Analysis of Hybrid Electric Aircraft Operations in the National Airspace System

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This paper investigates fuel burn and flight time impacts of hybrid electric aircraft operating in the National Airspace System. Future scenarios with flights serviced by hybrid electric aircraft instead of conventional aircraft were created. In the scenarios, flights serviced by hybrid electric aircraft were selected such that the future scenario had the same passenger travel capacity as a baseline scenario from recorded historical data. Aircraft that serviced select flights in the baseline scenario were replaced with hybrid electric aircraft based on the flight's range and seat capacity. Additional hybrid electric flights were added to future scenarios when necessary to keep the future scenario passenger capacity equal or greater to that of the baseline scenario. The baseline and future scenarios were simulated in the NAS Digital Twin, a live, virtual, and constructive environment for building and executing simulations of the National Airspace System. Results showed that the future scenarios with hybrid electric flights saved fuel burn, but increased flight time. In the future scenarios, the additional hybrid electric flights did not cause any airports to exceed their operational capacity.

I. Introduction

NASA's Electrified Powertrain Flight Demonstration (EPFD) project is developing propulsion technologies to enable a new generation of electric-powered aircraft. These aircraft will have different fuel-burns, emissions, flight times, and passenger loads from those of aircraft powered by carbon-based fuel. The differences will cause changes to operations in the National Airspace System (NAS). Some examples of these changes are reduced consumption of carbon-based fuel, additional flights needed to satisfy demand between city pairs because initial electric-powered aircraft concepts will have lower passenger capacities, need for more electricity and charging stations at airports, and modifications to the flight network due to changes in city pair transportation demand and travel mode selection.

Whereas EPFD is studying multiple electric-powered aircraft concepts including several hybrid electric concepts, this study focused on an early demonstrator hybrid electric concept. It investigates future NAS operational scenarios that include flights serviced by the concept. The future scenarios were created by inserting hybrid electric aircraft into a baseline scenario that was derived from historical data recorded through the FAA. The baseline and future scenarios were simulated in NASA's NAS Digital Twin [1]. Results of the simulations were analyzed to estimate changes in

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fuel-burn, flight time changes, and increased airport operations. Airport operations were compared with airport capacities published by the FAA.

In this study, flights in the future scenarios serviced by the hybrid electric concept were selected based on performance criteria (range and seat capacity). In real operations, as hybrid electric aircraft become available, airlines will purchase and use them to service flights according to their business and cost objectives. These would be additional constraints that would determine how hybrid electric flights get utilized in the future NAS.

The paper is organized as follows. First, the hybrid electric aircraft is presented. Then the process used to build future scenarios is illustrated. The simulations are described, and results are provided. Finally, future work and conclusions are given.

II. Hybrid Electric Aircraft

The hybrid electric aircraft concept studied in this paper is a notional configuration, approximately based on a technology demonstrator aircraft being developed through an industry partnership between magniX and NASA under the EPFD project.

For the demonstration, magniX has partnered with AeroTEC and Air Tindi to test their hybrid powertrain installed on a modified DeHavilland "Dash 7" aircraft (DHC-7-100) [2]. The original Dash 7 is a four-turboprop regional aircraft with a capacity of 50 passengers and a maximum range of 690 NM. It will be hybridized to feature a hybrid architecture [3] by outfitting it with two inboard PT6 gas turbine engines and two outboard 700-kW magni650 electric propulsion units. With 250 Wh/kg specific energy density batteries, the demonstrator Dash 7 is estimated to have a 200 nm range and 45% fuel savings. Follow on versions to the demonstrator could have better range by improving battery energy density and using larger PT6 gas turbine engines. Figure 1 depicts the demonstration Dash 7 hybrid concept.

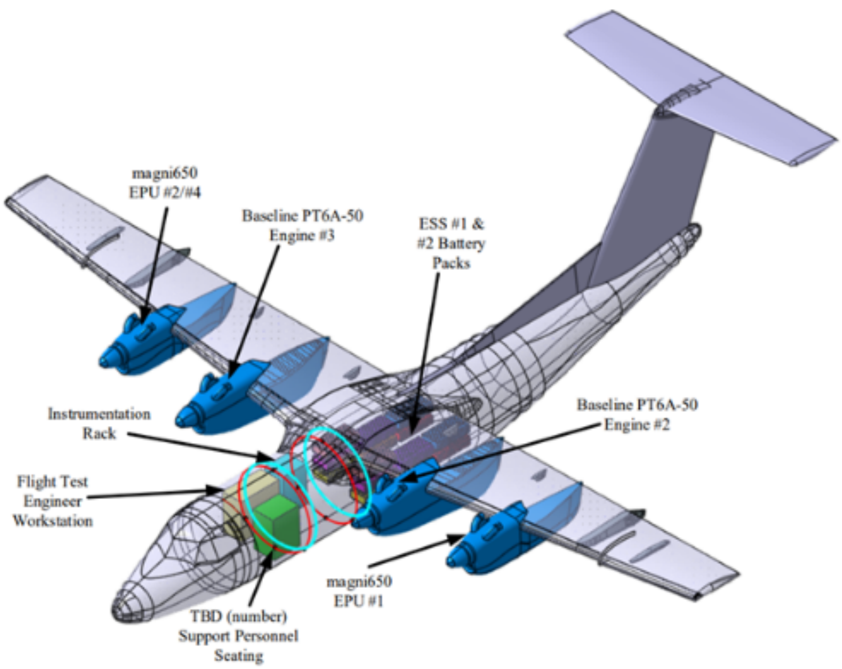


Figure 1. EPFD DHC-7 Parallel Hybrid Concept [4]

Electric aircraft are being proposed for all types of missions. This paper focuses on a hybrid electric aircraft concept sized to carry out the small commercial passenger mission. The concept starts with the demonstrator Dash 7 and adds theoretical batteries with a higher energy density of 500 Wh/kg and larger PT6 gas turbines. With these improvements, it is assumed that the modified demonstrator Dash 7 will carry 50 passengers up to 300 nm, and that it will cruise at 21,000 ft at 220 kts.

Because hybrid electric aircraft have gas turbines and electric motors, different strategies for allocating power between them are possible. While sizing the modified Dash 7 used in this paper, the following power allocation assumptions were made.

- Taxi-Out/In was done using 100% electric power, which is referred to eTaxi.
- Takeoff was done with the gas turbine engines at maximum takeoff power and the electric motors at maximum power output.
- Climb was done with the gas turbine engines at maximum climb power and the electric motors at maximum power output.
- Cruise was done with the gas turbines at normal rated power and the electric motors providing the thrust difference needed to cruise.
- Descent was done with gas turbine engine power only and the electric motors set to idle.
- The minimum state-of-charge (SOC) was 20%.

III. Creating Future NAS Operational Scenarios

In this paper, a NAS operational scenario was defined as a list of flights that were planned to operate throughout a day. Each flight had a callsign, aircraft type, departure time, cruise speed and altitude, and route that contained the origin and destination airports. This was the minimum information required to simulate a flight in the NAS Digital Twin. The sum of the flights included in the scenario comprised the NAS operations for the day that were able to be simulated in the NAS Digital Twin and determined the amount of traffic in the simulation.

A. Baseline Scenario

The approach to creating future NAS operational scenarios was to start with a baseline scenario built using historical data recorded through the FAA. The FAA's System Wide Information Management (SWIM) system provided NAS operational flight data that was stored in NASA's Sherlock data warehouse. The operational data included flight plans submitted and updated by operators and controllers. The baseline scenario was created using the flight plans stored in Sherlock for August 1, 2022.

August 1, 2022 was selected for its medium summer traffic level. Figure 2 shows airport operation (departure or arrival) counts between January 2020 and September 2023. The data was gathered from the FAA's Operational Network (OPSNET) system. The operation count is the sum of operations at 77 airports tracked in Aviation System Performance Metrics (ASPM). According to Fig. 2, on August 1, 2022, there were 153,881 operations, which was about average during the summer 2022.

The spring 2020 dip in traffic due to the pandemic is visible in Fig. 2. By summer 2022 traffic levels had recovered.

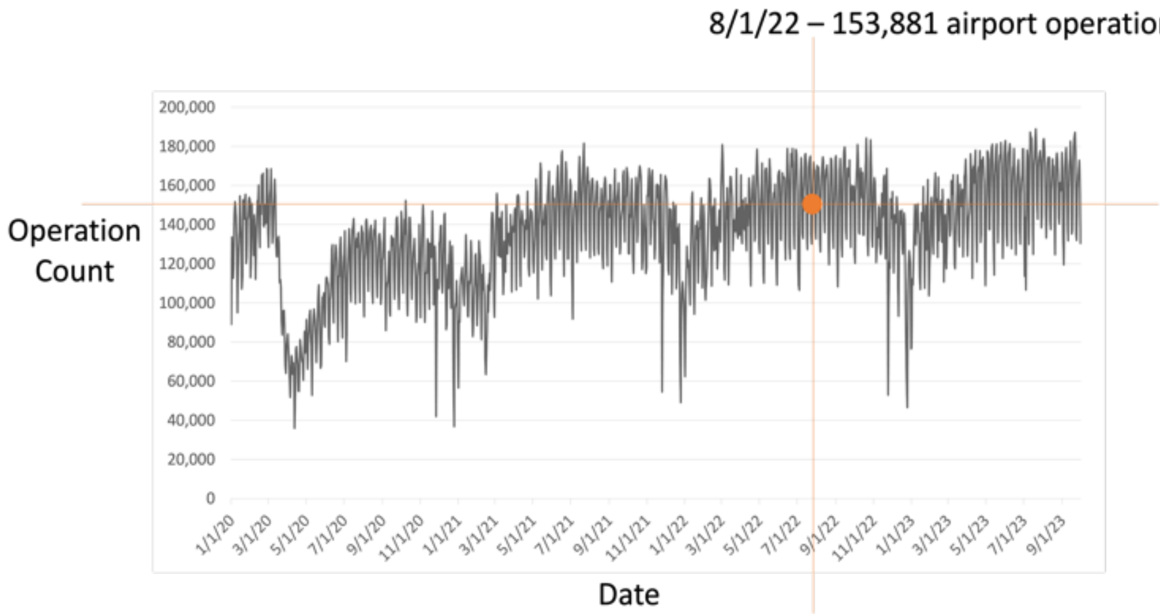


Figure 2. Total Airport Operations vs. Date

The baseline scenario contained a measure of current demand for passenger travel between city pairs. The measure for a specific city pair was estimated by summing the number of seats provided by all flights between the pair. Future scenarios were created in a way that ensured passenger capacity between each city pair was large enough to meet the demand estimated in the baseline scenario. The process for accomplishing this is presented next.

B. Generating Future Scenarios

None of the flights in the baseline scenario were serviced by hybrid electric flights because there were not any of them operating in the NAS on August 1, 2022. Future scenarios were created by inserting hybrid electric aircraft into the baseline scenario in two ways. The first way was to identify flights in the baseline scenario that could be serviced by a hybrid electric aircraft instead of the aircraft type that they were serviced by on August 1, 2022. This type of modification was named hybrid electric replacement because the original aircraft type that serviced the flight was replaced by a hybrid electric. Replacement did not increase the number of flights in the scenario. The second way was to insert additional flights serviced by hybrid electric flights into the scenario. This type of modification was named hybrid electric flight addition because it added to the total number of flights in the scenario. Hybrid electric flight addition was used to match the capacity of the future scenario to the demand of the baseline scenario.

Range and seat count were the primary variables used to identify flights in the baseline scenario for hybrid electric replacement. Two steps were used. First all flights in the baseline scenario with a range between 50 and 300 nm were selected. This set of flights was named the range flight set. Flights with a range less than 50 nm were not included because they were assumed to be for purposes other than transporting paying passengers. The operator’s purpose for each flight was not known. However, there were very few flights, captured in the August 1st data and serviced by aircraft types of interest, that traveled less than 50 nm. Of the flights that did travel less than 50 nm, most took off and landed at the same airport. Flights with a range greater than 300 nm were not included because of the assumption that the hybrid electric aircraft maximum range was 300 nm.

In the second step, the aircraft types servicing each of the flights in the range flight set were considered. Only flights serviced by specific aircraft types were selected for hybrid electric replacement. Table 1 lists the specific aircraft types. These aircraft types were selected based roughly on their seat capacity, range, and prevalence in the system. The number of seats was an estimate because the actual number of seats an aircraft has depends on how the operator configured the seats to accommodate different ticket classes, which was not known.

Table 1. Specific Aircraft Types Used in Replacement

Name	Engine Type	Estimated Number of Seats	Number of Flights Serviced by Type in Baseline Scenario	Future Scenario Case (see section C)
Embraer 120	Turboprop	30	33	1,2,3,4
Short 360	Turboprop	36	39	1,2,3,4
ATR 42	Turboprop	48	36	1,2,3,4
DeHavilland Dash 8	Turboprop	79	101	2,3,4
Embraer 135	Turbofan	37	49	1,2,3,4
Embraer 145	Turbofan	50	395	2,3,4
Bombardier CRJ2	Turbofan	50	395	2,3,4
Bombardier CRJ7	Turbofan	70	320	2,3,4
Embraer 170	Turbofan	72	149	2,3,4
Bombardier CRJ9	Turbofan	83	329	2,3,4
Embraer 75L	Turbofan	83	293	2,3,4
Boeing 717-200	Turbofan	134	128	3,4
Boeing 737	Turbofan	139	351	3,4
Boeing 737-800	Turbofan	162	267	4
Airbus 320	Turbofan	168	112	4

Once a flight was identified for replacement, its aircraft type was changed to a hybrid electric in the future scenario. The next step was to identify how many, if any, additional hybrid electric flights to add to the future scenario. This was accomplished based on number of seats, and it was done in a way that matched replacement and additional hybrid electric aircraft seat capacity with that of the flight from the baseline scenario that they replaced.

Given a flight replacement, if the number of seats of the aircraft type that serviced the flight in the baseline scenario was between 30 to 49, then no hybrid electric flights were added. If the baseline aircraft type had between 50 to 99 seats, then one additional hybrid electric flight was added. If the baseline aircraft type had between 100 to 149 seats, then two additional hybrid electric flight were added. Finally, if the baseline aircraft type had between 150 to 200 seats, then three hybrid electric flights were added. Figure 3 illustrates this process. Boxes outlined in blue represent the flight in the baseline scenario. Boxes outlined in orange represent hybrid electric replacement flights in the future scenario, and boxes outlined in green represent hybrid electric additional flights. Note that the seat capacity of the hybrid electric flights (orange and green boxes) was equal to or greater than baseline scenario flight capacify (blue boxes).

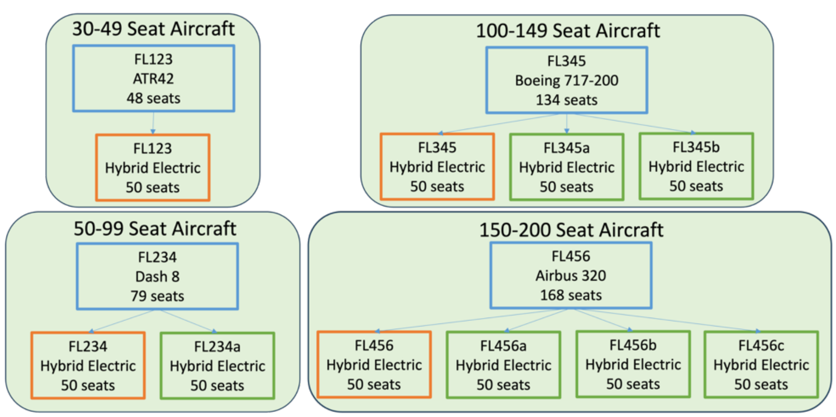


Figure 3. Matching Future Scenario Flight Seat Capacity with that of the Baseline Scenario

New departure times had to be created for additional hybrid electric flights so that they did not takeoff at the same time as their corresponding replacement flight. This was accomplished by adding time to or subtracting time from the corresponding replacement flight's departure time. Table 2 lists the time augmentations depending on whether the additional flight was the first, second, or third additional flight.

Table 2. Departure Time Augmentation

Number Of Added Flight	Departure Time Augmentation
First	+ 10 minutes
Second	- 10 minutes
Third	+ 20 minutes

C. Future Scenario Cases

Four future scenarios were generated to show how impacts change with more aggressive replacement policies. Table 3 lists the scenarios. In scenario 1, only flights in the baseline that were serviced by aircraft types with between 0 and 49 seats were selected for replacement. Scenarios 2 through 4 were generated similarly using the baseline aircraft seat number ranges shown in Table 2. Column 4 in Table 1 matches the scenarios with their replacement aircraft types. All aircraft types in the table were replaced in scenario 4, whereas only a few types in the table were replaced in scenario 1.

Table 3. Scenarios

Scenario	Baseline Aircraft Type # of Seats: # of Replacement and Additional Hybrid Electric Flights
Baseline	none
1	30-49:1
2	30-49:1 and 50-99:2
3	30-49:1, 50-99:2, and 100-149:3
4	30-49:1, 50-99:2, 100-149:3, and 150-200:4

Figure 4 contains bar charts of the flight counts in each scenario. The chart on the left shows total flight counts, and the chart on the right shows hybrid electric flight counts. In the left of Fig. 4, the baseline and scenario 1 have the same number of flights because there were no additional hybrid electric flights inserted into scenario 1. In the right of Fig. 4, the orange portions of the bars represent hybrid electric replacement flights, while the blue portions of the bars represent hybrid electric additional flights. In scenario 1, there were no hybrid electric additional flights. As shown in Table 2, scenario 2 relative to 1 increased the maximum seat capacity of the flights in the baseline that were eligible for replacement. This increase from 49 to 99 seats caused the number of replacement flights identified to increase from 157 to 2,139, scenario 1 to 2 respectively. The increases in hybrid electric replacements in scenarios 3 and 4 were not as large.

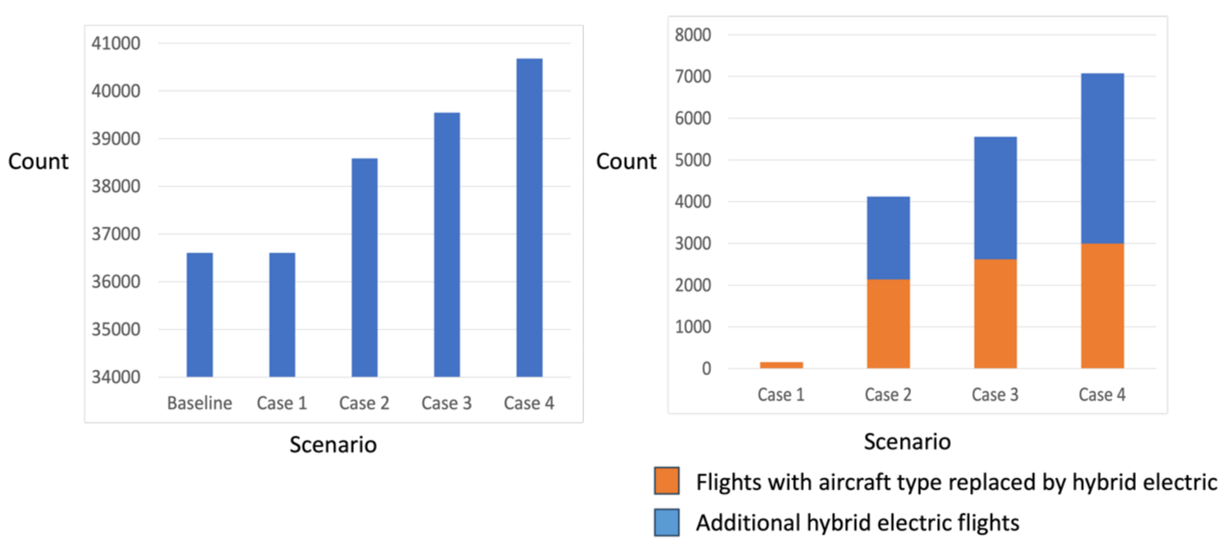


Figure 4. Total (left) and Hybrid (right) Flight Counts in the Scenarios

Figure 5 shows the routes of the hybrid electric replacement flights. In scenario 1, the routes were sparse and were mostly located in California, Florida, and the Caribbean. As the number of replacement flights increased in the scenarios, major hub airports became visible.

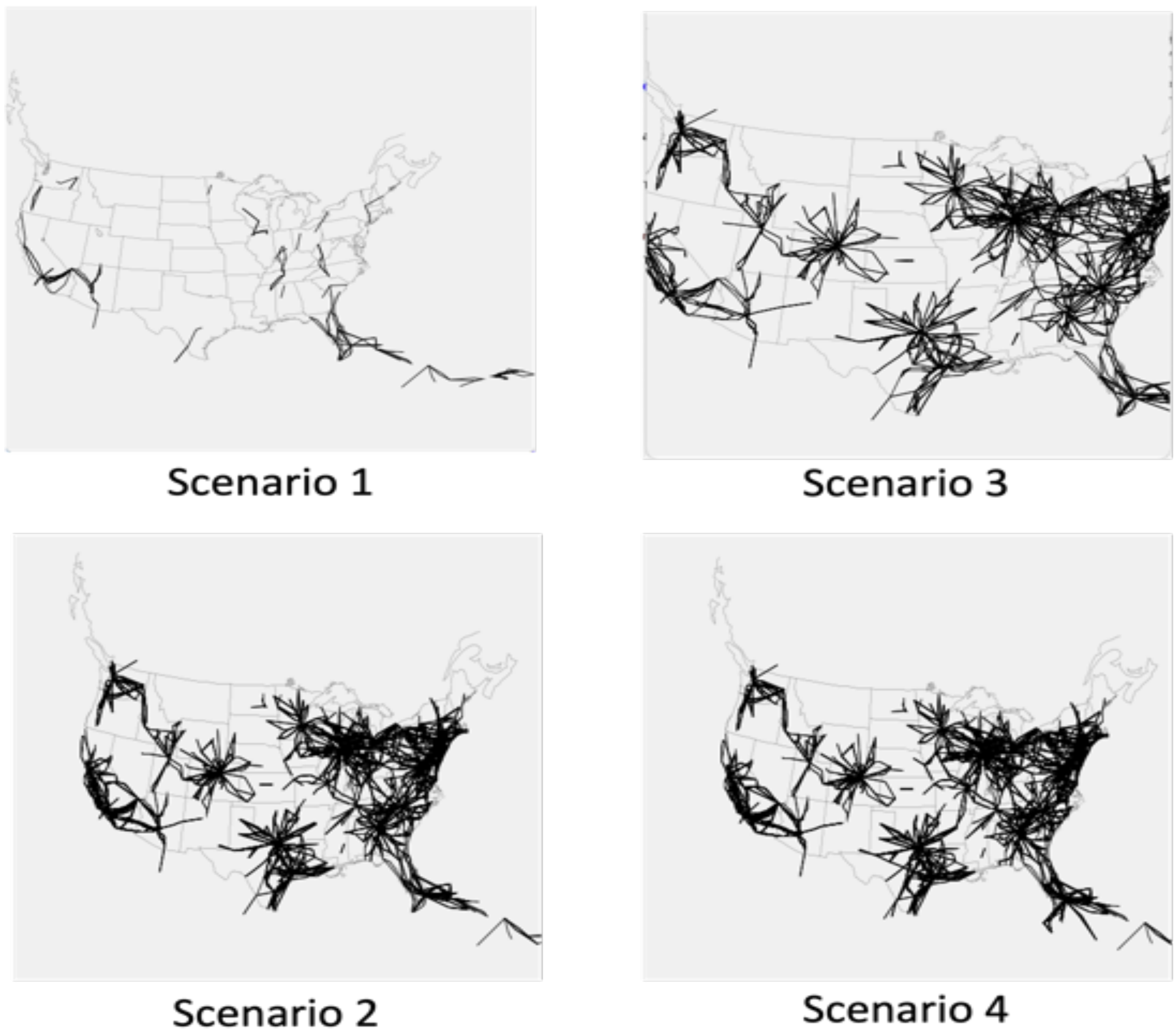


Figure 5. Hybrid Electric Route Structure for the Scenarios

IV. Simulation

NASA's NAS Digital Twin [1] was used to execute the simulations. The NAS Digital Twin is a live, virtual, and constructive (LVC) environment for building and executing simulations of the NAS. In this case, its simulation capability was used to simulate the scenarios. The simulations ran in fast time on a desktop computer. Each flight flew its route, as defined in the scenario file, with no deviations. Since separation was not a focus of this study, the air traffic control and traffic flow management capabilities of the NAS Digital Twin were turned off. The simulation calculated flight tracks, landing times (takeoff times were taken from the scenario file), and fuel burns and stored them to file for post analysis.

Figure 6 shows a screen shot of the baseline and scenario 2 simulations. In scenario 2, hybrid electric flights are denoted with green targets. Other flights are denoted with cyan.

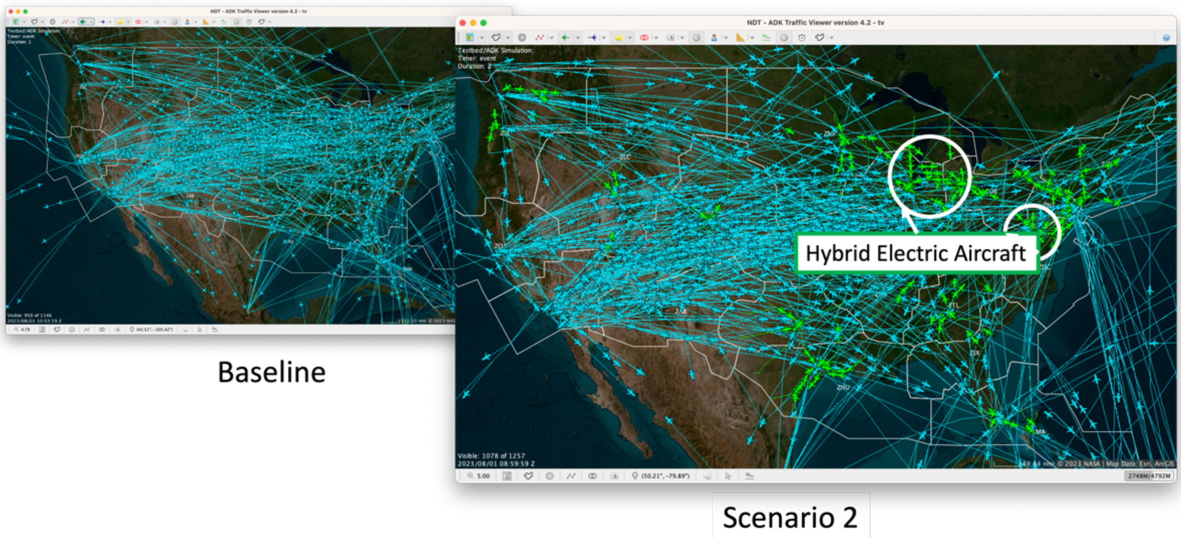


Figure 6. Screen Shots of NAS Digital Twin Simulations

The NAS Digital Twin modeled aircraft using aircraft performance parameters taken from its catalog of aircraft models. The catalog did not have a model of the modified Dash 7, or plain Dash 7, aircraft so an alternate approach to modeling it was needed. The alternate approach was to use the De Havilland Dash 8 model, which was included in the catalog, and reduce its fuel burn rate by half, since half of its engines were electric. The Dash 7 was designed for short takeoff and landing (STOL) capability. Hence, it was high powered for takeoff and climb and less efficient in cruise compared to the Dash 8, which was not designed for STOL. The use of the Dash 8 model made the fuel burn savings reported in this study smaller than would be observed in actual flight of the modified Dash 7.

V. Results

Metrics for flight time, fuel burn, and airport congestions were calculated for the simulation scenarios.

A. Flight Time

Three flight time metrics were investigated. P_1 was the sum of the flight times of the set of hybrid electric flights as a percentage of that of the set of all flights in the baseline scenario. Eq. (1) shows how P_1 was calculated and values are illustrated in the left part of Fig. 7.

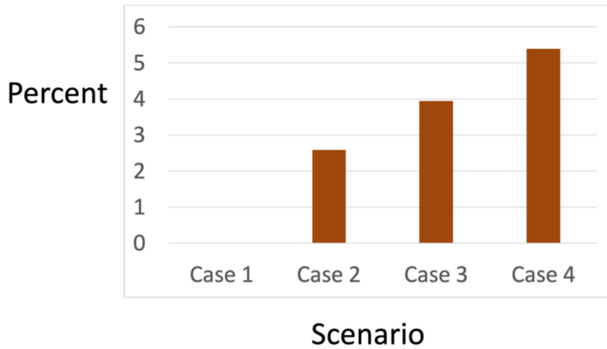
$$P_1 = \frac{\sum_{hybrid\ electric\ flights} t_i}{\sum_{all\ baseline\ flights} t_i} \quad (1)$$

where t_i equals the flight time of the i^{th} flight.

P_2 was the sum of the flight times of the set of hybrid electric flights as a percentage of that of the set of replacement flights in the baseline scenario. Since the set of replacement flights is a subset of the set of all flights in the baseline scenario, P_2 is much larger than P_1. Eq. (2) shows how P_2 was calculated and values are illustrated in the right part of Fig. 7.

$$P_2 = \frac{\sum_{hybrid\ electric\ flights} t_i}{\sum_{replacement\ baseline\ flights} t_i} \quad (2)$$

Flight time is important to operators because it is proportional to crew pay, and it affects maintenance and replacement costs. In the future scenarios, flight time increases were due to the slower cruise speed of hybrid electric aircraft and the additional hybrid electric flights. P_1 and P_2 increases were larger for scenarios 2, 3, and 4 because additional hybrid electric flights were added to those scenarios. For example, crew costs due to flight time increased by 190% with respect to the subset of replacement flights, but only 4% with respect to all flights, for Scenario 3, see Fig. 7 right and left respectively. Although Fig. 7 left does not show a bar for scenario 1, there was a small amount of P_1 that was too small to display.



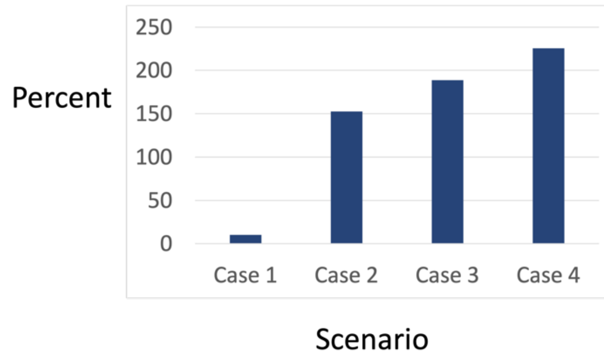


Figure 7. Hybrid Electric Flight Time Increase (P_1, percent flight time of all flights in the baseline (left) and P_2, percent flight time of replacement flights in baseline (right))

Figure 8 presents P_3. It is the hybrid electric average flight time as a percent increase of the average flight time of the replacement flights in the baseline scenario. Eq. (3) shows how this was calculated.

$$P_3 = \frac{\frac{\sum_{hybrid\ electric\ flights} t_i}{number\ of\ hybrid\ electric\ flights}}{\frac{\sum_{replacement\ baseline\ flights} t_i}{number\ of\ replacement\ baseline\ flights}} \tag{3}$$

Taking the flight time average as opposed to its sum reduces the effect of additional flights on P_3. Average flight time is important to passengers as this approximates the flight duration that they would experience. Average flight time increased because hybrid electric aircraft cruised slower than the aircraft types that they replaced. Increases were larger for scenarios 2, 3, and 4 because in those scenarios many of the aircraft types that were replaced were jets. Few jets were replaced in scenario 1.

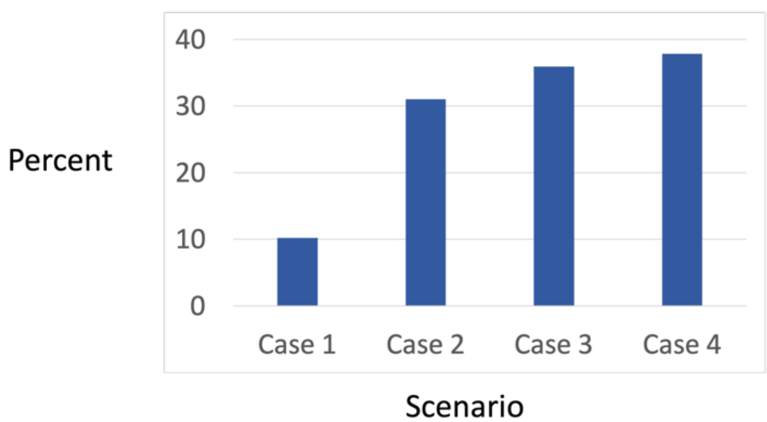


Figure 8. Hybrid Electric Average Flight Time Increase (percent of the average flight time of the replacement flights in the baseline)

B. Fuel Burn

Figure 9 shows the hybrid electric aircraft fuel burn sums as a percentage of those of all flights in the baseline (left) and of the replacements flights in the baseline (right). These fuel burn percentages were calculated similarly to the flight times percentages in Eq. (1) and Eq. (2). Flight times in the equations were replaced by fuel burns. The percentages in the left are two orders of magnitude less than the percentages in the right chart. This is because the number of hybrid electric flights (~200-3,000, orange Fig. 4 right) is small compared to the total number of flights in the baseline (~36,500, Fig. 4 left). In the left of Fig. 9, there is a jump of fuel burn savings (0.39%) from scenario 1 to 2. This is because there was a large increase of flights identified for replacement from scenario 1 to 2. The increases of replacement flights in scenarios 3 and 4 were modest leading to modest increases in fuel burn savings. In the right of Fig. 9, percent fuel burn savings decreased from scenario 1 through 4. This was because increasing numbers of hybrid electric flights were added to the scenarios.

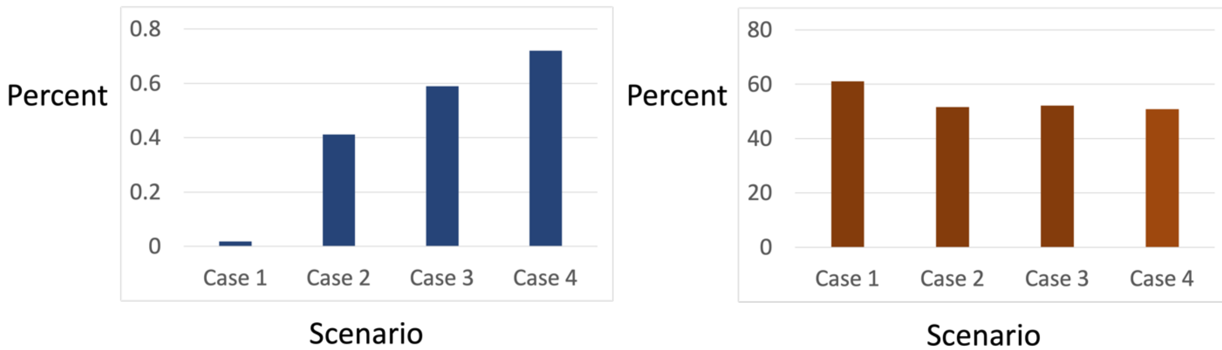


Figure 9. Hybrid Electric Aircraft Fuel Burn Savings (percent of the fuel burn of all flights in the baseline (left) and of the replacement flights in the baseline (right))

According to the left chart in Fig. 9, as the number of flights identified for replacement increased, the percent fuel burn savings increased. Thus, it is useful to consider how many more flight replacements could be gained by increasing the hybrid electric aircraft maximum range. Figure 10 shows a range histogram of flights in the baseline. Flights are placed in 50 nm bins depending on their range. Orange bars denote counts of all flights, and blue bars denote counts of flights served by one of the aircraft listed in Table 1. The blue bars in the box in the lower left denotes the set of replacement flights in scenario 4. According to the chart, if the maximum range of the hybrid electric aircraft could be extended to 350 nm, 1051 more flights would be identified for replacement.

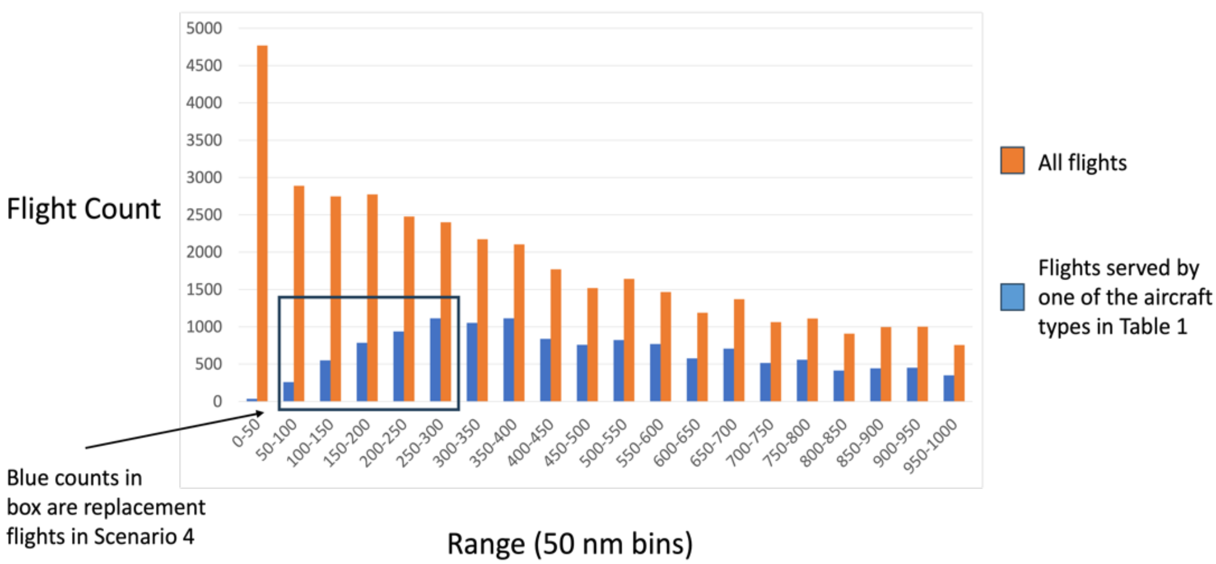


Figure 10. Range Histogram of Flights in the Baseline Scenario

C. Airport Operations

In scenarios 2, 3, and 4 additional hybrid electric flights were inserted to match seat capacity of the future scenarios with that of the baseline. Airport departure and arrival operations were analyzed to understand if the additional hybrid electric flights caused an airport to exceed its capacity.

There were many airports and four scenarios. It was decided to down select scenarios and airports to keep scope of the work manageable. Scenario 3 was selected for airport operations and city pair studies over scenario 4, even though scenario 4 had more addition hybrid electric flights. This was because scenario 4 included replacement of several aircraft types (Boeing 737-800 and Airbus A320, see Table 1) with high seat counts and long ranges. These replacements were considered the least likely of the replacements considered in the work.

The top 19 airports by most operations on August 1, 2022 were analyzed. Chicago O'Hare International Airport (ORD) was selected for in depth study because it had the highest peak hourly operations rates. Figure 11 shows hourly operation counts at ORD. Blue bars denote baseline operations, and orange bars denote scenario 3 operations. The increased height of the orange bars versus the blue bars was due to the additional flights in scenario 3. The high visibility operational capacity of ORD (214 operations per hour) as reported by the FAA is illustrated in Fig. 11. The peak number of operations at the 9th hour from simulation start did not exceed the capacity.

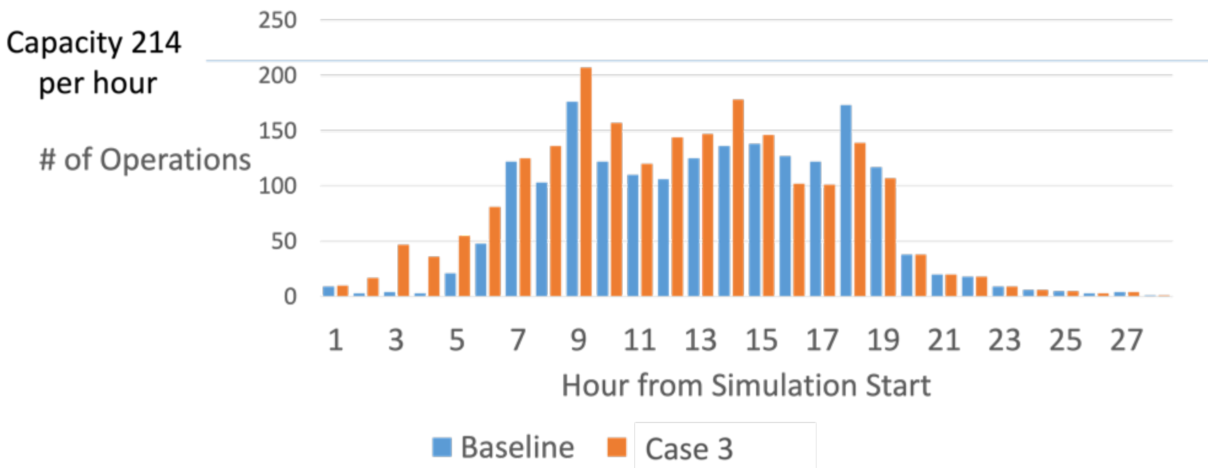


Figure 11. Chicago Airport Hourly Operations for Baseline Scenario and Scenario 3

Table 4 lists selected airport peak hourly operations and capacities for the baseline and scenario 3. These were picked either due to peak operations approaching capacity or large amounts of additional hybrid electric flights. The closest airport to exceeding capacity was JFK at 94% of capacity. The table also shows the airports with the highest increase in operations due to additional hybrid electric flights. The two greatest increases were ATL with 17% and LAS with 15%.

Table 4. Airport Peak Operations and Capacities

Airport	Baseline Peak Operations	Scenario 3 Peak Operations	Peak Operation Percent Increase	Capacity in High Visibility	Scenario 3 Peak Percent of Capacity
ATL	146	175	17%	250	70%
DFW	152	162	6%	204	79%
DEN	143	163	12%	266	61%
ORD	172	193	11%	214	90%
LAX	103	114	10%	176	65%
JFK	84	85	1%	90	94%
LAS	81	95	15%	118	81%
MCO	67	68	2%	160	43%
CLT	134	155	14%	172	90%

An important challenge with building the baseline was including all the flights that operated in the NAS on August 1, 2022. If there were flights that operated in the NAS on that day, but did not appear in the baseline, the traffic in the baseline simulation would not be representative of the actual traffic that occurred on that day. Flights were missing from the baseline because they were missing from the data used to generate the baseline or they were in the data but missing key information needed to simulate the flight.

Figure 12 shows a bar chart of airport operation counts for 19 US airports with the greatest number of operations on August 1, 2022. Orange bars denote operations in the baseline scenario, whereas blue bars denote operations recorded in the FAA's OPSNET system. According to Fig. 12, OPSNET counted more operations than are in the baseline scenario. On average the baseline scenario counts are 82% of the OPSNET counts. Las Vegas airport is an outlier with the baseline scenario count being 58% of the OPSENT counts. It is believed that Las Vegas is an outlier due to it serving a larger number of flights operating under visual flight rules and in uncontrolled airspace.

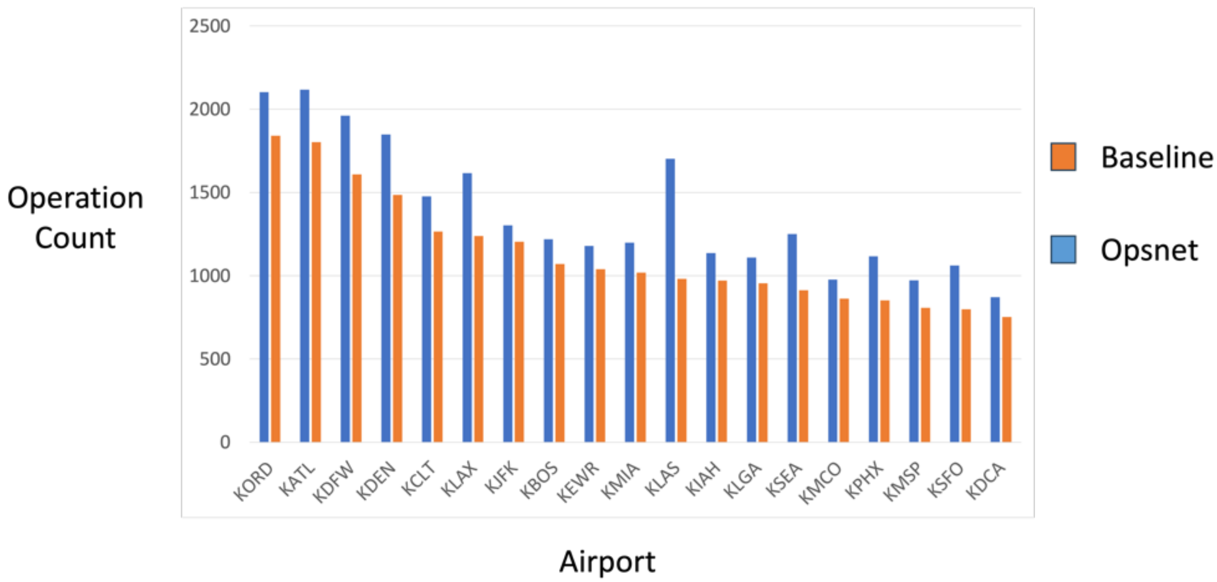


Figure 12. Airport Operation Counts for Top 19 Airports

Given the short fall of airport operations in the simulations shown in Fig. 12, the hourly airport operations count in the future simulations could be low. Accounting for this affect may cause some airports to exceed capacity during peak hours. However, if an airport did exceed capacity in a peak hour, the excess operations could be moved into an adjacent hour that did not exceed capacity. This would either cause delays or the airlines to shift departure times in future flight schedules.

In addition, the airport capacities listed in this paper are for high visibility conditions. Airports being affected by other visibility or bad weather conditions could be highly impacted by the additional hybrid electric flights. Another caveat was that an average summer traffic day was selected. On a peak traffic day, peak hourly operations at some airports may exceed capacity.

D. Airport Pair Analysis

Travel from Ronald Reagan Washington National Airport to Newark Liberty International Airport was selected to be presented because this airport pair had had a large amount of hybrid electric replacement and additional flights. In addition, the aircraft replacement type was thought to be interesting. It was a CRJ7, which is a jet with a little more seat capacity than the Dash 7. There were 18 flights between these two airports in the baseline. All 18 flights were serviced by CRJ7s, which have 70 seats. In scenario 3, these 18 flights were substituted with 18 replacement and 18 additional hybrid electric flights, providing a total of 38. Table 5 lists fuel and time metrics for the airport pair. In scenario 3, even with 18 additional flights total fuel burn of scenario 3 was less than half of that of the baseline.

However, passengers waited 53 minutes in scenario 3 versus 36 minutes in the baseline for the flights to complete. In addition, crew costs for scenario 3 were approximately three time those of the baseline.

Table 5. Metrics for Ronald Reagan Washington National Airport to Newark Liberty International Airport

Metric	Baseline	Scenario 3
Total Fuel Burn (pounds)	30,678	12,957
Point to point time (minutes)	36	53
Total Crew Time (hours)	10.3	30.4

VI. Future Work

Metrics for airports, scenarios, and city pairs thought to be interesting were presented in the paper. The study could be repeated, except analyzing a larger number of airports, scenarios, and city pairs.

Operators use an aircraft to support multiple flights in a day, where each flight is commonly called a leg. In this study, flight legs with less than 300 nm ranges were identified for hybrid electric aircraft replacement. If one of these legs was preceded or followed by a leg with greater than 300 nm, replacement with a hybrid electric would mean that a different aircraft would be needed to support the other leg with greater than 300 nm range. This could compromise the operator's business strategy. Future work could study this issue.

The Electrified Powertrain Flight Demonstration project is studying other different electric aircraft concepts with different ranges and payloads. Future studies could investigate the fuel burn and time impacts of these aircraft.

Gate turn around for electric powered aircraft will require changes from today's gate turn around process. Batteries will need to be recharged. This would require additional electricity capacity at airports and time for charging. A future study could look at these challenges.

This study focused on fuel burn savings without addressing electric energy use. A future study could investigate the electric energy use in more detail.

VII. Conclusions

This study investigated the impacts on fuel burn and flight time of hybrid electric aircraft operating in the National Airspace System. The approach was to create future scenarios containing flights serviced by hybrid electric aircraft and supplying today's capacity for transportation of passengers between city pairs. These scenarios were simulated in NASA's NAS Digital Twin. Four scenarios were created with progressive ones containing more flights that had their aircraft type replaced by hybrid electric aircraft. When an aircraft with more seats than the hybrid electric aircraft was replaced, additional hybrid electric flights were added to the future scenario to keep its total number of seats equal or greater to those in the baseline scenario.

Simulation results showed that hybrid electric operations saved, depending on the scenario, 0.01 to 0.7 percent of the total fuel burn of all flights. The savings were 50 to 60 percent of the fuel burn of flights that had their aircraft types replaced by hybrid electric airplanes. The savings percent of all flights could be increased by identifying more flights for hybrid electric replacement. Savings were greater for scenarios with more hybrid electric replacement flights.

Flights operating today (Baseline scenario) were considered eligible to be serviced by hybrid electric aircraft in the future based on their aircraft type, seat capacity, and range. If only flights serviced by turbo props with between 30 to 50 seats were considered eligible (Scenario 1), there were only 157 hybrid electric operations in the future. By expanding the set of eligible flights to include those serviced by turbo fans with between 50 to 100 seats (Scenario 2), there were 2,139 hybrid electric operations in the future, over 10 times increase. However, this increase came with the cost of adding additional hybrid electric flights to make up for lost seat capacity.

Hybrid electric operations increased, depending on the scenario, total flight time 0.01 to 5.5 percent of the total flight time of all flights. The increase was 25 to 225 percent the total flight time of flights that had their aircraft type replaced by hybrid electric airplanes. Total flight time is important to the operator because that time is directly related to the costs of paying flight crews. Increases were greater for scenarios with more hybrid electric replacement flights.

Average flight time increased, depending on the scenario, by 10 to 38 percent of the average flight time of the flights that had their aircraft type replaced by hybrid aircraft. This occurred because the hybrid electric aircraft cruised slower than the aircraft that they replaced. Later scenarios had longer average flights times because these scenarios had more jets replaced by hybrid electric aircraft and had more additional hybrid electric flights.

The additional hybrid electric flights added to scenario 3 did not cause any airports to exceed their operational capacity. These results are valid for days with clear weather and low winds.

Flights identified as being serviceable by hybrid electric aircraft in the future were identified in this study based on performance criteria, seat capacity and range. Other criteria such as cost, business goals, and environmental regulations will also affect an airline's future decision to purchase and operate hybrid electric aircraft.

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