4.75**
2.3	Up-Gauging and Route Frequency	**4.5**
4.1	Additive Manufacturing	**4.5**

For Scenario 1, the Opportunity Areas that score higher across all 4 Evaluation Factors rank higher, as no one factor is prioritized over the other and each have 25% equal weighting. As a result, the Opportunity Areas in Strategy 1 generally score well because they have high Scalability Timeline, Implementation Cost, and Accessibility Scores. Although Strategy 1's CO2 reduction impact as not as large as for example Strategy 2 or 3, because all weighting is equal, the other factors contribute to an overall higher weighted score for Strategy 1.

In addition to Strategy 1, Strategy 3 also scores well overall. While Scalability Timeline and Implementation Scores are slightly lower than in Strategy 1, Strategy 3 scores high in what Strategy 1 lacks— CO2 emission reduction. Therefore, Strategy 3 has balanced results, scoring well in Accessibility and CO2 emissions reduction, outpacing Strategies 2 and 4.

It is also worth noting that although Strategy 2 ranks third overall, an outlier Opportunity Area, All-Electric Short-Range Regional Routes ties for the top Opportunity Area for Scenario 1. This Opportunity Area is the only one that has a high score, or a 9, in Accessibility. Due to the equal weighting, it is likely that the Accessibility score for All-Electric Short-Range Regional Routes contributes to its high ranking.

5.2 Scenario 2: Preferred Scenario Results

Scenario 2 is the "preferred" scenario because it takes a holistic approach towards weighting each of the Evaluation Factors agreed upon through NASA guidance. This scenario prioritizes Carbon Impact (40% weighting) and Scalability (30% weighting), as they are considered the most important Evaluation Factors towards reaching net-zero CO2 emissions by 2050. Implementation Cost (20%) receives a slightly lower but still significant weighting because it could have major impact on strategy implementation. Accessibility was weighted the lowest (10%), because while important, it is not the primary consideration in reaching decarbonization by 2050.

The following Table 30 shows the total Weighted Scores for each Strategy for Scenario 2.

Table 30: Scenario 2—Preferred Scenario Results for Strategies

Strategy Name	Weighted Total Score
Strategy 3: Optimizing Fleet Modernization & Expansion	**6.15**
Strategy 1: Optimization Tools for Flight Operations	**5.43**

Strategy 2: Align Aircraft & Airport Technology to Optimized Applications	**5.3**
Strategy 4: Production and Recycling of Aircraft	**4.05**

More specifically, the following Table 31 shows the total Weighted Scores for each Opportunity Area for Scenario 2.

Table 31: Scenario 2—Preferred Scenario Results for Opportunity Areas

Strategy #	Opportunity Area	Weighted Total Score
3.2	Aircraft Repurpose for U.S. Secondary Market	**6.6**
1.1	AI for Taxiing	**5.7**
1.2	AI for Flight Path Optimizations	**5.7**
2.2	All Electric Short-Range Regional Routes	**5.7**
3.1	Accelerated Replacement of Inefficient Aircraft	**5.7**
2.3	Up-Gauging and Route Frequency	**5.4**
2.1	Electrification of Regional Air Carrier Aircraft Replacements	**5.1**
2.4	Renewable Energy and Optimizing Airport Emissions	**5.0**
1.3	AI for Reducing Contrails	**4.9**
4.1	Additive Manufacturing	**4.2**
4.2	Recycled Composite Manufacturing	**3.9**

For Scenario 2, the Opportunity Areas that score highest tend to have high CO2 impact, Scalability Timeline, and Implementation Cost scores based on the 40%, 30%, and 20% weightings respectively. Overall, Strategy 3 scores the highest for this Scenario because all Opportunity Areas score high in CO2 Impact (both 9s) despite more modest scores for Scalability Timeline and Cost. Within Strategy 3, Opportunity Area 3.2 (Aircraft Repurpose for the U.S. Secondary Market) ranks well above the rest of the field, due to high CO2 emission reduction and Scalability scores. The Opportunity Areas within Strategy 1 also generally score well in this Scenario, despite lower CO2 scores, because in comparison to all other Opportunity Areas, their Scalability Timeline and Implementation Cost scores are relatively high (all 9s). However, it is worth noting that AI for Reducing Contrails individually ranks low as the only Opportunity Area that increases CO2 emissions, earning a low score of 1.

While Strategy 2 scores third overall, it is not a large margin behind Strategy 1 because Strategy 2 Opportunity Areas score around the median. This is because Strategy 2 has high CO2 emissions reduction compared to Strategy 1, with mixed scores for other Evaluation Factors.

5.3 Scenario 3: Carbon Reduction First Results

Scenario 3, "Carbon Reduction First", prioritizes reaching decarbonization by 2050 over all other factors. This scenario takes an approach that prioritizes decarbonization and weights CO2 as the most important factor (60%). This scenario also considers scalability timeline because the sooner a strategy can be implemented, the sooner it may begin to realize CO2 reductions (40%). This scenario does not consider cost (0%) and accessibility (0%) and takes a dual-variable optimization approach to reach decarbonization by 2050.

The following Table 32 shows the total Weighted Scores for each Strategy for Scenario 3.

Table 32: Scenario 3—Carbon Reduction First Results for Strategies

Strategy Name	Weighted Total Score
Strategy 3: Optimizing Fleet Modernization & Expansion	**7.2**
Strategy 2: Align Aircraft & Airport Technology to Optimized Applications	**6.1**
Strategy 1: Optimization Tools for Flight Operations	**5.0**
Strategy 4: Production and Recycling of Aircraft	**3.2**

More specifically, the following Table 33 shows the total Weighted Scores for each Opportunity Area for Scenario 3.

Table 33: Scenario 3—Carbon Reduction First Results for Opportunity Areas

Strategy #	Opportunity Area	Weighted Total Score
3.2	Aircraft Repurpose for U.S. Secondary Market	**7.8**
3.1	Accelerated Replacement of Inefficient Aircraft	**6.6**
2.3	Up-Gauging and Route Frequency	**6.6**
2.4	Renewable Energy and Optimizing Airport Emissions	**6.0**
2.2	All Electric Short-Range Regional Routes	**6.0**
2.1	Electrification of Regional Air Carrier Aircraft Replacements	**5.8**
1.1	AI for Taxiing	**5.4**
1.2	AI for Flight Path Optimizations	**5.4**
1.3	AI for Reducing Contrails	**4.2**
4.1	Additive Manufacturing	**4.2**
4.2	Recycled Composite Manufacturing	**2.2**

For Scenario 3, Opportunity Areas with the highest CO2 impact and fastest Scalability Timeline score the highest. As a result, Strategy 3 scores the highest because its Opportunity Areas both have high CO2 scores (9s) and reasonable Scalability timelines (6 and 3). While Strategy 3 ranked low in Implementation Cost, because it was not accounted for in Scenario 3, it allowed the total weighted Strategy score to significantly outpace the others.

Strategy 2 also scores well in Scenario 3, but not as well as Strategy 3, because it has generally high CO2 impact scores, but a mixed range of Scalability Timelines. For example, the highest scoring CO2 impact Opportunity Area is Electrification of Regional Air Carrier Aircraft Replacements in Strategy 2, however, due to a low Scalability Timeline score of 1, it ranks as the median Opportunity Area.

Scenario 3 demonstrates the gap in magnitude of CO2 impact between Strategies 1 and 4 when compared to Strategy 3 and 2. Because the other factors of Cost and Accessibility were not included, they did not help to balance out where these strategies score lower.

It is worth noting that Recycled Composite Manufacturing appears to be a significant outlier ranking the lowest in Scenario 3. This is because it is the only Opportunity Area to score a 9 in Implementation Cost, an Evaluation Factor not included in Scenario 3.

5.4 Comparison of Scenarios

This section provides a combined analysis of the total weighted scores between each Scenario. The analysis is intended to provide a comparison and high-level overview of the final scores for each Opportunity Area and Strategy to support future NASA research and decision-making in reaching decarbonization by 2050.

The following Figure 7 displays a side-by-side comparison of the weighted total score for each Opportunity Area and Strategy for each Scenario. The ordering of the Opportunity Areas down the list does not reflect a ranking but is in numerical order. Rather, the colors of the chart form a “heat map” that indicates the best scoring Opportunity Areas and strategies out of a total potential score of 9. The closer the color is to the green spectrum, the higher the weighted score, and the closer the color is to the red spectrum, the lower the weighted score.

Figure 7: Total Heat Map Comparison of All Weighted Total Scores for Each Opportunity Area and Strategy

			Scenario 1: Equal Weighting		Scenario 2: Preferred Scenario		Scenario 3: Carbon Reduction First	
Strategy Name	**Strategy #**	**Opportunity Area**	**Weighted Total Score**	**Weighted Strategy Total**	**Weighted Total Score**	**Weighted Strategy Total**	**Weighted Total Score**	**Weighted Strategy Total**
Strategy 1: Optimization Tools for Flight Operations	**1.1**	AI for Taxiing	6	5.83	5.7	5.43	5.4	5.00
	1.2	AI for Flight Path Optimizations	6		5.7		5.4	
	1.3	AI for Reducing Contrails	5.5		4.9		4.2	
Strategy 2: Align Aircraft & Airport Technology to Optimized Applications	**2.1**	Electrification of Regional Air Carrier Aircraft Replacements	4.75	5.00	5.1	5.30	5.8	6.10
	2.2	All-Electric Short-Range Regional Routes	6		5.7		6	
	2.3	Up-Gauging and Route Frequency	4.5		5.4		6.6	
	2.4	Renewable Energy and Optimizing Airport Emissions	4.75		5		6	
Strategy 3: Optimizing Fleet Modernization & Expansion	**3.1**	Accelerated Replacement of Inefficient Aircraft	5.25	5.63	5.7	6.15	6.6	7.20
	3.2	Aircraft Repurpose for U.S. Secondary Market	6		6.6		7.8	
Strategy 4: Production and Recycling of Aircraft	**4.1**	Additive Manufacturing	4.5	4.63	4.2	4.05	4.2	3.20
	4.2	Recycled Composite Manufacturing	4.75		3.9		2.2	

At a high level, Strategy 3 scored the highest for both Scenario 2 and 3, while Strategy 1 scores the highest for Scenario 1. The heat map above displays a trend from left to right, as the CO2 impact evaluation factor weighting increases from 25% in Scenario 1, to 40% in Scenario 2, to 60% in Scenario 3, as did the resulting score for Strategy 3, followed by Strategy 2. Conversely, as the weighting of Implementation Cost increased relative to other factors, the resulting scores for Strategy 1 increased. This could suggest that Strategies 2 and 3 have the greatest CO2 reduction potential but may take longer and be more costly to implement. In specific, within those strategies, the Opportunity Areas 3.2, Aircraft Repurpose for U.S. Secondary Market and 2.2, All-Electric Short-Range Regional Routes consistently scored high across the board in the "green" for every Scenario. In contrast, Strategy 1 could be achieved in a shorter, more cost-effective timeframe but may not reduce CO2 emissions to the same degree.

Consistently, Strategy 4 lagged in scores compared to the other Strategies, with its highest total score in Strategy 1. This may be due to Strategy 4 including Opportunity Areas that focused on aircraft production and manufacturing processes. When CO2 saved from these processes were aggregated across the entire lifespan of the aircraft, CO2 savings were significantly diluted on a per-flight basis. However, the Opportunity Areas in Strategy 4 both still demonstrate potential CO2 reductions, and other benefits such as future cost savings.

In the “Equal Weighting” Scenario 1, the Opportunity Areas that have higher cost and accessibility scores rank higher than in other Scenarios due to the increased weighting of those Evaluation Factors. The Opportunity Areas that have higher CO2 impact and scalability timeline scores are demoted somewhat as those two Evaluation Factors combine for just 50% of the overall score, whereas in Scenarios 2 and 3 they account for 70% and 100% of the overall score, respectively. This results in Accelerated Replacement of Inefficient Aircraft (with a CO2 emissions reduction score of 9) ranking sixth in Scenario 1, but second in Scenario 3. Similarly, All-Electric Short-Range Regional Routes scored first in Scenario 1 as the only Opportunity Area that increases public accessibility to aviation, an Evaluation Factor that is given 25% weighting in this Scenario. More broadly, Scenario 1 is the only Scenario where Strategy 1 ranks first, as Strategies 2, 3, and 4 have lower Scalability Timeline and Implementation Cost scores.

In the “Preferred” Scenario 2, there was more dispersion between the highest and lowest Opportunity Area scores compared to Scenario 1. (In Scenario 2 the highest Opportunity Area score is 6.6 and the lowest is 3.9, compared to 6 as highest and 4.5 lowest in Scenario 1). Strategy 3 scores the highest in Scenario 2 because there is an increased weight on CO2 impact and a slight decrease in Implementation Cost weightings compared to Scenario 1. Strategy 2 also scores similar, but still slightly lower than Strategy 1. While the dispersion between the overall scores in Strategy 1 and 2 was greater in Scenario 1, as CO2 impact was given more weight, Strategy 2’s overall score increased. This is because Strategy 2’s Opportunity Areas have higher CO2 Impact scores than those of Strategy 1. Strategy 2 notably contains the Opportunity Area with the highest overall CO2 reduction Impact, Electrification of Regional Air Carrier Aircraft Replacements. As emphasis on CO2 Impact and Scalability Timeline increased and Implementation Cost decreased, Strategy 4’s total score decreased.

In the “Carbon Reduction First” Scenario 3, Opportunity Areas show the greatest dispersion, with the highest Opportunity Area score of 7.8 and lowest Opportunity Area score of 2.2. This is due to an emphasis on CO2 impact which boosts Strategies 2 and 3 because they have the highest total CO2 impact scores. Scenario 3 favors Opportunity Areas that display higher CO2 emissions reduction scores, to the extent that Strategy 3 ranks first in this scenario, despite ranking second in Scenario 1. With a 60% CO2 emissions reduction Evaluation Factor weighting, Opportunity Areas such as Aircraft Repurpose for U.S. Secondary Market, Accelerated Replacement of Inefficient Aircraft, and Up-Gauging make up the top 3.

When considering the rankings in the Heat Map Figure, all the Opportunity Areas demonstrate a range of benefits in the Impact Evaluation Factors outlined. In addition, all the rankings and scores are relative to each other, and each of the Opportunity Areas were carefully down-selected over other previous strategies as shown in Appendix C. Therefore, this report’s assessment demonstrates the potential for CO2 reduction savings in almost all the Opportunity Areas—the only exception being AI for contrails, where there may be other tangential benefits of ERF reduction. As a result, every Opportunity Area should be considered and explored because reaching decarbonization goals requires an aggregate and multifaceted approach.

6.0 Summary and Conclusion

Due to growing demand for aviation, emissions from the aviation sector are expected to grow significantly in the next few decades. To reduce the climate impact of aviation, the U.S. has set a climate goal to achieve net-zero CO2 emissions in the U.S aviation sector by 2050. While Sustainable Aviation Fuels (SAF) will likely provide the greatest impact within this timeframe, additional Strategies, and pathways towards decarbonization will also be needed. This effort documents additional strategies that can be used in conjunction with SAFs and carbon offsets to reach net-zero emissions by 2050.

This report explored, assessed, and evaluated multiple strategies and Opportunity Areas that represent areas the industry overall could pursue, and NASA may be able to assist in reaching the U.S. decarbonization goals.

This document included:

- Identification of 3 key emission drivers: Ground Transportation to and From the Airport, Airport and Airline Operations, and In-Flight Emissions.
- Creation of 4 final strategies that provide overarching guidance and topic areas with CO2 emission reduction potential:
    1. Optimization Tools for Flight Operations
    2. Align Aircraft & Airport Technology to Optimized Applications
    3. Optimizing Fleet Modernization & Expansion
    4. Production and Recycling of Aircraft
- The identification and in-depth assessment of 11 potential Opportunity Areas for decarbonization.
    1. AI for Taxiing
    2. AI for Flight Path Optimizations
    3. AI for Reducing Contrails
    4. Electrification of Regional Air Carrier Aircraft Replacements
    5. All-Electric Short-Range Regional Routes
    6. Up-Gauging and Route Frequency
    7. Renewable Energy and Optimizing Airport Emissions
    8. Accelerated Replacement of Inefficient Aircraft
    9. Aircraft Repurpose for U.S. Secondary Market
    10. Additive Manufacturing
    11. Recycled Composite Manufacturing

- Descriptions of sample use cases for each Opportunity Area detailed, and a corresponding estimate of kg CO2 per flight.
- Development of an evaluation and scoring process for four different Evaluation Factors to compare and analyze potential impacts, and feasibility of each Opportunity Area and strategy.
- Creation of three scenarios that assign different weightings to each Evaluation Factor provides a more robust answer at the end that will appeal to a wider range of decision makers with different objective functions, evaluation accuracy, and correct for potential bias.
- Aggregation of total evaluation and scenarios to produce final scores and recommendations.

While not intended to be exhaustive, this report provides a foundation for understanding the potential implementation, feasibility, and impacts of a range of transformational decarbonization strategies for aviation. Throughout the research process, Strategy 3 and 4 results emerged as relative surprises given initial assumptions. Namely, the CO2 emission reduction potential for Strategy 3 surprised researchers, as the aircraft decommission process and significant gap between supply and demand in cargo aircraft was incorporated into the report. Conversely in Strategy 3, the dilution of CO2 emissions saved during manufacturing over the lifespan of the aircraft ranked lower than initially assumed. However, it is worth noting that additional benefits for Strategy 4 could be realized, as reducing the number of aircraft components may accelerate future aircraft production times, if scaled throughout development.

In aggregate, the combination of the strategies discussed in this paper could be explored to create a holistic and cumulative aviation decarbonization effort. This report shows a potential cumulative decrease of -25,229 kg CO2 per flight. Given the average U.S. flight length of 942 miles, a representative full flight from MCI to DCA of 948 miles, carrying 143 passengers emits 28,886 kg CO2e.[126] [127] [128] [129] Thus, all the strategies together would represent a ~87% decrease in emissions per flight compared to the current state. However, these Opportunity Areas could not all be applied to the exact same flight and area based on different use cases. Therefore, this cumulative number will vary significantly based on the circumstances of each use case implementation.

Additionally, the work performed in this report highlights, when applicable, NASA's past and current research with an emphasis on emerging aviation technologies such as contrails, taxiing, Regional Electrification, Regional Air Mobility (RAM), and composite materials.

The following Table 34 provides an overview of potential next steps for NASA. Note, this table is structured in the numerical order that Opportunity Areas appear in the document and should not be understood as a ranking order.

Table 34: Recommendations by Opportunity Area for Future Research

#	Opportunity Area	NASA Research Recommendations
1.1	AI for Taxiing	➢ Determine how multiple AI programs, such as one for departing aircraft (such as NASA's ATD-2 program) and one for arriving aircraft (such as the Intelligent Gating Program), could be used in tandem for maximum benefit.
1.2	AI for Flight Path Optimizations	➢ Evaluate how AI in-flight programs work together if implemented by multiple airlines including the implications on Air Traffic Management (ATM) and safe separation.
1.3	AI for Reducing Contrails	➢ Examine the tradeoff between savings in net surface warming achieved by avoiding contrails versus the increased CO2 needed to avoid them. ➢ Examine impacts to ATM to ensure safe separation.
2.1	Electrification of Regional Air Carrier Aircraft Replacements	➢ Continue to develop component technologies for these aircraft, which could include more demonstrator aircraft. ➢ Study airspace and operational concepts that can enable higher capacity at large hub airports (which may get strained if demand goes up for these electrified aircraft if operating costs are reduced as predicted). ➢ Develop aircraft concepts (similar to PEGASUS) that consider both updated component technologies in aircraft and operational concepts to maximize benefits of hybrid-electric aircraft.
2.2	All-Electric Short-Range Regional Routes	➢ Continue development of electric aircraft, such as advancing modeling tools to handle electrical components or advancing the TRL of electric components.
2.2	Up-Gauging and Route Frequency	➢ Examine changes in air traffic management needs or changes in the hub-and-spoke system (e.g., reducing # of flights enable more smaller aircraft to come into capacity constrained airports).
2.3	Renewable Energy and Optimizing Airport Emissions	➢ Research Digital Twins and other optimization tools that could be used to develop a sustainability system that could be applied to more airports.
3.1	Accelerated Replacement of Inefficient Aircraft	➢ Develop a tool that helps airlines and industry make more holistic decisions that consider the downstream impacts of the entire decommission and repurpose journey.
3.2	Aircraft Repurpose for U.S. Secondary Market	➢ Examine the current incentives and factors at play that govern decommissioning and destination decisions. Understand the upstream factors leading to current state.
4.1	Additive Manufacturing	➢ Examine advancing AM processes, enabling higher strength and (repeatably) higher quality parts.

4.2	Recycled Composite Manufacturing	➢ Explore enhancing processes to extract the carbon fiber with even less carbon emitted. ➢ Explore developing aircraft parts that can more easily be recycled after their useful life.

The authors gratefully acknowledge the guidance, support, and contributions of NASA's Contracting Officer's Representative (COR), Nancy Mendonca, and Technical Monitor, Dr. Lee Kohlman, and others within NASA working to advance the mission of aviation sustainability.

7.0 Appendix A: Carbon Impact Calculations

For each CO2 per flight calculation, please note the following:

1) Each per flight metric is linked to the specific use case, can vary, and cannot be extrapolated to larger scopes than the use case without major assumptions.
2) The per flight metric should not be understood as a marginal rate, but rather a representation of the average change of kg CO2 over the number of flights in the applicable use case period, to best compare Opportunity Areas.
3) The purpose of each calculation is to provide a comparison point amongst other use cases.
4) When calculating CO2 emission reductions, the conversion factor of 1 gallon jet fuel equating to 9.58333 kg CO2 was used based on the use case of Alaska Airlines using Flyways AI [30]

7.1: Strategy 1 Calculations

Below are the CO2 impact calculations for Strategy 1.

7.1.1: AI for Taxiing

Figure 8: AI For Taxiing Calculation

Use Case: Intelligent Gating Program: American Airlines at DFW	
Numbers in Use Case	• American Airlines saved 870,000 gallons of fuel using the Intelligent Gating Program at DFW[25]
Additional Numbers Researched *(with Sources)*	• In 2022, American Airlines at DFW had 161,987 flights and 34,340,052 passengers[130] • 1 gallon jet fuel = 9.58333 kg CO2[30] ○ Calculated from 480,000 gallons of jet fuel equating to 4,600 Mt CO2 emissions
Assumptions	• The fuel savings per flight is an average, realizing some flights yield more or less fuel savings than others
Calculation: 870,000 gallons of jet fuel saved * 9.58333 kg CO2 = 8,337,497 kg CO2 saved 8,337,497 kg CO2 saved / 161,987 flights = 51.47 kg CO2 Per passenger reference: 8,337,497 kg CO2 saved / 24,340,053 passengers = 0.34 kg CO2 per passenger	
Δ kg CO2 per Flight	**-51.47 kg CO2**

7.1.2: AI for Flight Path Optimizations

Figure 9: AI For Flight Path Optimizations Calculation

Use Case: Flyways AI for Flight Path Optimizations	
Numbers in Use Case	• 6-month pilot program in 2020 saved 480,000 gallons of jet fuel and avoided 4,600,000 kg CO2 emissions[30]
Additional Numbers Researched *(with Sources)*	• In 2020, Alaska Airlines had 141,931 flights[130]**Error! Bookmark not defined.**
Assumptions	• The 6-month pilot program could be doubled to estimate the whole year • The savings is on average per flight, realizing some flights have yield more or less fuel savings
Calculation: 4,600,000 kg CO2 emissions * 2 = 9,200,000 kg CO2 emissions/year 9,200,000 kg CO2 emissions / 141,931 flights = 64.82 kg CO2	
Δ kg CO2 per Flight	-**64.82 kg CO2**

7.1.3: AI for Reducing Contrails

Figure 10: AI For Reducing Contrails Calculation

Use Case: American Airlines, Google Flights, and Breakthrough Energy Contrails Avoidance	
Numbers in Use Case	• A 0.3% increase in fuel per flight (across all flights) was used to avoid contrails across their fleet[38]
Additional Numbers Researched *(with Sources)*	• There was a total of 1,050,867 AA flights in 2022[130] • AA used 3,901 million gallon of jet fuel in 2022**Error! Bookmark not defined.** • 3,901 million = 3.9 billion gallons jet fuel in 2022
Assumptions	• Using numbers for 2022 • The pilot program to avoid contrails is implemented fleet wide • The fuel change is applied on average across all flights
Calculation: 3.9 billion gallons jet fuel used total for AA *1.003 increase in fuel usage to avoid contrails **= 11,703,000-gallon increase in jet fuel** $\frac{11,703,000\ gallons}{1,050,867\ total\ AA\ flights\ 2022} = 11.14\ increase\ gallons\ of\ jet\ fuel\ per\ flight$ 11.14 * .00958333 = 0.106758 Mt increase in CO2 → **106.76 kg increase CO2 per flight**	
Δ kg CO2 per Flight	**+106.76 kg CO2**

7.2: Strategy 2 Calculations

Below are the CO2 impact calculations for Strategy 2.

7.2.1: Electrification of Regional Air Carrier Aircraft Replacements

Figure 11: Electrification of Regional Air Carrier Aircraft Replacements Calculation

Use Case: Average Regional Air Carrier Flight with Embraer 175	
Numbers in Use Case	• A hybrid-electric flight based on PEGASUS uses 60% electric power and 40% carbon neutral fuel[55]
Additional Numbers Researched	• 494 mile flight distance from Salt Lake City, UT (SLC) → Albuquerque, NM (ABQ) is representative of the average regional air carrier flight distance of 500 miles.[59]
Assumptions	• The hybrid-electric flight will leverage fully carbon neutral SAF, for 40% of its energy consumption, by 2050. • The 60% electric power will produce zero operational emissions and is based on a fully sustainable electricity source, by 2050.
Calculation: 173 kg CO2 * 76 passengers = 13,148 kg CO2 per flight	
Δ kg CO2 per Flight	**-13,148 kg CO2**

7.2.2: All-Electric Short-Range Regional Routes

Figure 12: Electrification of Regional Routes Calculation

Use Case: Comparable Regional Flight: Cape Air	
Numbers in Use Case	Electrified regional flights are generally envisioned to: • Have up to 9 passengers if operating scheduled passenger service out of airports.[131] • Demonstrate approx. a 150-mile range, up to 190 miles, so far.[72] A comparable regional flight was selected to provide a sense of the scale of potential emissions reduction. Generally, aligns with a: • Cape Air regional route.
Additional Numbers Researched	• 175 miles flight distance of Cyril E. King Airport (STT), St. Thomas → Vance W. Amory International Airport (NEV), Nevis, (falls in this estimated electrified regional range bracket.)[63] • 945 kg CO2 emitted per Cessna 402 flight on STT to NEV route.[xxiv] • Electrified regional aircraft produces zero operational emissions produced from their aircraft.
Assumptions	• Electrified regional aircraft is powered by full electric propulsion. • Numbers for the sample comparable flight may vary based on route/distance, the Cape Air flight represents one of the flights that could be replaced with an electrified regional aircraft. Although it may fly different routes, etc. the model and distance match electrified regional aircraft estimated market entry. • By the time that electrified regional flights are operational, airports will have shifted towards increasingly renewable and sustainable energy sources to power electrified regional flights.
Calculation: **945 kg CO2** total produced per regional flight– **0** operational emissions produced in an electrified regional flight = 945kg CO2 saved/flight	
Δ kg CO2 per Flight	**-945 kg CO2**

[xxiv] Based on 105 kg Co2 emitted per passenger, for a Cape Air Cessna 402 that carries 9 passengers.

7.2.3: Up-Gauging and Route Frequency

Figure 13: Up-Gauging and Route Frequency Calculation

<table>
<tr><th colspan="2">Use Case: Potential Up-Gauging from Narrow-body to Wide-body on Popular Short MCO→ATL Delta Route</th></tr>
<tr><td>Numbers in Use Case</td><td>Delta runs 16 flights from Orlando International Airport, (MCO)→ to Hartsfield-Jackson Atlanta International Airport, (ATL) per day[79]
13 of these flights with 757-200 narrow-body aircraft emit 14,820 kg CO2 per 757 flight, and 192,660 kg CO2 total per day. [xxv]
3 of these flights with 767-300 ER wide-body aircraft, emits 14,464 kg CO2/wide-body flight, and 43,392 kg CO2 total per day.[xxvi]</td></tr>
<tr><td>Additional Numbers Researched</td><td>A total of 3148 passengers' capacity on this route per day.[xxvii]</td></tr>
<tr><td>Assumptions</td><td>Number of flights data from October 2023.
Delta is flying 757-200s and 767 300 ERs.[xxviii]
When up-gauging, passenger capacity remains the same.</td></tr>
<tr><td colspan="2">Calculation:

Total emitted on day, with current status quo=192,660 kg CO2 per day + 43,392 kg CO2 = 235,784 kg CO2 for this route per day.

3148 total pax/226 pax on wide-body=13.929 ~14 wide-body flights per day needed to carry same number of pax if up-gauged.

Total wide-body emissions per flight (14,464 kg CO2) *(14 flights per day) =202,496 kg CO2 total per day with up-gauged strategy.

235,784kg CO2-202,496kg CO2=33,288 kg CO2 saved per day.

Step 2: Calculation of Saved Per Flight:

$$\frac{33,288 kg\ CO2\ saved\ per\ 1\ day\ up\ gauging}{(16\ flights\ original)} = 2080.5\ kg\ CO2\ saved/flight$$</td></tr>
<tr><td>Δ kg CO2 per Flight</td><td>-2080.5 kg CO2</td></tr>
</table>

[xxv] 13 flights are run with 757-200 narrow-body aircraft, emits 78 kg CO2 per passenger, Narrow-body emissions for 1 flight: (78 kg CO2 pp) *(190 seats) = 14,820 kg CO2 total/flight.

[xxvi] Wide-body emissions for 1 flight: (226 pax) * (64 kg CO2) = 14,464 kg CO2/wide-body flight
Wide-body emissions for all flights in day: 14,464 kg CO2/ flight *3 times a day run= 43,392 kg CO2 from 767-300 ER per day.

[xxvii] Calculated from: The 757-200 (Narrow) Delta configuration has 190 seats and the 767-300 ER Delta Configuration on this route has 226 seats. Total passenger count= (190*13) = (226*3) = 3148 pax total on this route per day.

[xxviii] As of December 2023, Delta has 100 757-200s in their fleet and 16 757 300s in their fleet. Assumption that they are running the 757-200s, even if occasionally a 300 may be used.

7.2.4: Renewable Energy and Optimizing Airport Emissions

Figure 14: Renewable Energy and Optimizing Airport Emissions Calculation

Use Case: Dallas Fort Worth (DFW) International Airport Decarbonization	
Numbers in Use Case	• In 2022, DFW saved a total of 109,099,000 kg CO2e [84]
Additional Numbers Researched	• In 2022, there were 306,663 total DFW passenger carrying flights. [130] *(This number includes both U.S. and international air carriers. This does not include cargo flights.)*
Assumptions	• Examines only 2022. • The total kg CO2e saved by DFW includes both fixed and variable energy, but for the purpose of the calculation, the total CO2e number is considered as a fixed energy. • The CO2 produced by airport is evenly distributed between flights. • Considers CO2e, based on data available from DFW.
Calculation: $\frac{\mathbf{109{,}009{,}000}\ \boldsymbol{Kt\ CO2e\ DFW\ saved\ in}\ \mathbf{2022}}{(\mathbf{306{,}663}\ \boldsymbol{DFW\ flights\ in}\ \mathbf{2022})} = \mathbf{355.76\ kg\ Co2}\ *$	
Δ kg CO2 per Flight	**-355.76 kg Co2**

7.3: Strategy 3 Calculations

7.3.1: Accelerated Replacement of Inefficient Aircraft

Figure 15: Accelerated Replacement of Inefficient Aircraft Calculation

Use Case: United Airlines Replacing Older Aircraft with New Aircraft	
Numbers in Use Case	• United Airlines expects a 17-20% reduction in CO2 emissions per seat by replacing older, smaller mainline aircraft and about 200 regional aircraft with 200 Boeing 737 MAX and 70 Airbus A321neo aircraft that were ordered in 2021[103]
Additional Numbers Researched	• In 2022, United had 774,827 flights and 30,400,715,000 kg CO2e emissions [103] [130]
Assumptions	• The effects of the aircraft ordered in 2021 could be studied using 2022's data (the most recent available) • The flights are full • The amount of CO2 saved is per flight that is replaced
Calculation: 30,400,715,000 kg CO2e emissions * .17 savings = 5,168,122,000 kg CO2e emissions savings 5,168,122 CO2e savings / 774,827 flights = 6670.03 kg / flight	
Δ kg CO2 per Flight	**-6670.03 kg CO2**

7.3.2: Aircraft Repurpose for U.S. Secondary Market

Figure 16: Aircraft Repurpose for U.S. Secondary Market Calculation

Use Case: American Airlines Passenger Fleet	
Numbers in Use Case	• In 2020, American Airlines sold 36 aircraft to the cargo fleet at an average age of 18.5 years[105]
Additional Numbers Researched	• Each generation of aircraft is about 17% more fuel efficient[10] • 15.3 years is the average time between the generations of the B737 (Original, Classic, NG, MAX) [132] • The average age of the cargo fleet is 21.9 years[i] • The oldest planes in the UPS fleet are the 75 B757-200s at 30.1 years[i] • UPS consumed 1,101,171,000 gallons of fuel in 2022[133] • UPS averages 1950 daily flights (711,750 / year)[134]
Assumptions	
Calculation: 36 aircraft were retired from the UPS fleet at 30.1 years and replaced with 36 aircraft at 18.5 years The average age on these 36 aircraft decreased 30.1 – 18.5 = 11.6 years 17% more fuel efficient / 15.3 years = 1.11% more efficient / year 11.6 years * .0111 = 12.88% more efficient 1,101,171,000 gallons of fuel / 711,750 flights = 1547 gallons fuel burned / flight 1547 gallons fuel * .1288 = 199.25 gallons fuel saved/flight 199.25 fuel saved * 9.5833 = 1,909.51 kg CO2	
Δ kg CO2 per Flight	**-1909.51 kg CO2**

[i]Calculated from the 10Ks of FedEx, UPS, and DHL, as well as planespotters.net when the information was not in the 10Ks

7.4: Strategy 4 Calculations

7.4.1: Additive Manufacturing

Figure 17: Additive Manufacturing Calculation

<table>
<tr><th colspan="2">Use Case: Additive Manufacturing Part Replaceable Empty Aircraft Mass Estimates</th></tr>
<tr><td>Numbers in Use Case</td><td>• Aircraft fuel consumption could be reduced by as much as 6.4% by replacing feasible parts with lighter AM components.[115]</td></tr>
<tr><td>Additional Numbers Researched</td><td>• In 2022, according to BTS 11,441.3 Consumption (million gallons) were consumed domestically for scheduled services.[133]
• In 2022 there were 7,421,585 domestic flights for U.S. carriers. [130]</td></tr>
<tr><td>Assumptions</td><td>• Uses the max estimate of 6.4%
• Numbers for 2022
• AM parts currently in aircraft are not adjusted for.</td></tr>
<tr><td colspan="2">Calculation:
(11441.3 million gallons fuel consumed in 2022) *0.064 = 732.24 million gallons saving per year

$$\frac{\mathbf{732,240,000}\ \boldsymbol{domestic\ gallons\ saved\ per\ year}}{\mathbf{7,421,585}\ \boldsymbol{domestic\ flights\ per\ year}} = \mathbf{9.866}\ \boldsymbol{gallons\ saved\ per\ flight}$$

(1 gallon jet fuel = 9.58333 kg CO2)
(9.58333 kg CO2) * (9.866 gallons saved) =94.55 kg CO2 saved per flight</td></tr>
<tr><td>Δ kg CO2 per Flight</td><td>-94.55 kg CO2</td></tr>
</table>

7.4.2: Recycled Composite Manufacturing

Figure 18: Recycled Composite Manufacturing Calculation

Use Case: Using Recycled Carbon Fiber in the B787 Dreamliner	
Numbers in Use Case	• The B787 Dreamliner is designed to have 44,000 average flight cycles[29]
Additional Numbers Researched	• One ton of virgin carbon fiber releases 29,450 kg CO2 in production[135] • One ton of recycled carbon fiber releases 4,650 kg CO2 in production[135] • The B787 Dreamliner is made with 23 tons of carbon fiber[136]
Assumptions	• The B787 Dreamliner is currently not made with any recycled carbon fiber • The B787 Dreamliner has 44,000 average flights in its lifetime
Calculation: Virgin carbon fiber: 29,450 kg CO2 * 23 tons carbon fiber = 677,350 kg CO2 Recycled carbon fiber: 4,650 kg CO2 * 23 tons carbon fiber = 106,950 kg CO2 677,350 – 106,950 = 570,400 kg CO2 saved using recycled carbon fiber 570,400 kg CO2 / 44,000 flights = 12.96 kg CO2	
Δ kg CO2 per Flight	**-12.96 kg CO2**

8.0 Appendix B: Scenario Analysis Applied Weightings Calculations

Table 35: Scenario 1 Weightings Applied to Opportunity Areas

Strategy	Opportunity Area	Carbon Weighting (25%)	Scalability Timeline Weighting (25%)	Cost Weighting (25%)	Accessibility Weighting (25%)	O.A. Score for Scenario 1
1	AI for Taxiing	3*.25=.75	9*.25=2.25	6*.25=1.5	6*.25=1.5	**6.0**
1	AI for Flight Path Optimizations	3*.25=.75	9*.25=2.25	6*.25=1.5	6*.25=1.5	**6.0**
1	AI for Reducing Contrails	1*.25=.25	9*.25=2.25	6*.25=1.5	6*.25=1.5	**5.5**
Total Strategy Average Score: 17.5/3 = 5.83						
2	Electrification of Regional Route Replacements	9*.25=2.25	1*.25=.25	3*.25=.75	6*.25=1.5	**4.75**
2	All-Electric Short-Range Regional Routes	6*.25=1.5	6*.25=1.5	3*.25=.75	9*.25=2.25	**6.0**
2	Up-Gauging and Route Frequency	9*.25=2.25	3*.25=.75	3*.25=.75	3*.25=.75	**4.5**
2	Renewable Energy and Optimizing Airport Emissions	6*.25=1.5	6*.25=1.5	1*.25=.25	6*.25=1.5	**4.75**
Total Strategy Average Score: 20/4 = 5.0						
3	Accelerated Replacement of Inefficient Aircraft	9*.25=2.25	3*.25=.75	3*.25=.75	6*.25=1.5	**5.25**
3	Aircraft Repurpose for U.S. Secondary Market	9*.25=2.25	6*.25=1.5	3*.25=.75	6*.25=1.5	**6.0**
Total Strategy Average Score: 11.25/2 = 5.625						

4	Additive Manufacturing	3*.25=.75	6*.25=1.5	3*.25=.75	6*.25=1.5	**4.5**
4	Recycled Composite Manufacturing	3*.25=.75	1*.25=.25	9*.25=2.25	6*.25=1.5	**4.75**
Total Strategy Average Score: 9.25/2 = 4.63						

Table 36: Scenario 2 Weightings Applied to Opportunity Areas

Strategy	Opportunity Area	Carbon Weighting (40%)	Scalability Timeline Weighting (30%)	Cost Weighting (20%)	Accessibility Weighting (10%)	O.A. Score for Scenario 2
1	AI for Taxiing	3*.4=1.2	9*.3=2.7	6*.2=1.2	6*.1=0.6	**5.7**
1	AI for Flight Path Optimizations	3*.4=1.2	9*.3=2.7	6*.2=1.2	6*.1=0.6	**5.7**
1	AI for Reducing Contrails	1*.4=0.4	9*.3=2.7	6*.2=1.2	6*.1=0.6	**4.9**
Total Strategy Average Score: 16.3/3 = 5.43						
2	Electrification of Regional Air Carrier Aircraft Replacements	9*.4=3.6	1*.3=.3	3*.2=0.6	6*.1=0.6	**5.1**
2	All Electric Short-Range Regional Routes	6*.4=2.4	6*.3=1.8	3*.2=0.6	9*.1=0.9	**5.7**
2	Up-Gauging and Route Frequency	9*.4=3.6	3*.3=0.9	3*.2=0.6	3*.1=0.3	**5.4**
2	Renewable Energy and Optimizing Airport Emissions	6*.4=2.4	6*.3=1.8	1*.2=0.2	6*.1=0.6	**5.0**
Total Strategy Average Score: 21.2/4 = 5.3						
3	Accelerated Replacement of Inefficient Aircraft	9*.4=3.6	3*.3=0.9	3*.2=0.6	6*.1=0.6	**5.7**

3	Aircraft Repurpose for U.S. Secondary Market	9*.4=3.6	6*.3=1.8	3*.2=0.6	6*.1=0.6	**6.6**
Total Strategy Average Score: 12.3/2= 6.15						
4	Additive Manufacturing	3*.4=1.2	6*.3=1.8	3*.2=0.6	6*.1=0.6	**4.2**
4	Recycled Composite Manufacturing	3*.4=1.2	1*.3=0.3	9*.2=1.8	6*.1=0.6	**3.9**
Total Strategy Average Score: 8.1/2= 4.05						

Table 37: Scenario 3 Weightings Applied to Opportunity Areas

Strategy	Opportunity Area	Carbon Weighting (60%)	Scalability Timeline (40%)	Cost Weighting (0%)	Accessibility Weighting (0%)	O.A. Score for Scenario 3
1	AI for Taxiing	3*.6=1.8	9*.4=3.6	0	0	**5.4**
1	AI for Flight Path Optimizations	3*.6=1.8	9*.4=3.6	0	0	**5.4**
1	AI for Reducing Contrails	1*.6=.6	9*.4=3.6	0	0	**4.2**
Total Strategy Average Score: 15/3=5						
2	Electrification of Regional Air Carrier Aircraft Replacements	9*.6=5.4	1*.4=.4	0	0	**5.8**
2	All Electric Short-Range Regional Routes	6*.6=3.6	6*.4=2.4	0	0	**6.0**
2	Up-Gauging and Route Frequency	9*.6=5.4	3*.4=1.2	0	0	**6.6**
2	Renewable Energy and Optimizing Airport Emissions	6*.6=3.6	6*.4=2.4	0	0	**6.0**
Total Strategy Average Score: 24.4/4 = 6.1						

3	Accelerated Replacement of Inefficient Aircraft	9*.6=5.4	3*.4=1.2	0	0	**6.6**
3	Aircraft Repurpose for U.S. Secondary Market	9*.6=5.4	6*.4=2.4	0	0	**7.8**
Total Strategy Average Score: 14.4/2=7.2						
4	Additive Manufacturing	3*.6=1.8	6*.4=2.4	0	0	**4.2**
4	Recycled Composite Manufacturing	3*.6=1.8	1*.4=.4	0	0	**2.2**
Total Strategy Average Score: 6.4/2=3.2						

9.0 Appendix C: Original 27 Strategies

1. **Alternative fuels for commercial fleet** - Accelerated introduction of other alternative fuels into the commercial aircraft fleet (particularly the single-aisle class), such as liquid hydrogen, liquid natural gas, and ammonia.
2. **Circular economy approach to aircraft production and use** - Adopting a circular economy approach to aircraft production and use by leveraging advanced remanufacturing, recycling, and digital twin simulation technologies.
3. **Cruise speed reductions** - Alternative operations, such as cruise speed reductions on all or strategic routes, assessing travel time and fuel savings for the existing fleet and for "optimized" fleet redesigned for slower cruise.
4. **Designing optimized routes** - Designing and implementing additional optimized routes, including Optimized Profile Descents (OPDs), Continuous Climb and Descent Operations (CCO and CDO) and formation flying.
5. **Develop new efficient aircraft production technologies** - Development of new aircraft production technologies that are significantly more efficient including additive manufacturing, additional use of light-weight composites, and the use of advanced coatings.
6. **Leverage Artificial Intelligence (AI)** - Leveraging of Artificial Intelligence and Machine Learning tools to perform data collection, aggregation, and analysis for weather conditions, flight conditions, aircraft taxiing, surface vehicle management, and other applications.
7. **Leverage smaller electrified transports** - Leveraging smaller electrified transports that use more direct-flight routes (not the same as Regional Air Mobility).
8. **Optimize historical flight routes** - Development of new tools to analyze airlines historical flight routes and operations to identify trends and flight efficiency factors.
9. **Re-map hub and spoke system** - Re-mapping of the hub-and-spoke system to reduce the overall number of flights while still meeting passenger demand.
10. **Retirement of non-SAF aircraft** - Development of regulations to accelerate the retirement of older aircraft that can't support "neat" SAF.
11. **Up-gauging aircraft size and reducing frequency** - Up-gauging aircraft size and reducing the number of flights on certain routes.
12. **Airport renewable energy** - Accelerating the adoption of local renewable electricity for heating and cooling of airport facilities and RNG or electricity for fueling of ground vehicles at the airport.
13. **ATM regulatory requirements for more efficient flight paths** - Development of ATM regulatory requirements for significantly more efficient flight paths.

14. **Develop efficient aircraft designs** - Development of aircraft designs that are significantly more efficient, such as the Transonic Truss Braced Wing (TTBW) concept.
15. **Develop efficient aircraft technologies** - Development of aircraft technologies that are significantly more efficient, such as open fan engine technology, SMARTWING, and enhanced hybrid laminar flow.
16. **Develop zero emission plane technology** - Development of Zero Emission Planes technology, including hydrogen, hybrid-hydrogen, and electric propulsion.
17. **Electric vehicles and infrastructure at airports** - Accelerating the adoption of electric vehicles and required infrastructure at airports to reduce traveler dependency on gas-powered vehicles.
18. **Federal SAF blending mandate** - Accelerating the production, deployment, and use of SAF by developing a federal SAF Blending Mandate for Airlines.
19. **Ground transportation batteries** - Use of significantly more sustainable vehicle technologies including alternative battery materials and charging systems for individual ground transportation.
20. **Invest in carbon offsets** - Supporting large investments in effective carbon offsets, such as direct air capture, for aviation.
21. **Investments in U.S. renewable energy grid** - Support large investments in the U.S. energy grid to accelerate the implementation of renewable energy projects.
22. **Low Carbon Fuel standard** - Development of nationwide Low Carbon Fuel Standard for aviation.
23. **Standard climate-fuel metric** - Development of a standard climate/fuel burn metric to recognize and measure emissions reductions performance.
24. **Regulation for amount of SAF produced by jet fuel producers** - Development of regulation outlining a required amount of SAF to be produced by jet fuel producers.
25. **SAF adoption for alternate stakeholder groups** - Accelerated introduction of SAF adoption for alternative stakeholder groups such as DOD, helicopter operations, and others.
26. **SAF Whole Life Cycle system** - Development of an SAF Whole Life Cycle (WLC) system for public authorities to better account for infrastructure and fuel management projects and operations.
27. **Sustainable multimodal transportation network** - Use of other transportation modes (where more efficient/sustainable) that tie into the air transportation network.

10.0 Assumptions

This report makes high-level assumptions that will be used throughout the document, as well as assumptions that are specific to a certain use case in the document. The high-level assumptions will be discussed here, while the specific assumptions are in the appendix. The assumptions below are organized by their respective sections.

Overview Assumptions

- This report assumes that carbon offsets and SAF will continue to be adopted over time.
- Primarily carbon is used in titles and headings and CO2 is used in body text, but these terms are considered synonymous.

In-Depth Assessment Assumptions

- Each Opportunity Area includes a unique use case describing the realistic potential of implementation of the Opportunity Area. This use case can be replicated by other entities to achieve CO2 reductions; however, these impacts may vary by implementation circumstance. Because of this, the "binning" approach to scoring is used, where it is assumed that the particular use case will result in the correct representative "bin."

Evaluation Assumptions

- The CO2 emissions number for each Opportunity Area is inherently connected to the individual use case. For example, there may be use cases that may produce greater or less CO2 impact.
- The CO2 per flight is a calculation represents the CO2 increase or reduction based on the average number of flights for the use case, not a marginal rate.
- Once a technology is implemented and scales beyond early adopters, it will continue to grow and be scaled.
- Implementation cost may be passed down to the end consumer.
- While the exact total implementation cost of a future technology is unknown, based on informed estimates and current research the general magnitude and increase or decrease compared to current cost was captured.
- Accessibility examined the end state of Opportunity Area implementation. The short-term rollout of these technologies, such as construction time, may have an impact on accessibility, but the time the use case reaches its "scaled" point is when the accessibility was captured.

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