Estimations of Aircraft and Airport Domestic Greenhouse Gas Emissions from 2016-2021

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Data and analyses are presented on the utilization of aircraft fuel in the U.S. and the resulting greenhouse gas emissions. Commercial passenger and freight flight data and airport fuel consumption usage from 2016-2021 are captured from the Bureau of Transportation Statistics website and the Sherlock Data Warehouse at NASA Ames. The resulting dataset is used to determine the miles flown by major aircraft. The corresponding aircraft fuel burn is estimated based on the International Civilian Aviation Organization fuel burn tables, and carbon dioxide emissions are calculated using a fuel-burn multiplicative factor. One conclusion of this analysis is that long-haul flights (flight distances > 2485 statute miles) create a disproportionately large amount of carbon dioxide emissions in the U.S, while short flights (< 311 statute miles) contribute less than five percent of the U.S. aviation-related carbon dioxide emissions. Although these short-haul flights may not have a large impact on overall carbon dioxide emissions, they will be valuable as demonstration missions for the next generation of electric, hybrid, and hydrogen-powered vehicles and their supporting energy infrastructures. This paper discusses recent trends in short-haul missions, their associated aircraft and airport types, and extracts several key requirements for future short-haul vehicles.

I. Introduction

On November 9, 2021, the Federal Aviation Administration (FAA) published the United States 2021 Aviation Climate Action Plan [1]. The stated goal of this government-wide plan is to achieve net-zero life cycle greenhouse gas (GHG) emissions from aviation in the United States by 2050 in order to avoid irreversible and potentially catastrophic climate change. Although aviation accounts for a relatively small portion of GHG emissions, (currently 1.9% of the total CO_2 emitted and 3.5% effective GHG when accounting for contrails) global aviation GHG emissions are projected to triple by 2050 [1].

The FAA plan is a policy framework with government and industry goals and actions. In the near-term, the plan anticipates GHG reductions through aircraft efficiency improvements and greater use of sustainable drop-in jet fuels. In the far term, advanced technologies such as cryogenic hydrogen-fueled, electric and electric-hybrid aircraft are encouraged but are not expected to have an impact on GHG until after 2050. Paths to net zero GHG will require major reworking of the national aviation and energy infrastructure at great cost. Achieving net zero GHG (i.e. eliminating fossil fuels) from aviation by 2050 is an ambitious goal, but the odds improve if decisions are guided by science and data.

The original motivation for studying aircraft utilization and CO_2 emissions is a surprising result published by EUROCONTROL [2], the main European flight safety and support intergovernmental organization, that shows long-haul flights are disproportionately large contributors to GHG (see Figure 1). Presented in Figure 1 are the number of European departures in 2020 (left bar) and their corresponding CO_2 emissions contributions (right bar). The data for each bar is segregated into four distance bins. The chart shows that more than half of European aviation's CO_2 emissions were emitted from just 6.2% of the flights. The data also indicates that 31% of the flights, with distance less than 500 km, accounted for only 4% of the emissions. The EUROCONTROL authors rightly see this situation as somewhat of a dilemma: while short-haul flights are those most likely to be successfully electrified, complete electrification of these flights using today's technology would reduce total emissions by not much more than 4%. The EUROCONTROL authors concluded that increasing the supply of sustainable aviation fuels to cover just 10% of the long-haul flights would be more impactful on emissions reductions than complete electrification of the entirety of short-haul flights.

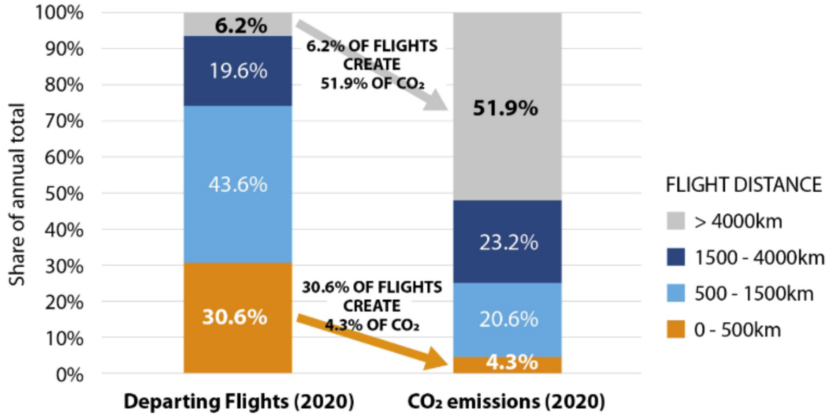

Figure 1. European flight data and aviation emissions estimates for 2020 (adapted from [2]).

A previous study by the authors [3] confirmed that similar trends generally held for 2020 U.S. departing flights. Additional insights into the U.S. flight patterns and emissions data were made using the flight data aggregated in the NASA Ames Sherlock Data Warehouse [4] and ICAO fuel consumption models [5] in reference [3]. To conform to the EUROCONTROL study, all departures of passenger and cargo flights from U.S. airports were identified and used for the emissions calculations using the simplified ICAO distance-based fuel calculations described in Reference [4]. In reference [3], several detailed inputs and operational considerations such as passenger load factors, airline seat layouts, taxi distances, indirect routings, engine sub-models, mail and cargo, etc., were not accounted for in the fuel consumption estimates, as this data were not generally available for each flight. Final carbon dioxide emissions were then calculated assuming that 3.16 lb of CO_2 are produced for each pound of fuel consumed.

In the current study, the Sherlock datasets are augmented with additional data reported by the Bureau of Transportation Statistics (BTS) [6]. The BTS data is mined to determine flight patterns and airport fuel consumption to gain a deeper understanding of fuel usage by aircraft type and airports, particularly for the regional jet (RJ) market, where introduction of new technologies like electrified aircraft propulsion will likely occur. We include all commercial passenger and cargo flights with a U.S. departure airport, traveling to any destination, domestic or international, by all carriers. Use of jet fuel by the military (U.S. Air Force alone consumes about 14% of the nation's aviation fuel supply as estimated using BTS data) is not included in the current analysis.

There are a couple of notable similar studies. Zeng and Rutherford [7] study the fuel use of commercial jet aircraft from 1960 to 2019. Their results showed that despite aircraft fuel efficiency increasing by a factor of two since 1960, aviation CO_2 emissions continue to increase because of the substantial growth of aviation. Quadros et al. [8] derived global civil aviation emissions estimates based on Automatic Dependent Surveillance–Broadcast (ADS-B) data coupled with a fuel use model to show that the majority of aviation fuel is consumed in North America, Europe and along the Pacific Rim. Seymour et al. [9] presented a high-fidelity fuel use and CO_2 emission estimation methodology that was validated against airline fuel consumption reports for 133 aircraft models. These studies along with the current study show that reaching net-zero GHG in the aviation sector is a daunting challenge exacerbated by the ever-increasing demand for air travel.

II. Recent U.S. Flight Trends

A. U.S. and European Departure and Emissions Comparisons

Shown in Figure 2 are the similarities and differences between the 2020 European and U.S. flight emissions. As in Europe, the majority of U.S. flights range between 500 and 4000 km (the light and dark blue layers), and the fractions of emissions produced by the shortest flights (orange layers) are very similar. Our calculations indicate that nearly one-third of the U.S. aviation CO_2 contribution comes from a relatively small number of long flights (grey layers), and a disproportionally small amount of CO_2 comes from a relatively large number of short flights (orange layers). Some differences include a smaller proportion of the longest U.S. flights compared to that from the EUROCONTROL data (~4% versus ~6%), with the emissions contribution scaling similarly (~30% versus ~50%). The other significant difference is that the largest portion of the U.S. emissions is produced by the longer flights under 4000 km (the dark blue layers), not the over 4000 km (grey layers) as in the EUROCONTROL data.

Flight Distance in Statute Miles	Flight Distance in km
> 2485	> 4000
932 - 2485	1500 - 4000
311 - 932	500 - 1500
0 - 311	0 – 500

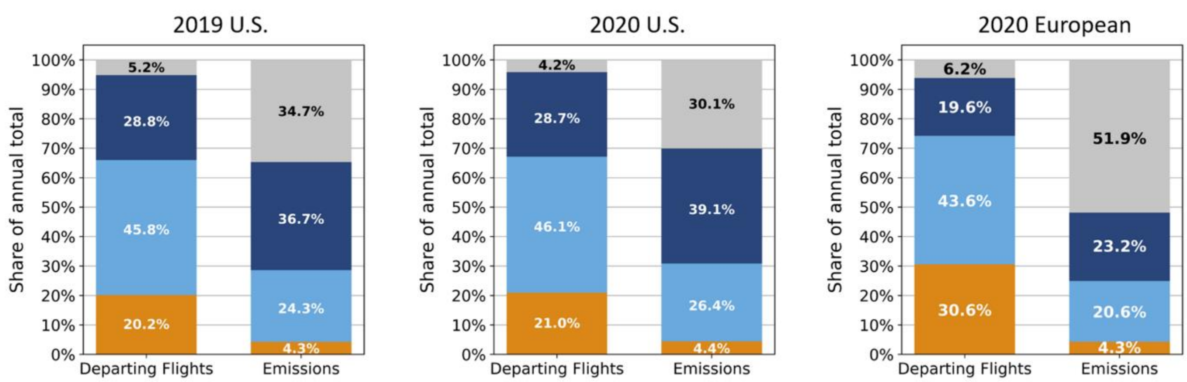

Figure 2. Comparison of 2019 and 2020 U.S. and European departure and emission data.

Pre-pandemic (from 2016 to 2019) flight patterns in the U.S. showed similar flight trends, with the long-haul flights dominating the total fuel used. A decrease in the number of long-haul flights (grey slice) can be seen in the 2020 data, dropping roughly 1% as compared to the number of long-haul flights between 2016-2019 (5.2-5.4%). This was due to the relatively larger decrease in international destinations starting in 2020, compared to the shorter domestic flights.

Air freight is a comparatively small portion of the aviation sector. For instance, in 2019, 75% of all flights carried no cargo, 20% carried less than 1% of their payload as cargo and 1.6% carried between 1 to 5% of payload as belly cargo. Only 0.18% of all flights were dedicated cargo flights.

B. U.S. Flight Data from 2016-2021

Figure 3 shows the cumulative percentage of total annual fuel used as a function of distance (in statute miles) between 2016 to 2021. The trends were very consistent from 2016 through 2021. This chart shows that roughly 30-

35% of the total annual fuel burned in the years 2016-2021 occurred on flights that were less than 1000 statute miles, and roughly 30% of the total annual fuel burned in the years 2016-2019 occurred on flights that were greater than 3000 statute miles. The relatively larger percentage reduction in longer flights due to the COVID-19 pandemic is more clearly seen by the large deviation of the 2020 and 2021 trend from those of the previous four years for flights longer than 1000 statute miles. In 2016-2019, 70% of the total annual fuel burned occurred on flights less than 3000 statute miles. In 2020, that fraction increased to 75% for flights less than 3000 statute miles, or conversely, flights greater than 3000 statute miles contributed only 25% of fuel used in 2020, compared to 30% for the years before the COVID-19 pandemic. For 2021, the fraction of longest flights (those greater than 3000 statute miles) continues to contribute proportionally less of the total fuel burned than in pre-pandemic years, indicating the effect from the pandemic on these longest flights still exists.

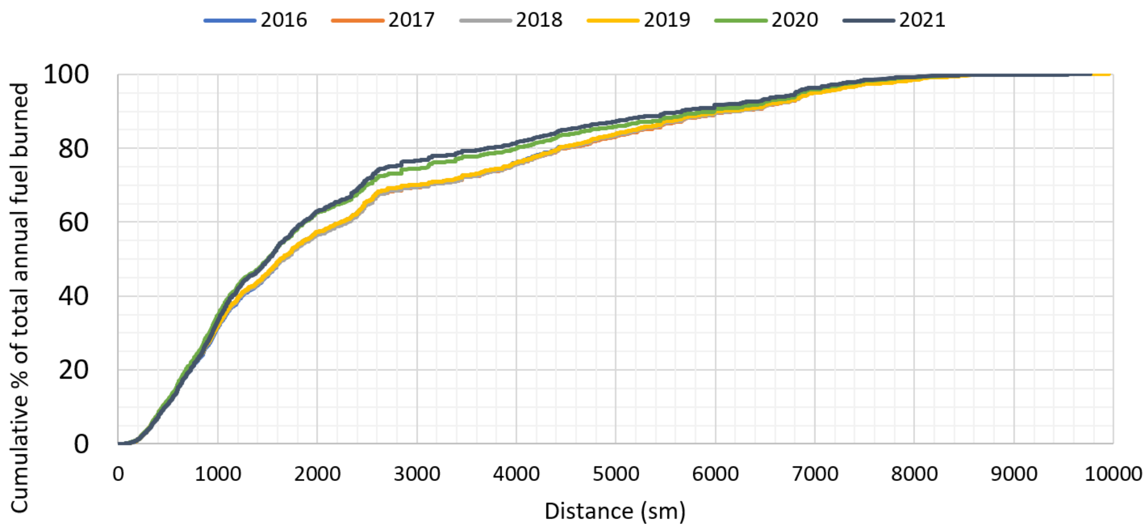

Figure 3. Cumulative percentage of total fuel used by distance traveled (statute miles), 2016-2021.

In the next section of this paper, we will focus on the pre-pandemic 2019 flight data and discuss the fuel efficiencies and missions flown by the top contributors to CO_2 emissions. Given the scaling factor of 3.16 lb of CO_2 created for each pound of fuel consumed, the remainder of this paper will report fuel usage estimates rather than CO_2 emissions directly.

C. Aircraft Capacity, Range and Fuel Efficiency

The scatter-bubble chart in Figure 4 shows multiple dimensions of the historical flight data for the top 100 aircraft types in 2019. The x-axis is the average distance in statute miles traveled per flight, and the y-axis shows the average fuel efficiency per available seat-mile (statute miles per gallon per seat). The bubble is sized by the fraction of fuel burned by aircraft type in 2019, and the color of the bubble represents the aircraft passenger capacity. All flight and vehicle data have been aggregated and averaged by vehicle type to create this chart. Several major assumptions are made in these plots. As with the previous plots in this paper, the fuel usage is based on a simplified ICAO fuel use model [5] implemented with a load factor of 1.0 (i.e., a full aircraft). The plotted values are subject to significant uncertainties.

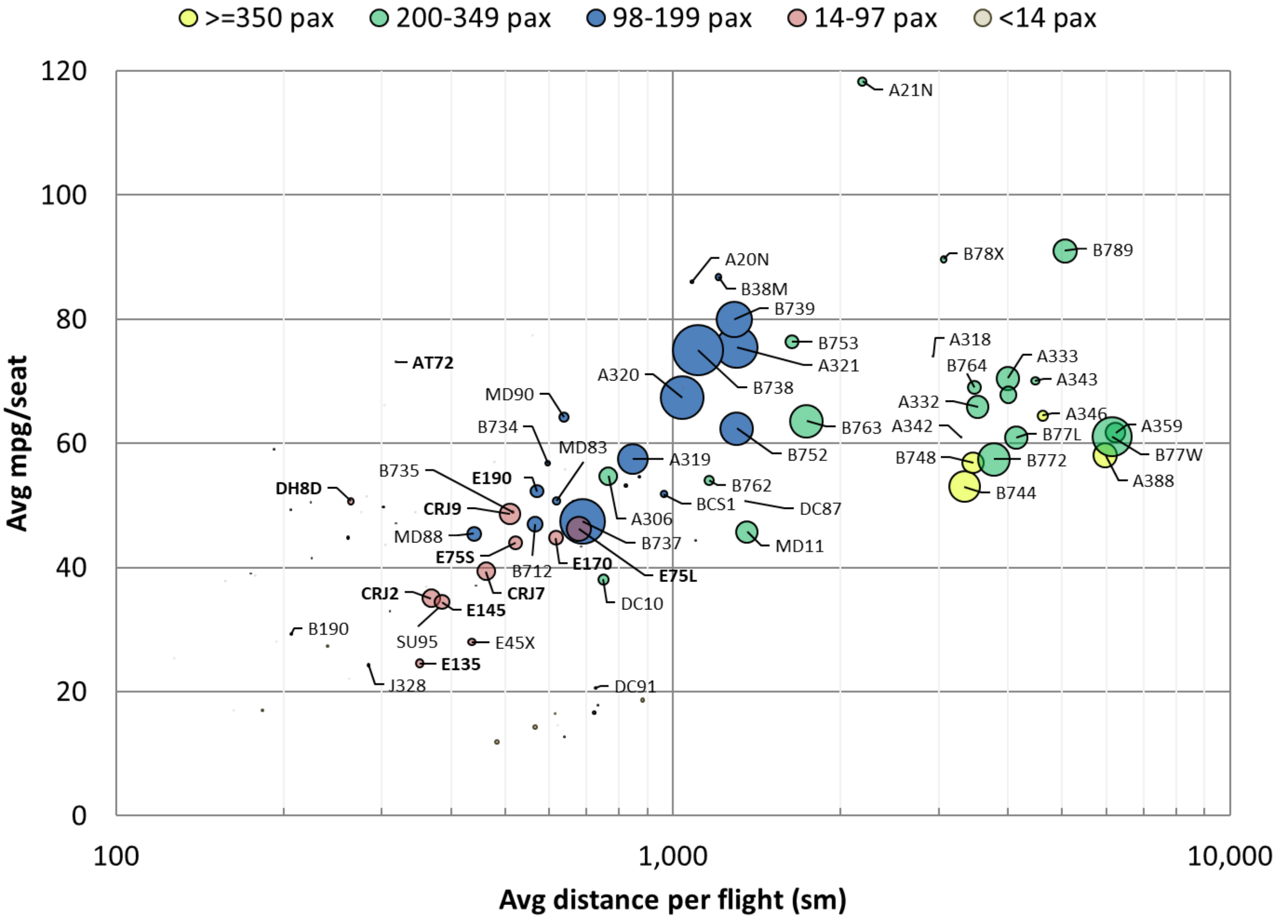

Figure 4. Fuel economy as a function of average flight distance, capacity and contribution to total fuel used for US departures of the top 100 aircraft models by average distance flown in 2019, labeled by ICAO aircraft designation. Bubble size is proportional to total annual fuel burned. Selected regional aircraft labels in bold.

This chart displays the expected clustering of the different vehicle passenger capacities as a function of average distance traveled per flight. Small aircraft (less than 100 passenger capacity) typically fly the shorter distances (less than 600 statute miles), while the larger aircraft fly the longer distances, with a clustering of the 100-199 passenger aircraft flying typical distances of 800-1400 statute miles. The two largest passenger capacity aircraft (greater than 200 passengers) are flown for distances greater than 2000 statute miles, with clusters of aircraft models for flights between 3200-3400 statute miles and another cluster for flights > 5000 statute miles.

Typical fuel efficiency values per available seats ranged between 40 and 80 miles-per-gallon-per-available-seat (mpg/seat), with the most fuel-efficient vehicles in terms of mpg/seat appearing along the top of this chart. Some newer aircraft are shown with higher fuel efficiency, estimated to be as much as 120 mpg/seat, with significantly lower contribution to overall fuel usage (size of bubble). This small contribution to total fuel consumed occurs not only because they are more fuel efficient, but also because these vehicles were recently introduced to the U.S. fleet and have fewer total flights and mileage in 2019. It should also be noted that the total fuel used by the B738 is less than the current usage because this plane was grounded for most of 2019. Most interesting is the linear trend seen between fuel economy per available seats and distance flown per flight for distances less than 1400 statute miles. For longer flights, the current vehicle fleet appears to reach a plateau in terms of fuel efficiency per available seat, in the range of 60-80 mpg/seat, regardless of distance flown. Notable is that a substantial portion of fuel is consumed by a relatively few aircraft models (and their variants) on long flights.

There are multiple aircraft types being used for flights between 400 and 1400 statute miles, with representation from four vehicle capacity categories. The largest contributor in terms of fuel burned in this flight range comes from aircraft with seating capacity between 98-199 passengers (blue bubbles) and flying between 600-1400 statute miles. Although aircraft with less than 100 passengers (rose and linen-colored bubbles) contribute a small amount to total annual fuel burned because of their shorter distances and capacities, these aircraft dominate the shorter ranges (less than 600 statute miles). These aircraft support a different niche in the national airspace, making it impractical to replace this market segment with fewer large vehicles and undesirable to do so because large aircraft flying short distances are not likely to be as fuel efficient as aircraft designed specifically for short routes and may be unsuitable for smaller airport ground facilities.

III. Regional Jets, Secondary Airports and Airport Fuel Consumption

Regional aircraft that connect small cities to major hubs and carry up to 100 passengers (limited to 76 passengers in the U.S. by the pilot-negotiated scope clause [10]) are an important subcategory of the aviation sector. These aircraft play a major role in the airline feeder industry for the large airlines, as the large airlines grow to reach air travel markets away from the major hubs. The regional airline market is expected to grow and the vehicle types in the regional aircraft class are well suited for the introduction of alternative propulsion systems, namely fully electrified or hybrid-electric vehicles.

We define a regional aircraft to include both jets and turboprops that carry fewer than 100 passengers. Cargo is defined as belly cargo for regional passenger flights or dedicated cargo for cargo-only flights. Regional jet cargo aircraft typically carry cargo payloads between 2000 and 20,000 lbs [11]. Because we expect that electrified or hybrid-electric aircraft adoption will likely begin with aircraft serving these regional markets, the rest of this paper will focus on these smaller, regional markets.

To identify the regional aircraft contribution to overall air traffic and emissions, Figure 5 shows the breakdown of total U.S. departures in 2019 into four distance bins, split by aircraft type. Figure 6 shows the breakdown of total fuel burned in 2019 into the same categories. In these figures, we have defined seven categories of aircraft – business, cargo, narrow body, wide body, regional, utility, and other based on generally accepted definitions. Cargo flights are those solely dedicated to cargo. Regional aircraft are those carrying up to 100 passengers. Belly cargo carried on passenger flights is a small fraction of payload and has been included in their respective categories (i.e. not in the cargo category).

As seen in Figure 5, in 2019 approximately half of all U.S. departures servicing flights up to 311 statute miles (sm) are regional aircraft. The RJ portion decreases with increasing flight distance up to 2485 sm. Note that dedicated cargo flights account for a small fraction of total flights and fuel consumption, particularly at the short mission ranges.

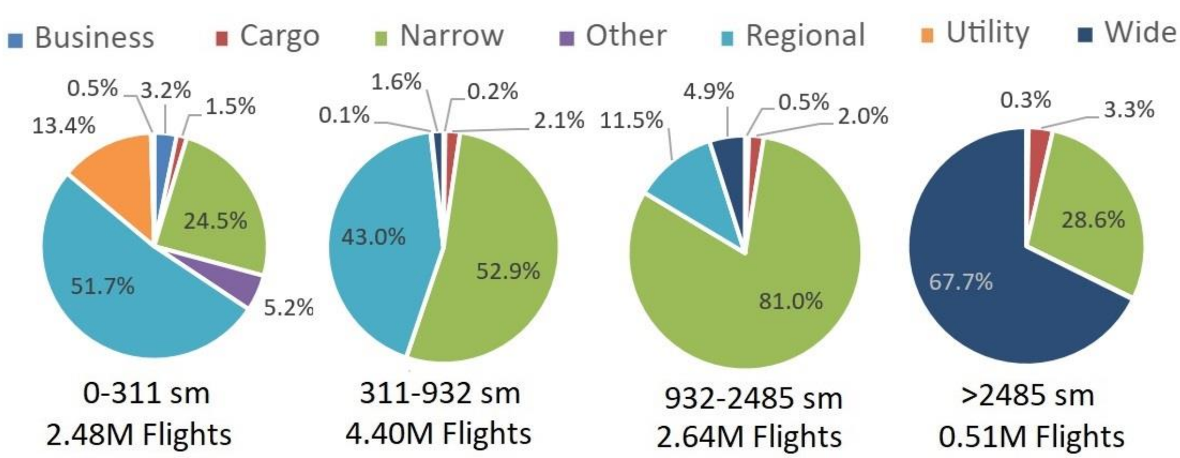

Figure 5. Share of 10.03 million total U.S. departures in 2019 by distance and carrier type. The total number of flights per pie chart is shown below the distance label.

Presented in Figure 6 is the fuel consumed by the seven categories of aircraft during 2019. Narrow body passenger aircraft consumed most of the fuel on routes up to 2485 sm. On the long-distance routes greater than 2485 sm, wide body passenger aircraft consumed the most fuel. Interestingly, narrow body aircraft are used across the flight distance spectrum.

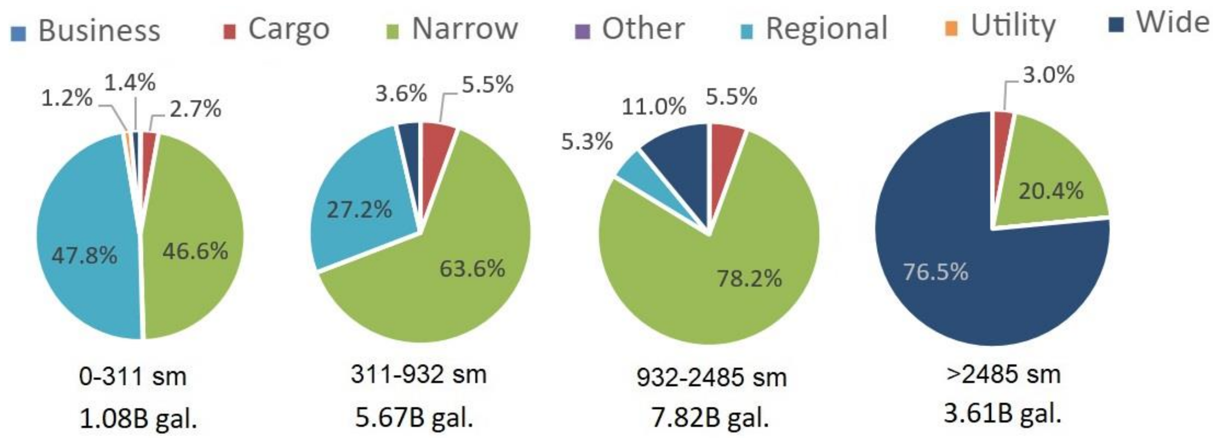

Figure 6. Share of 18.3 billion gallons of fuel consumed in 2019 by distance and carrier type. The total amount of fuel per pie chart is shown below the distance label.

Table 1 lists details of the flight characteristics of the top 12 regional aircraft with U.S. departures for 2019. This aircraft list includes all vehicles that carry between 40 and 100 passengers (or the cargo equivalent). These vehicles typically travel 250 to 650 sm per flight, with 600-650 sm being the most popular distance in 2019. The average range for the regional aircraft increased in 2021. This short list of 12 aircraft spans more than two orders of magnitude difference in terms of total distance flown between the most and least utilized types, indicating that the market for these vehicles is dominated by an extremely small number of manufacturers. Scope clause restrictions (unique to the U.S.) place restrictions on the number of passengers (limited to 76) and the size of aircraft for regional airlines. The scope clause prevents some aircraft models (e.g. Embraer E195-E2) from flying at full capacity which compromises their fuel efficiency. Figure 4 shows that regional aircraft (labels in bold) achieve between 25 and 74 mpg/seat, which is low in comparison to the efficiency achieved by larger aircraft on longer routes.

Table 1. Top 12 regional aircraft statistics in 2019. The lists are sorted in descending order of average available seat-miles (sm, statute miles). All regional aircraft in this list are turbofan aircraft, except the boldfaced aircraft, which are turboprop vehicles.

Top 12 regional aircraft statistics for 2019								
Name	Average seats	Average range per flight (sm)	Total flights in 2019	% of total flights	Total distance flown in 2019 (sm)	% of total distance flown (sm)	Total avg avail seat-miles (sm)	% of total avg avail seat-miles (sm)
Embraer 175 (long wing), (short wing)	75	631	8.0E+05	24.9%	5.1E+08	33.0%	3.8E+10	36.5%
Canadair Regional Jet 900	76	494	5.1E+05	15.8%	2.5E+08	16.4%	1.9E+10	18.4%
CANADAIR RJ-700	67	462	3.9E+05	12.2%	1.8E+08	11.8%	1.2E+10	11.7%
Canadair Regional Jet 200	50	363	6.0E+05	18.6%	2.2E+08	14.1%	1.1E+10	10.4%
Embraer RJ145	50	391	4.9E+05	15.1%	1.9E+08	12.4%	9.5E+09	9.1%
Embraer 190 / Lineage 1000, E2, 195	100	528	1.4E+05	4.2%	7.1E+07	4.6%	7.1E+09	6.8%
Embraer 170	70	596	1.0E+05	3.1%	6.0E+07	3.9%	4.2E+09	4.0%
Embraer RJ135, RJ140	44	362	9.9E+04	3.1%	3.6E+07	2.3%	1.6E+09	1.5%
De Havilland Canada DHC-8-400 Dash 8Q	76	250	7.7E+04	2.4%	1.9E+07	1.2%	1.5E+09	1.4%
Bombardier CRJ 550	50	361	4.6E+03	0.1%	1.7E+06	0.1%	8.3E+07	0.1%
Aerospatiale/Alenia ATR 72-200 series, -500, -600	67	319	3.2E+03	0.1%	1.0E+06	0.1%	6.9E+07	0.1%
Aerospatiale/Alenia ATR 42-300 / 320, -500, -600	44	123	1.0E+04	0.3%	1.2E+06	0.1%	5.4E+07	0.1%
Overall (average range weighted by % total distance flown)		**503**	**3.2E+06**		**1.5E+09**		**1.0E+11**	

As show in Table 1, the Embraer E175 is the most popular aircraft in this class by a large margin in terms of cadence (number of flights), total distance flown and available seat-miles. The E175 flies more than twice the total distance of the second most popular aircraft in this list, the Canadair CRJ-900. When considering available seat-miles, this difference is even greater since the E175 flies longer routes (600 sm versus 470 sm).

The difference between the 2019 and 2021 data shows that the impact of COVID-19 on domestic regional aircraft travel still exists and is roughly 20% less when compared to average available seat-miles flown in 2019. These vehicles are flying slightly longer routes, but most noticeable is the sharp increase in market share of the E175s, capturing 47% of average available seat-miles in 2021, up from 37% in 2019.

Turboprop-powered regional aircraft (listed in bold in Table 1) burned 0.39% of the total jet fuel consumed in 2019 with 62% of this fuel consumed on flights up to 311 sm. The fuel consumption of piston-powered aircraft was only 0.023% of the total fuel used in 2019, with 66% used on flights less than 311 sm. Although the fuel efficiency of turboprops is higher than turbofans for short flights, the turboprop share of the regional aircraft market is small. The most common turboprop in commercial service is the De Havilland Canada (Bombardier) Q400 aircraft that seats 68 to 90 passengers. As seen in Table 1, this aircraft made only 2% of the total number of regional flights in 2019. Note that the ATR-72, a turboprop that is comparable to the Q400 in many respects, is considerably more fuel efficient than the Q400, as shown in figure 4. This is in part because the scope clause restricts Q400 flights to no more than 76 passengers even though the aircraft is designed to carry more. The ATR-72-600 carries up to 78 passengers, cruises at a slower speed and its engines are about half of the power of the Q400 and so it is significantly more fuel efficient. With increasing energy prices expected in the future, the airline profitability equation may change to favor aircraft like the ATR-72 that are more efficient but slower.

IV. Electrification of Aircraft for Decarbonization

The paths to aviation decarbonization are technically challenging and the cost to decarbonize aviation will be high. Leading alternative-fuel candidates include sustainable aviation fuels (SAF), electrification of aircraft and hydrogen combustion. Appreciable reduction in GHG can be gained through hybrid-electric aircraft that burn SAF but hybridization is seen by many as an initial stepping-stone along the path to all-electric and hydrogen-powered aircraft. Furthermore, there are significant concerns about the long-term viability of biomass-derived SAF to meet the future demands of aviation [12,13]. The scenario that stands the best chance of achieving net-zero GHG is electrification of short flights and use of green hydrogen (hydrogen produced by electrolysis of water using electricity from renewable sources) for long flights.

An estimate of the amount of electricity to meet the demand of green aviation of the future can be made based on the current jet fuel usage and the projected U.S. 1.4 × aviation growth factor between now and 2050 [13]. Figure 7 shows the top 50 airports in 2019 in terms of fuel usage, broken out by fuel consumed by regional aircraft (blue bubbles) and all aircraft (red bubbles). The bubbles are sized by percent of total fuel consumed at that airport. The blue bubbles are enlarged for visibility (i.e. different scale than the red bubbles). As can be seen in the figure, the fuel usage is distributed across the country and roughly tracks with the population centers. Alternative fuels would therefore have to be distributed similarly. Because regional aircraft serve the feeder airline market, most major hubs also have significant regional aircraft traffic, as can be seen in the graphic. The map shows the location of the secondary airports that are part of the feeder market, mostly located in the eastern half of the United States and tracks with the larger population densities in the smaller states. In 2019, 18.3 billion gallons of jet fuel was consumed by civil aviation within the U.S. Without intervention, the projected fuel consumption would be 25.9 billion gallons in 2050.

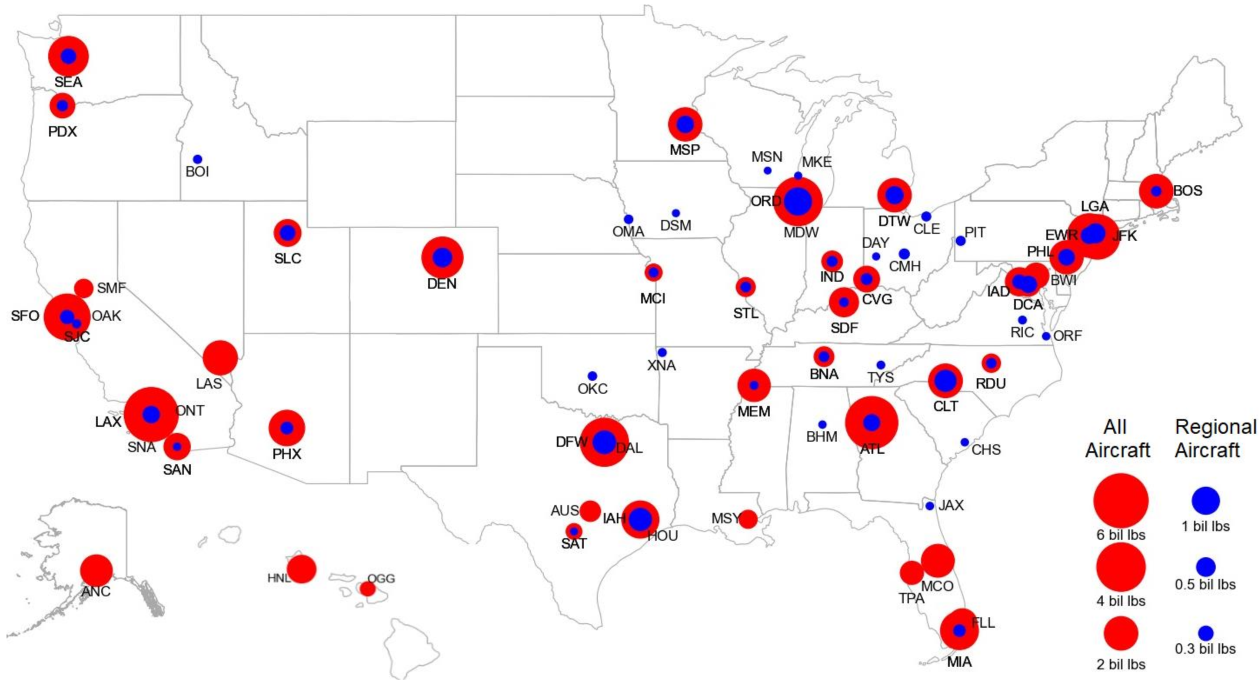

Figure 7. Top 50 airports by total fuel consumption in 2019.

Ideally, after 2050 all aircraft will operate on energy derived from renewable sources. Electric aircraft are projected to be twice as energy efficient as those driven by thermal engines. Based on the data that led to Figure 2 (see reference [3]) and simple energy calculations, it can be shown that if all aircraft departing U.S. airports and flying routes less than 840 NM are electric and those flying routes greater than 840 NM are hydrogen powered, 1.25 million GWh/annum of electricity would be required to generate green liquid hydrogen. This is roughly equivalent to 30% of the 4.2 million GWh of electricity generated in the U.S. in 2022.

To realize an all-electric aircraft that can lead to meaningful GHG reductions, a safe battery with specific energy of approximately 2000 to 2500 Wh. If such a battery is realized, a 150-passenger aircraft with a range of 840 NM could be produced that would supplant 66% of all U.S. departures (2019) and reduce aviation GHG by 29%. Currently, a 150 passenger fully electric aircraft is not feasible but hybrid-electric aircraft for short to medium range regional missions are on the near horizon provided the safety issues with batteries can be satisfactorily addressed. Solid-state lithium batteries are proving to be much safer than the lithium-ion batteries currently being implemented on most prototype aircraft (because solid state batteries do not promote dendrite growth that can cause battery fires). For medium and long-range flights that currently consume the majority of jet fuel, SAF and hydrogen-fueled turbofans are the only technologies identified that can be realistically implemented in the 2050 timeframe.

As new aircraft technologies and aircraft are introduced into the airspace, a natural consideration is how to do this with the least disruption to the current airspace and airport infrastructure. Table 2 shows the distribution of the type of airport pairs that would be affected by the 3.2 million regional flights in 2019 that could be replaced by new hybrid-electric aircraft traveling short to medium range regional missions. The airport types are ordered largest to smallest according to the FAA’s definition using overall passenger boardings in the U.S., with the rows showing the origin airport type and the columns showing destination airport type. Green cells show the highest fractions while yellow shows the lowest fractions of all regional flights. The role of the regional aircraft as feeder vehicles is clearly visible in the table, where the green cells all have a large hub as one of the airports in the airport pair (the first row and the first column). Routes that involve a large hub to any other airport type, or any other airport type to a large hub airport comprise nearly half of all regional aircraft routes, with the large hub-small hub pairs making up the most popular routes for regional aircraft travel (contributing over 30% of the total flights in 2019). Large hub to large hub travel occurs 9% of the time. The proportion of routes between only small and non-primary (smallest) hubs is very small, less than 2% of all regional routes. This shows that point-to-point travel remains very small, and efforts to introduce new aircraft and develop the required new airport infrastructure into the system at these small airports first, to avoid the large hubs, may be a challenge. Focusing on these routes, however, could prove least disruptive to the airport network and even open up new point-to-point air travel opportunities. The slight asymmetry of the table is due to flights with an international airport (Canada or Mexico), as departures from these airports do not contribute to U.S. departure statistics.

Table 2. Regional aircraft routes in 2019 by airport pair.

Origin-Destination airport types (% of regional flights) in 2019						
Origin\Destination	**Large Hub**	**Medium Hub**	**Small Hub**	**Non-primary Hub**	**Unclassified**	**Grand Total**
Large Hub	9.0%	9.9%	15.7%	10.7%	3.2%	**48.5%**
Medium Hub	9.9%	1.1%	0.6%	1.1%	0.8%	**13.5%**
Small Hub	15.7%	0.6%	0.2%	0.3%	0.5%	**17.3%**
Non-primary Hub	10.7%	1.0%	0.3%	1.0%	1.6%	**14.6%**
Unclassified	1.1%	0.8%	0.5%	1.6%	2.0%	**6.1%**
Grand Total	**46.4%**	**13.5%**	**17.3%**	**14.7%**	**8.1%**	**100.0%**

Production and distribution of electricity from renewable sources for the short-range regional aircraft of the future looks to be feasible and cost effective. Presented in Table 3 is an accounting of the number of solar panels required to electrify all flights of 840 NM or less (i.e. 66% of all U.S. departures). Entered quantities are in red and calculated quantities in black. As shown in table 2, a total land area of 21 sm × 21 sm covered in solar panels arrays would address the anticipated 2050 electricity needs by regional aviation. Surprisingly, the cost of electricity is roughly 1/3 the cost of Jet A that the electricity would supplant based on the current $1.8/W installed cost of solar panels and assuming that Jet A costs $5/gal on average in the future.

Table 3. Estimation of number of solar panels to meet 2050 potential U.S. electric aviation energy needs for all flights less than 840 NM.

Item	Quantity	Units	Remarks
U.S. airline jet fuel consumption in 2019	18.3	Bgal	U.S. consumed 18.3 billion gallons 2019
Expected aviation growth factor between 2019 and 2050	1.415		
2050 predicted U.S. annual airline jet fuel usage	25.9	Bgal	
Energy/Gal of jet fuel	0.0395	MWh/gal	
2050 predicted U.S. airline annual aviation energy usage	7.23E+08	MWh	
Fraction of aviation that potentially could be electrified	0.29		29% of GHG come from flights < 840 nm
Propulsive efficiency factor (jet fuel --> electricity)	2.15		Electric propulsion is 2X more efficient
Total annual electric energy required	**97,501**	GWh	
Panel density	158	kW/acre	Pavagada Solar Park 2050 MW array (13000 acres, panel η=15.6% $2.1 billion)
Number of peak sunlight hours/day	6	h/day	
Annual peak sunlight total	2,190	h	
Energy produced annually by 1 acre of solar panels	345	MWh/acre	
Number of solar panel acres required to meet U.S. 2050 electric aviation energy needs	282,327	acre	**(i.e. 21 mi x 21 mi)** 640 acres to 1 sq mile
Total solar panel power required	44,521	MW	
Installed cost/watt	$1.80		U.S. EIC (2019)
Cost of primary solar energy per year spread over 25 years (including interest)	$8.0	$B/yr	Total cost =2.5 x installed cost
Annual transmission and distribution	$3.21	$B/yr	40% of total cost
Total delivered annual electricity cost	$11.2	$B/yr	
Projected average cost of jet fuel	$5.00	$/gal	
Equivalent cost of Jet fuel consumed annually	$37.5	$B/yr	
Annual electricity/fuel cost ratio	**0.30**		

The 97,500 GWh/annum of renewable energy required for all-electric aircraft flying all routes of 840 NM or less in 2050 is only 2.3% of the electricity generated in the U.S. in 2022 (U.S. Energy Information Administration). The electrification of these short to medium flights that make up 66% of all U.S. departures appears to be feasible from a power generation point-of-view. A recent 2022 review paper from the National Academies presents some estimations of the 2040 electric energy demand at several major hubs as a function of electric aircraft market penetration [14]. For Atlanta Hartsfield (ATL) with full market penetration, the monthly electrical energy to service supporting regional aircraft operations would be approximately 5M kWh. At the international airports Dallas-Fort Worth (DFW) and San Francisco (SFO), the monthly estimates are 3.6M and 2.75M kWh, respectively. Their estimate for the total annual regional electric aircraft energy from just these three airports would be approximately 136 M kWh (136 GWh) if the regional market was completely electrified.

The key to the all-electric aircraft of the future having a meaningful impact on GHG is improved battery specific energy (requiring a factor of 3-4× improvement over the current state-of-the-art). If such a battery cannot be developed, the prospects of all-electric aviation displacing a significant amount of GHG are not good. Sustainable electrification of aviation will draw on multiple renewable energy sources including solar, wind, hydro and nuclear power depending on location and cost. Regardless of the renewable energy source, some form of carbon capture will also be required to reach the 2050 net-zero GHG aviation goal.

V. Conclusions

An analysis of U.S. flight departure patterns from 2016 to 2021 and their contribution to greenhouse gas emissions was done using a combination of publicly available aircraft, airport, and flight data, primarily from the BTS website and the Sherlock data warehouse maintained by NASA Ames Research Center. Aircraft fuel utilization was then broken down into various aircraft categories and the prospects for decarbonization were analyzed.

A comparison of 2020 U.S. passenger and cargo departures and emissions shows similar trends to the ones found by the 2020 EUROCONTROL data. Based on the number of U.S. departures in 2020, long-haul flights (those traveling more than 2485 statute miles) create 30% of aviation related CO_2 emissions but make up only 4% of the total number of U.S. departures. Short-haul flights (those traveling less than 311 statute miles) make up 21% of the total number of U.S. departures yet created less than 5% of aviation-related CO_2 emissions.

The 2020 analysis was extended to cover U.S. departure flights between 2016 and 2019. Key findings from the five-year timeframe were observed. In 2020, the COVID-19 pandemic caused a significant reduction in total air traffic, with a proportionally larger reduction in long-haul flights caused by the cancellation of more international than domestic flights. The very long-haul flights (those traveling more than 2485 statute miles), while less than 5% of the total number of flights, generated 30–36% of CO_2 emissions. The greatest portion of U.S. aviation CO_2 emissions (36–39%) were created by flights traveling 932 to 2485 statute miles. A reduction of 10% in fuel use in the vehicles flying these missions has the potential to result in a 4% emissions reduction. This is the same amount generated by all the short-haul flights annually. Flights ranging from 932 to 2485 statute miles also account for the greatest portion (40–44%) of U.S. available seat-miles.

Although the shorter flights contribute a relatively small fraction of total CO_2 emissions, their frequency is high, serving a different consumer market than the less frequent, long-haul market. Adoption of new aircraft configurations and technologies for reducing GHG emissions from aviation will likely start from and expand within this market.

The feasibility of electrification of all flights up to 840 NM was explored and it was shown that if a battery of sufficient specific energy is developed, the investment cost in power generation infrastructure to support all-electric aviation is competitive with the future cost of jet fuel. Meeting the electricity demand to generate green hydrogen for flights longer than 840 NM is more problematic.

Future work will include additional data mining to understand flight patterns, such as seasonal variations and network connectivity, and to quantify the potential benefits of fleet turnover and substitution, both domestically and internationally, to support future sustainable aviation studies. This data can also be used to assess the potential of new technologies (e.g., electric aircraft) on projected GHG emission and to help inform future climate-related decisions being made by governments and industry.

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