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

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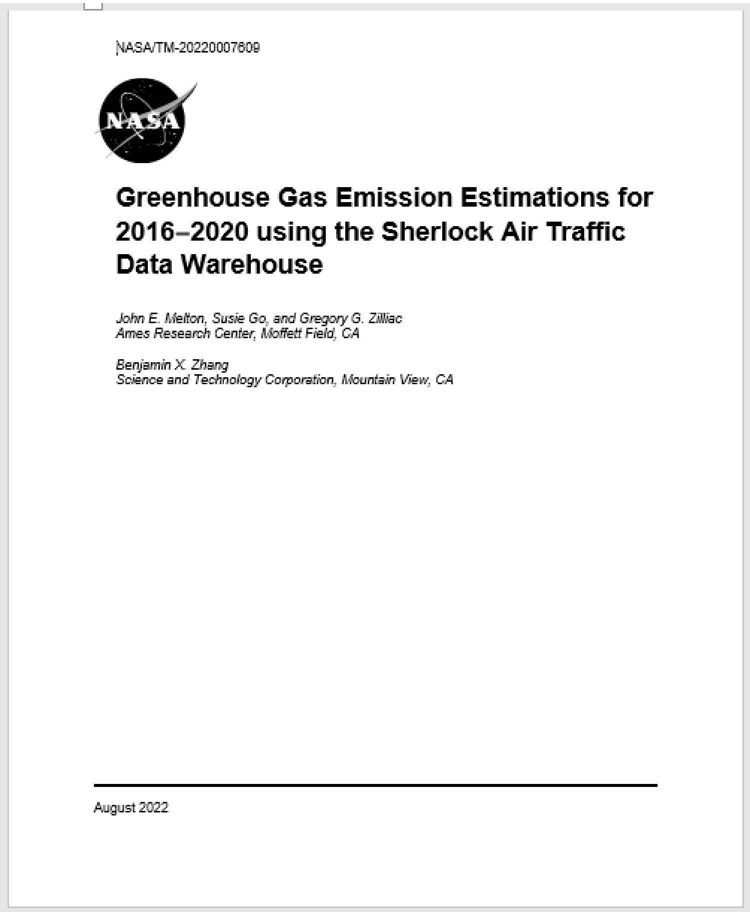
Motivation and Acknowledgements

- Follow-on to NASA Technical Memo on Greenhouse Gas Emissions estimates using historical US air traffic patterns
- Updated with new 2021 data, but emphasis still on 2019 flight patterns
- Focus on understanding regional aircraft and airports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Greenhouse Gas Emission Estimations for 2016–2020 using the Sherlock Air Traffic Data Warehouse

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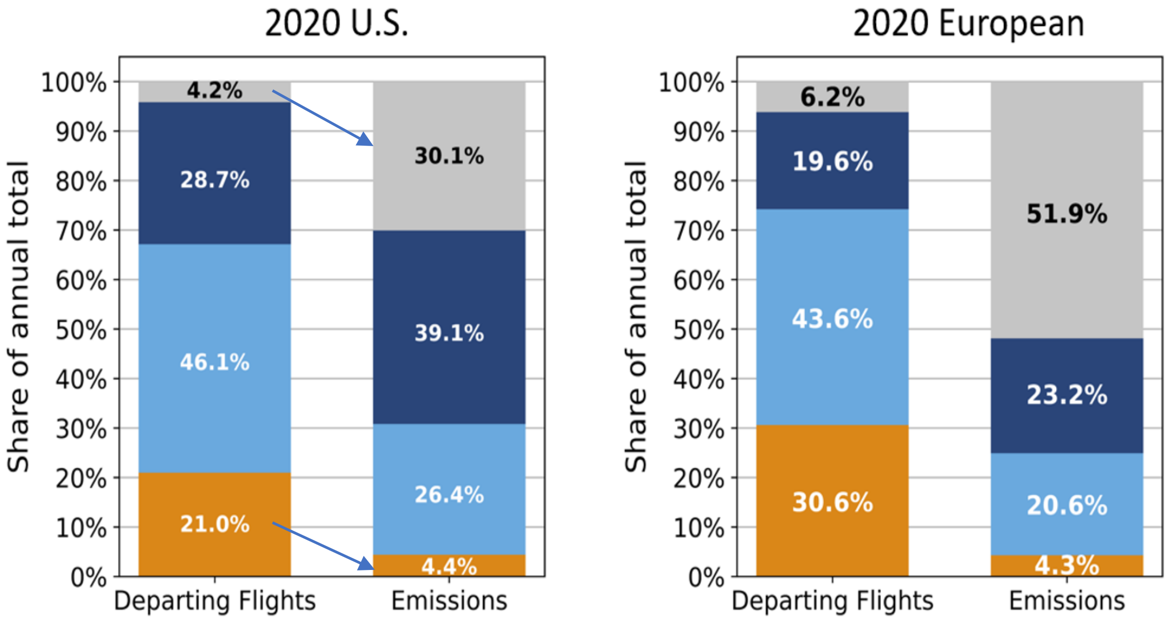
2020 Departures by Flights and CO_2 Emissions

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

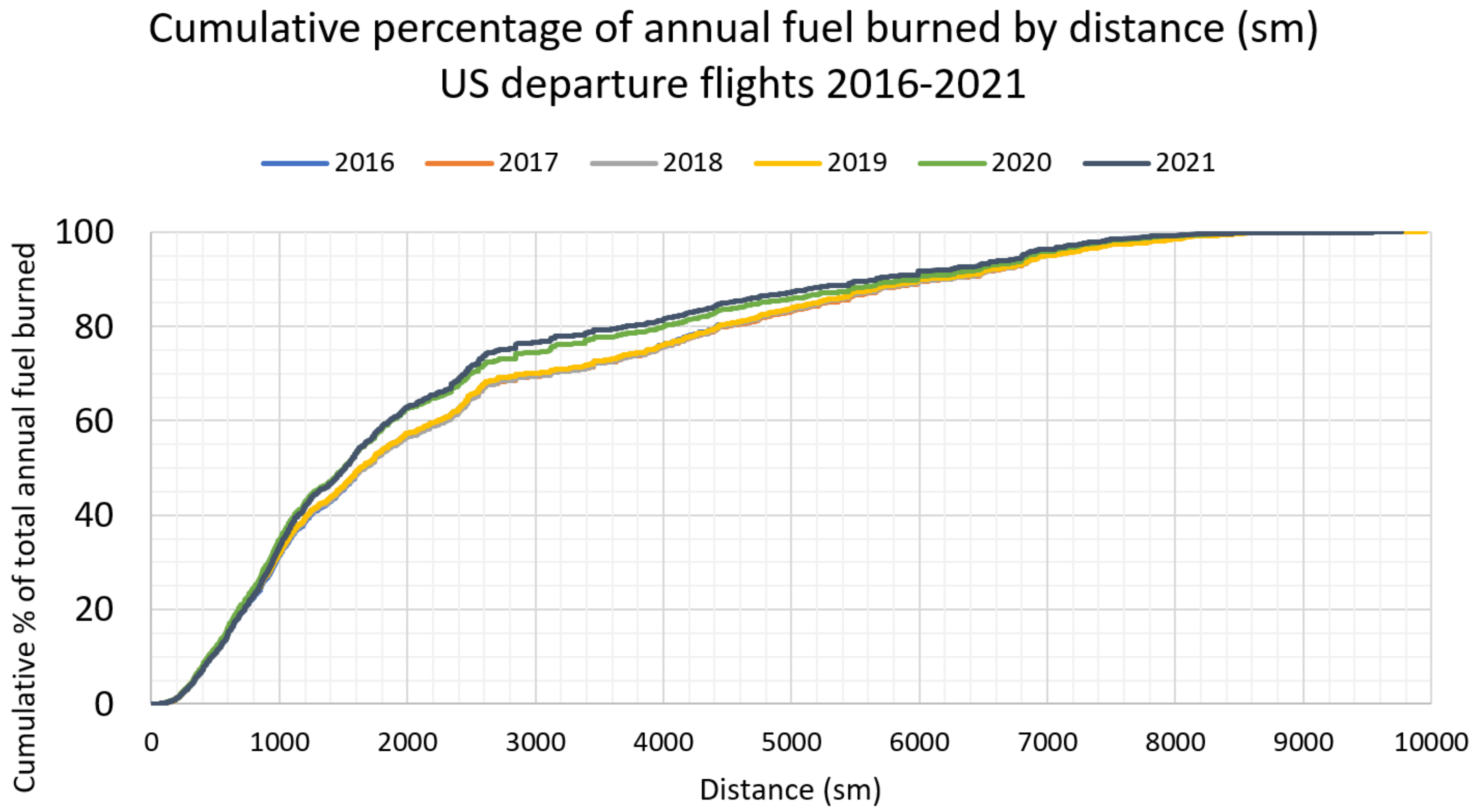
- US and European flight patterns are similar
- US has more even splits of CO_2 emissions for the non-short-haul flights than European flights
- Short-haul flights are a natural entry point for introducing next-generation aircraft while minimizing disruptions to the existing airspace (but minimal impact on GHG)
- Successful adoption of new aircraft technologies depends on understanding airport infrastructure requirement changes

2020 Departures by # Flights and CO_2 Emissions



European data adapted from EUROCONTROL Data Snapshot #4 on CO_2 Emissions by Flight Distance

Pandemic Effects on Air Travel

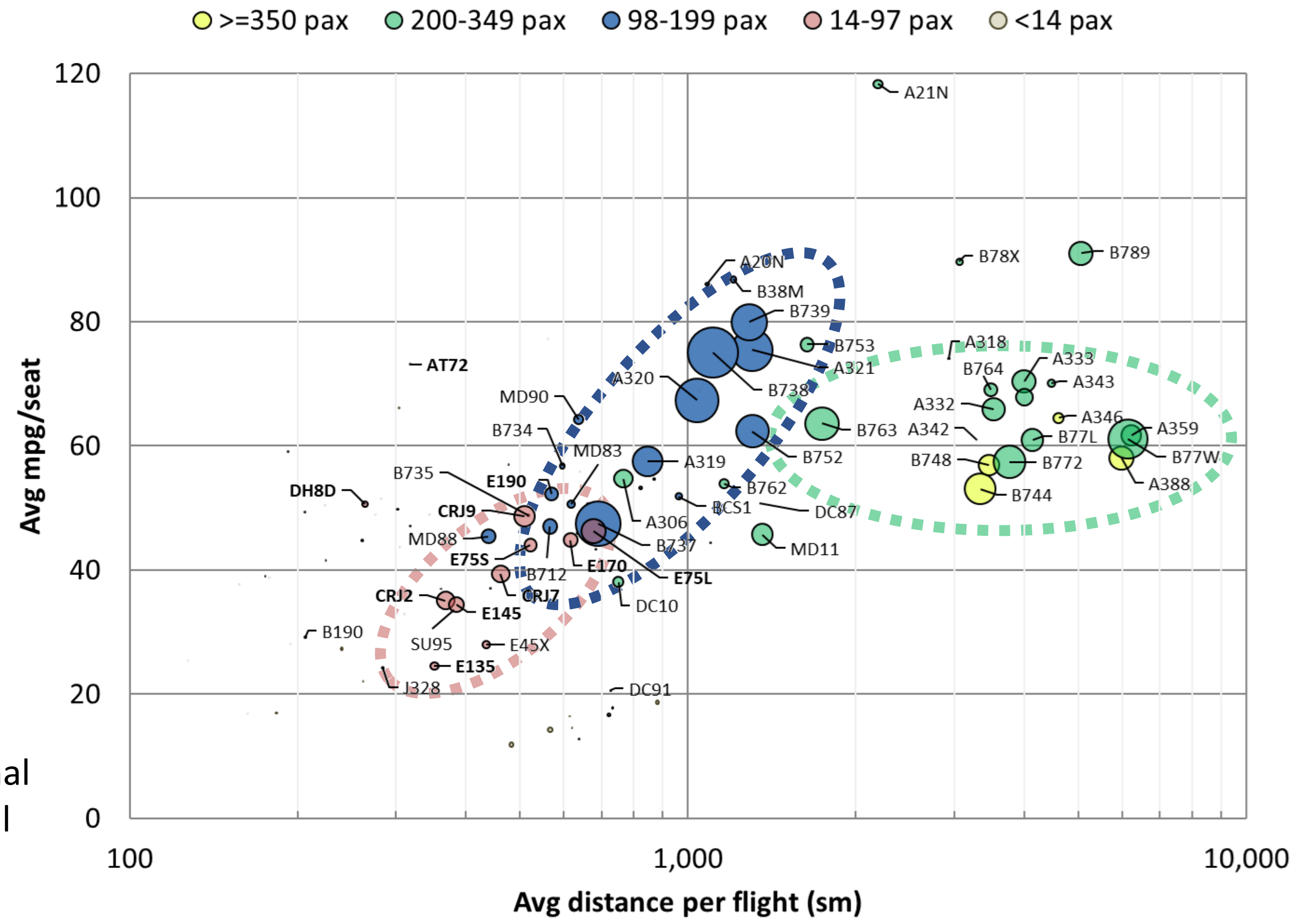


- Fuel burn estimates used the ICAO Carbon Emissions Calculator Methodology (function of aircraft type, distance, load factors)
- Travel patterns are pretty consistent from 2016-2019
- Effects of the pandemic are most apparent in the long flights

Aircraft Size, Fuel, Range and Fuel Economy

- Majority of vehicles average 40-80 mpg/seat, flying longer distances (> 700 statute miles)
- Lower fuel efficiency (30-50 mpg/seat) on the shorter flights
- Turboprops are most efficient for short flights (e.g. AT72, DH8D)
- Greater fuel efficiency could be had on medium range flights if fleet modernized (e.g. A21N)
- Substantial portion of fuel is consumed by a relatively few aircraft models (and their variants) on long flights

Top 100 US Departure Vehicles by Fuel Usage in 2019 by Vehicle Type, Distance, Capacity and Fuel Usage

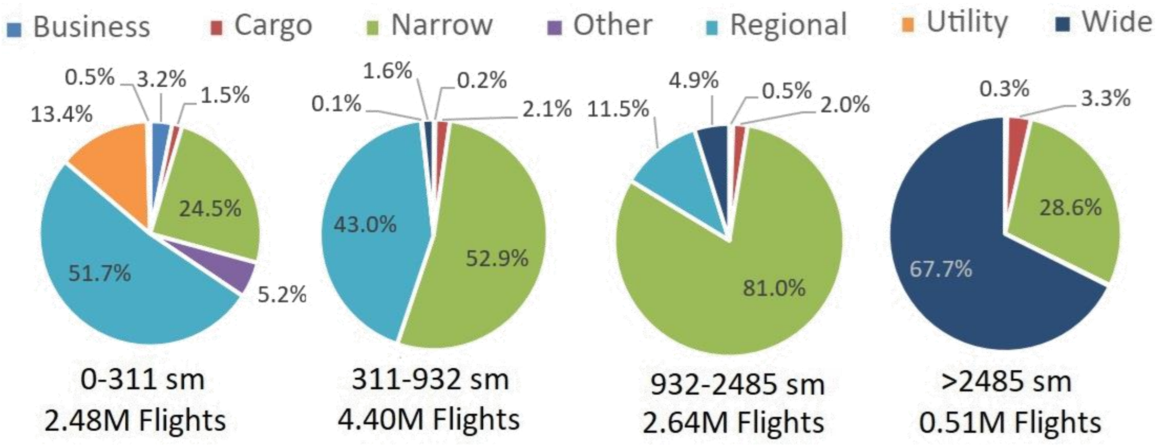


Size of bubbles is proportional to the contribution to overall fuel used in 2019

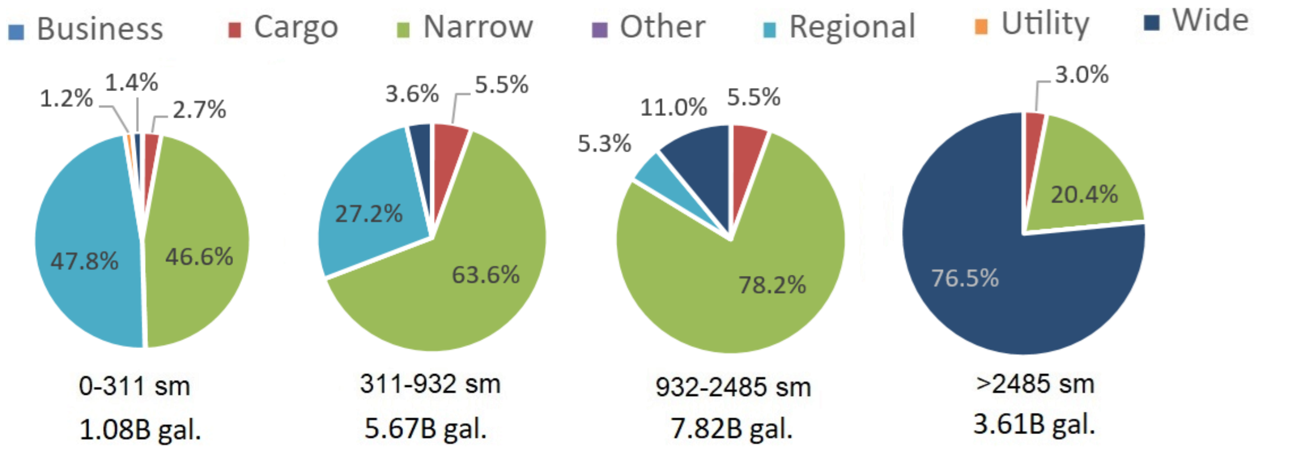
Departures and Fuel by Carrier Type and Distance

- Regional flights (teal) in 2019
  - Made up half of the flights and consumed half the fuel for short distance routes (< 311 sm)
  - Regional aircraft usage drops off significantly for ranges > 1000 sm
- Dedicated cargo flights (red) consumed small fraction of fuel in 2019 for all distances
- Narrowbody aircraft are used across all flight distances

Share of 10.0m Total U.S. Departures in 2019 by Distance and Carrier Type



Share of 18.3b gal of Fuel Consumed in 2019 by Distance and Carrier Type



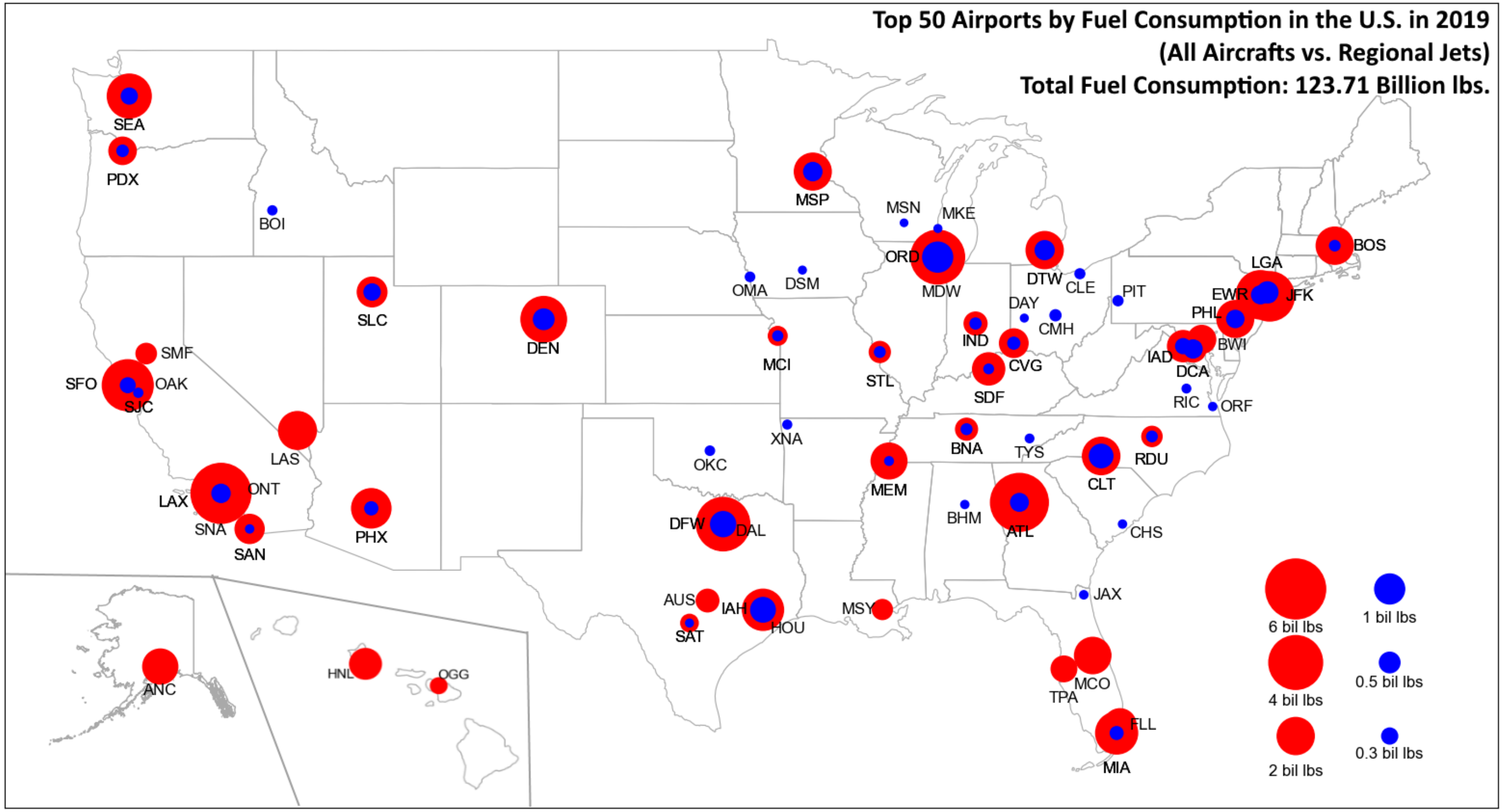
Regional Aircraft Statistics

Top 12 Regional aircraft statistics for 2019								
Name (Turboprops are **boldfaced**)	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**	

- Top 12 regional aircraft (40-100 passengers) statistics. 2021 statistics were similar.
- Embraer 175 variants were the most popular in the US, more than double the next most popular (CRJ-900)
- Turboprop regional aircraft (ATRs and the De Havilland DHC-8 Dash-8) tend to fly the shorter routes and are fuel efficient

As fuel prices increase, the higher fuel efficiency of turboprops make them a more attractive option

Airport Map and Fuel Consumption by Aircraft Type



- Most major hubs also serve regional aircraft, feeding secondary spoke airports
- Green energy will need to be distributed similarly

Regional Aircraft Routes 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%**

Airport categories based on FAA definitions, using overall passenger boarding in the US

3.2 million regional flights in 2019

- Slight asymmetry due to airport pairs with one international airport (Canada, Mexico)
- Roughly 50% of regional routes involved one large hub
- Over 30% regional aircraft routes travel between a large and a small airport
- Large-to-large airport hubs make up 9% of regional routes
- A small number of regional routes travel between small and non-primary airports (<2%)
  - Strategies to minimize airspace and airport infrastructure disruptions could start here
  - May open up point-to-point air travel

Introduction of vehicles with new fuel needs requires strategic route selection and airport changes

Energy Estimates for Regional Electrification

- Estimation of the amount of green electricity (solar panels) required to electrify all U.S. flights < 840 NM in 2050
  - 66% of all departures --> 29% GHG reduction
  - Need 97,500 GWh annually, which is 2.3% of 2022 U.S. production
- Electricity cost is 30% of the projected Jet A cost
- Battery specific energy > 4x state-of-art required to realize
- Electricity for green H2 production for long range flights is more problematic (4.2 million GWh or 30% of electricity generated in the U.S. in 2022)

Estimation of Number of Solar Panels to meet Potential 2050 US Electric Aviation Needs for all Flights > 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**		

Note: Input assumptions in red

Conclusions

- Modernization of U.S. fleet could save substantial energy
- Regional operations currently dominated by Embraer
- Large proportion of regional operations in eastern U.S.
- Regional-to-regional airport routes is a small fraction of operations
- Full electrification of regional operations is possible and with potential energy cost savings
- Battery technology is a key driver

Thanks again to EPFD for support and funding

Questions?