ANALYZING THE IMPACTS OF SUSTAINABLE POWERTRAINS FOR SHORT-HAUL COMMUTER AIRLINES

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Abstract

In this abstract we have retrofitted an AVGAS-fueled 9-pax small commuter aircraft with three powertrains: all-electric, hybrid-electric, fuel cell hybrid-electric. The retrofitted aircraft will be employed to perform routes currently flown with the conventional version of the aircraft. For each fleet, we estimated the amount of fuel/hydrogen used, necessary electric energy to recharge the batteries, and the resulting well-to-wake CO_2 emissions.

Keywords: hybrid-electric aircraft, electrified aircraft operations, sustainable aviation, advanced air mobility, commuter aircraft

1. Introduction

All-Electric (AE), Hybrid-Electric (HE), and Fuel Cell Hybrid Electric (FCHE) powertrains promise lower noise, lower fuel burnt, and lower gaseous emissions [1], [2], but their adoption has been limited by the heavy weight of electrical machines and batteries. Small regional aviation represents a good study case to test electrified aircraft, since battery technology is mature enough for short-term application (~2030), while it remains a long-term option for medium-sized jet airplanes. Electrified regional aviation has been the focus of multiple research and industrial efforts in recent years, like the Sweden-based Heart Aerospace [3], Los Angeles-based Wright Electric [4], Israeli/American Eviation Alice [5], Slovenian Pipistrel with the first certified electric aircraft [6], Universal Hydrogen [7] and many more. It is worth noting that there are numerous other prototypes and ongoing projects in the field of AE and HE aircraft development, and the list is constantly expanding as new projects emerge.

Although the emission share of regional aviation is low compared to jet liners, amounting to less than 6% of CO_2 emissions from the aviation industry in 2019 [8], decarbonization of the regional segment might open the door to new types of short haul transportation for underserved communities, exploiting existing and under-utilized airport infrastructure, and turning rural airports into hubs for renewable energy and hydrogen storage [9], in addition to serving as a platform to test the safety and operational aspect of using sustainable powertrains in aviation.

This paper makes use of the results obtained in [10] and [11] where Aeronomie, a medium-fidelity simulation framework developed at Argonne National Laboratory was used to retrofit a small regional 9-pax aircraft similar to [12] with an AE, HE, and FCHE powertrain. The retrofitted versions of the airplane are then employed to replace the flights currently done with conventional aircraft in the USA by [13] a regional airline that makes use of similar aircraft for small regional transportation. The company has already shown interest in transitioning their fleet towards an AE alternative, by signing a letter of intent to buy 75 all-electric 9-seater aircraft [14].

2. Methodology and application

2.1 Aircraft specifications

The four variants of the Small Commuter Aircraft (SCA) are labeled SCA-CONV for the conventional, SCA-AE for the all-electric, SCA-HE for the series hybrid-electric, and SCA-FCHE for the fuel-cell hybrid-electric version. The aircraft variants were sized such that the Maximum Take-Off Mass

(MTOM) of the original conventional aircraft would not be exceeded, and that the original aircraft airframe could be reused. Table 1 shows a summary of the aircraft specifications for each variant, detailing the payload/range capabilities, graphically depicted in Figure 1.

Table 1: Specifications of the small commuter aircraft in all the powertrain variants.

	CONV	AE	SHE	FCHE
Maximum take-off mass (MTOM)	3,600 kg (7,937 lb)			
Max cruising speed (10,000 ft)	194 KTAS (223 mph)			
Take-off/landing distance	791/743 m (2,596/2,438 ft)			
Take-off power	2 x 280 kW (2 x 375 hp)			
Range (km)	824	103.5	263	368
Fuel burned (kg)	467.9	-	150	37
Battery energy used (kWh)	-	334.3	37.9	37.9
Average fuel flow (kg/h)	127.20	-	84.8	17.5
Batt. energy use per pax-km (Wh/pax-km)	-	359.0	16.0	11.4
Well-to-wake CO2 emissions (kg/km)	2.10	0.56	2.09	1.12

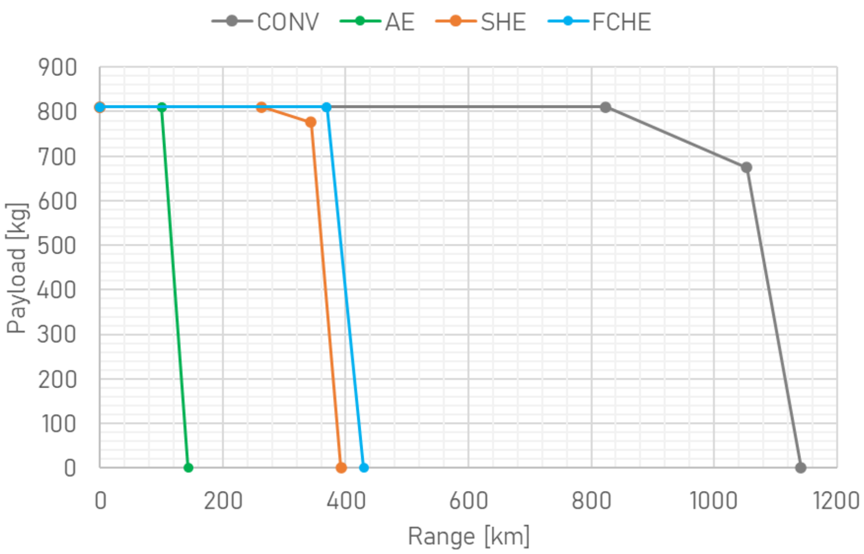


Figure 1: Payload-range curves of all aircraft variants.

A typical mission of the conventional version is 824 km, and includes climbing at 500 ft/min, cruise at 6,000 ft and 148 KEAS, descent at -500 ft/min, 45 min loiter at 1,500 ft, approach, and landing. The limited rates of climb and descent are due to the lack of cabin pressurization. All the retrofitted variants of the aircraft can fly the same payload but for a reduced range. In particular, the SCA-AE can only fly 103.5 km, SCA-HE 263 km, and SCA-FCHE 368 km plus 45 min reserve. All the variants can provide the same engine power as SCA-CONV; hence takeoff/landing distance, maximum rate of climb, and peak cruising speed are preserved.

Battery technology envisioned for SCA-AE, SCA-HE, and SCA-FCHE is based on 500 Wh/kg at cell level and peak C-rate of 6.5. This type of battery specific energy is expected to be available before 2030 [15]. SCA-FCHE is equipped with two 400 L Type-IV hydrogen pressure vessels, and Proton Exchange Membrane (PEM) fuel cells with 2,100 W/kg at the pack level, which is in line with DOE

Technical Targets for Fuel Cell Systems and Stacks for 2020 and similar to FC packs employed for ground applications [16]. More data about the four aircraft can be found in [10] and [11].

2.2 Current fleet operation

The BTS-100 database, which details all US flight origin-destination, range and passenger data was used to identify all flights operated by a small US regional airline Cape Air [13] in 2022. The total number of flights performed was 74,951 across 92 routes. The current fleet includes 67 Cessna 402s, 4 Britten-Norman Islanders, and 30 Tecnam P2012 Traveller [17]. The BTS-100 database does not distinguish flights operated among the three aircraft, but by analyzing current flight routes it emerged that all flights in the USA (including flights occurred in Puerto Rico and Virgin Islands), are suitable candidates for SCA-CONV. Table 2 shows a list of the considered airports and the respective number of departures.

Table 2: List of considered airports and departures.

IATA Code	ICAO Code	Location	No. Departures
BOS	KBOS	Boston, MA	14523
SJU	TJSJ	San Juan, PR	6215
ACK	KACK	Nantucket, MA	6075
STT	TIST	Saint Thomas, VI	3510
HYA	KHYA	Hyannis, MA	3430
STL	KSTL	St. Louis, MO	3413
BIL	KBIL	Billings, MT	3298
MVY	KMVY	Vineyard Haven, MA	3105
STX	TIST	Saint Croix, VI	2483
VQS	TJVQ	Vieques, PR	2250
LEB	KLEB	Lebanon, NH	2013
ORD	KORD	Chicago, IL	1853
MWA	KMWA	Marion, IL	1694
PVC	KPVC	Provincetown, MA	1433
SDY	KSDY	Sidney, MT	1420
BHB	KBHB	Bar Harbor, ME	1376
MAZ	TJMZ	Mayaguez, PR	1344
RKD	KRKD	Rockland, ME	1279
BNA	KBNA	Nashville, TN	1166
AUG	KAUG	Augusta, ME	1142
UIN	KUIN	Quincy, IL	1054
SLK	KSLK	Saranac Lake, NY	1014
OWB	KOWB	Owensboro, KY	988
RUT	KRUT	Rutland, VT	972
GDV	KGDV	Glendive, MT	969
IRK	KIRK	Kirksville, MO	961
MBL	KMBL	Manistee, MI	910
BRL	KBRL	Burlington, IA	758
OLF	KOLF	Wolf Point, MT	739
GGW	KGGW	Glasgow, MT	731
HPN	KHPN	White Plains, NY	636
HVR	KHVR	Havre, MT	627
CPX	TJCP	Culebra, PR	604
JFK	KJFK	New York, NY	484
EWB	KEWB	New Bedford, MA	416
PWM	KPWM	Portland, ME	66

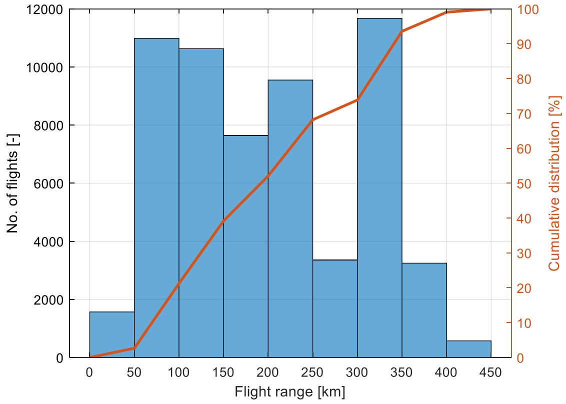


Figure 2: Flight distance distribution.

Figure 2 depicts the flight distance distribution of the considered routes. We can see that 93% of them are 350 km or shorter, while about 52% of flights were within 200 km. Only a limited percentage of the flights are above 350 km, making most flights within reach of SCA-HE or SCA-FCHE.

2.3 Off design simulations

The four aircraft variants were simulated with Aeronomie [18] on several off-design missions at different values of payload and range. Data from these simulations was used to compile lookup tables to quickly estimate fuel burnt, consumed hydrogen, and battery energy when simulating all flights mentioned in Section 2.2. All the off-design missions were simulated in nominal ISA conditions and following the same mission profile described in [10] and [11]. These maps are shown in Figure 3 (a), (b), and (c) for what concerns the fuel consumption of SCA-CONV, SCA-HE, and SCA-FCHE (hydrogen consumption in this case). Figure 3 (d) shows the energy consumption of SCA-AE, while the energy used in every SCA-HE and SCA-FCHE flight amounts to 70% of the total battery energy, i.e. 26.1 kWh. The maps do not include reserve fuel, which is accounted for separately and is added to the take-off mass of the aircraft.

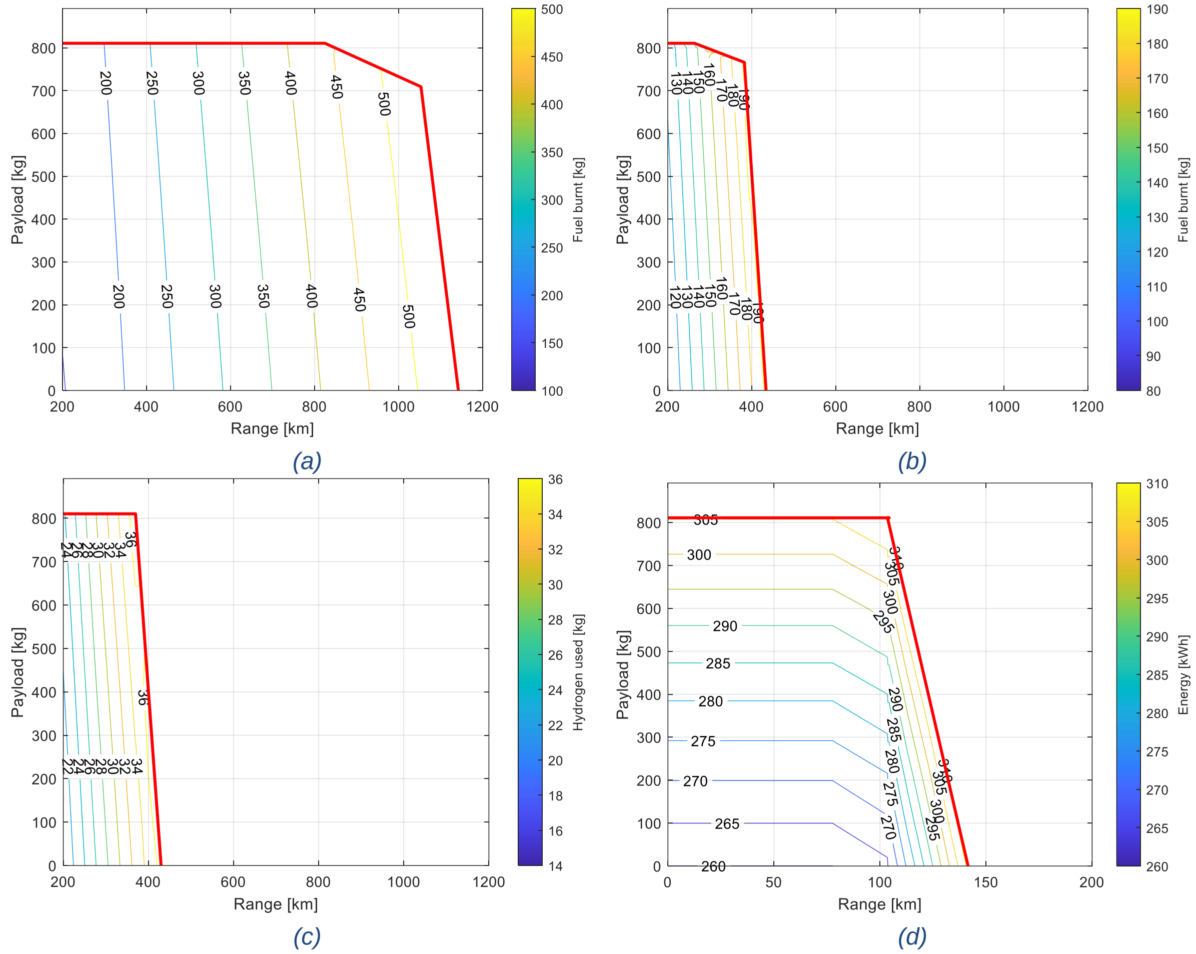


Figure 3. Lookup tables for SCA-CONV fuel burnt (a), SCA-HE fuel burnt (b), SCA-FCHE hydrogen consumed (c) and SCA-AE battery energy used (d).

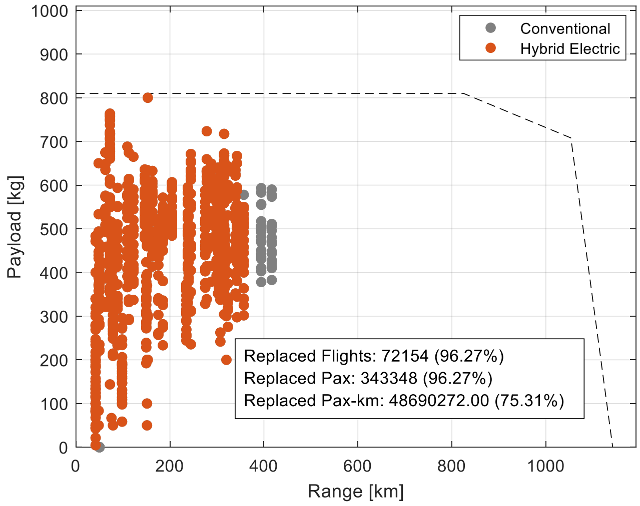
2.4 Fleet replacement results

Once all the routes of interest for the SCA have been identified, we started assessing whether it is possible to operate some of these with the retrofitted *electrified* aircraft. Four scenarios have been evaluated:

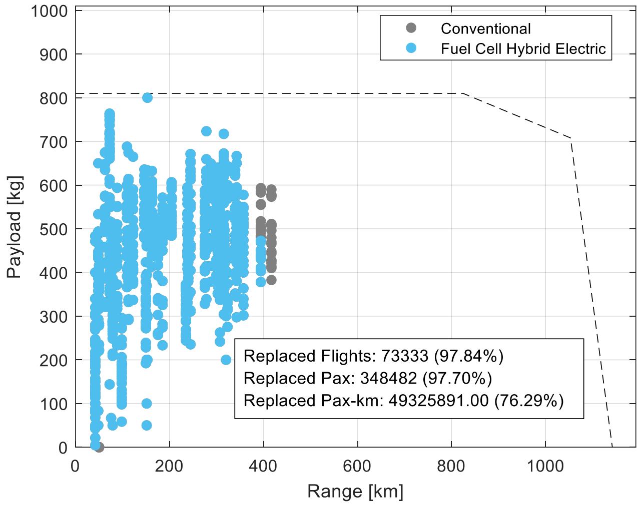
- **Scenario 0**: only conventional aircraft are used. This scenario is used as reference for comparing other powertrain options.
- **Scenario 1**: HE aircraft (SCA-HE) are used whenever it is possible, SCA-CONV is used for remaining missions.
- **Scenario 2:** FCHE aircraft (SCA-FCHE) are used whenever it is possible, SCA-CONV is used for remaining missions.

- **Scenario 3**: AE aircraft (SCA-AE) are used whenever it is possible, SCA-CONV is used for remaining missions.

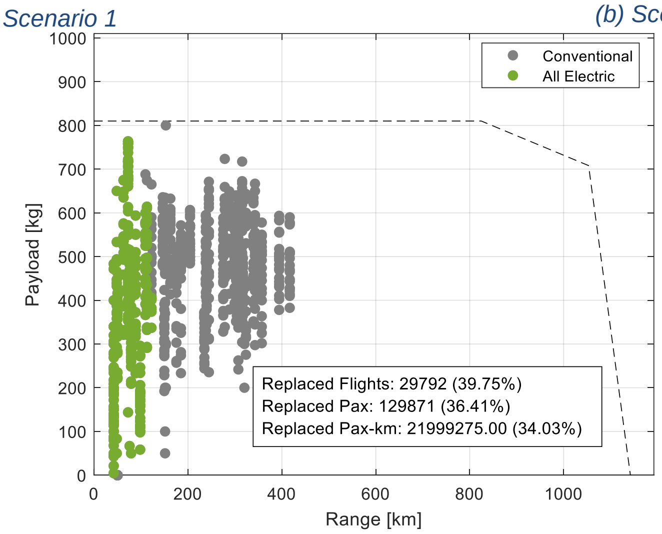
In each scenario, the fleet replacement is done by comparing the payload and range of each flight with the payload/range limits of the new aircraft version. If the new aircraft can fly that mission, then that aircraft will be used.



(a) Scenario 1



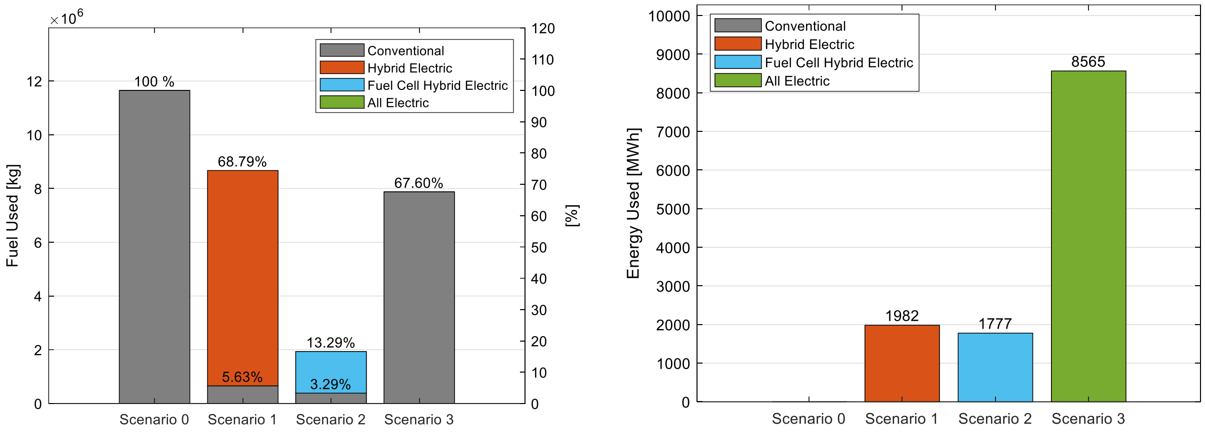
(b) Scenario 2



(c) Scenario 3

Figure 4. Replaced flights with new aircraft variants.

Figure 4 (a), (b), (c) show the resulting feasible missions for Scenario 1, Scenario 2, and Scenario 3 respectively. It emerges how 96.3% of all flights can be replaced in Scenario 1 with the HE airplane, 97.8% in Scenario 2 with the FCHE airplane and 39.8% in Scenario 3 with the AE airplane. The figures also highlight the share of transported pax, and pax-km flown for various powerplants. The outer dotted line represents the payload range graph of the conventional aircraft. We can see how none of the flights has a range greater than 416 km. This makes Scenario 1 and Scenario 2 seem particularly favorable for what concerns a possible replacement of the conventional fleet.



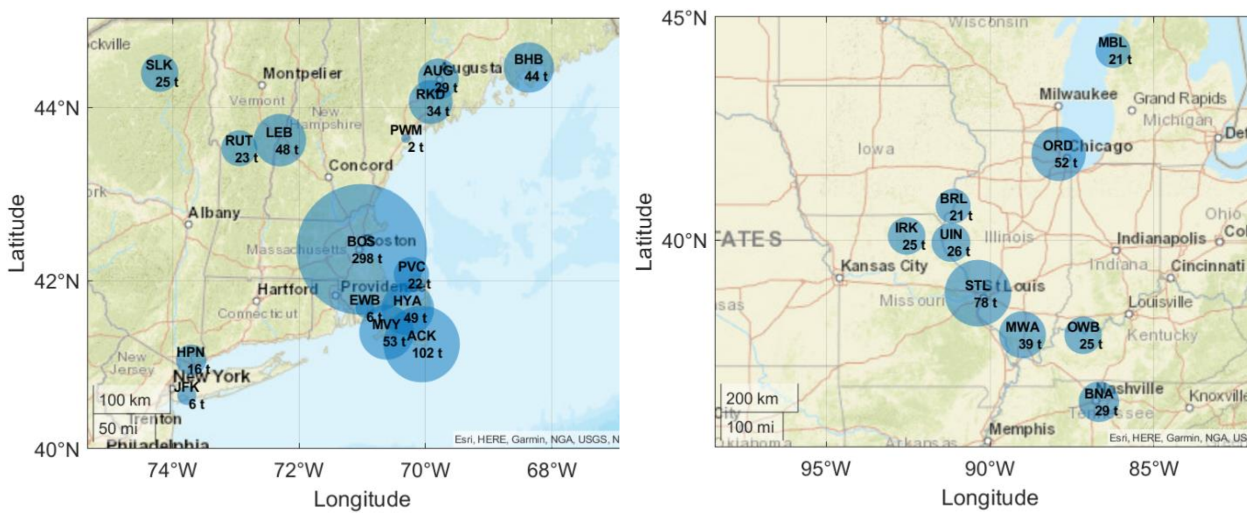
(a) (b)

Figure 5. (a) Fuel or hydrogen used in each scenario. (b) Energy used in each scenario.

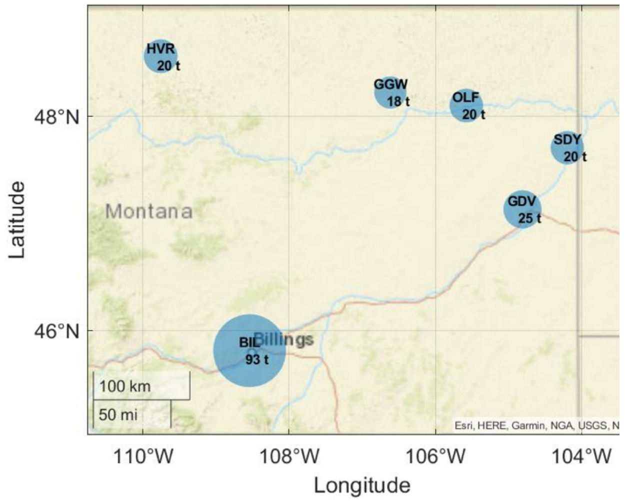
Fuel used in each of the three scenarios is compared in Figure 5 (a) where Scenario 0 is also reported as reference. Since not all the flights can be replaced with, HE or FCHE variant, a residual part of fuel due to conventional aircraft is also present in each case. The fuel reported in the Scenario 3 is only due to the conventional part of the fleet and amounts to 67.6% of the Scenario 0 baseline value. Scenario 2 displays a much smaller value of fuel used, because of the use of hydrogen, whose specific energy (120 MJ/kg) is 2.69 times that of AVGAS (44.7 MJ/kg).

Figure 5 (b) shows the amount of necessary electrical energy to feed each of the fleet. Despite only serving 34.03% of the flights, Scenario 3 displays the highest amount of battery energy necessary, followed by Scenario 1 with 1,982 MWh and Scenario 2 with 1,777 MWh. For perspective, the total U.S. electricity generation in 2019 was 4.12 million GWh [19].

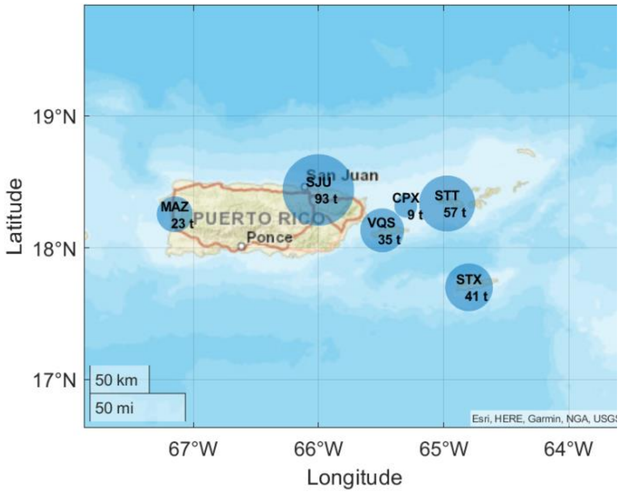
While Scenario 1 could benefit from the existing airport infrastructure for just refueling, with the addition of small chargers to recharge the batteries of SCA-HE - the battery is 37.9 kWh and could be fully recharged in less than 15 min with 250 kW chargers, compatible with the current turnaround time - the same cannot be assumed for Scenario 2 and 3.In addition to battery charging, Scenario 2 is also going to need access to hydrogen supply. This will have an impact on the existing airport infrastructure [20] especially at smaller airports like the ones in Puerto Rico and Virgin Islands. Figure 6 shows the yearly hydrogen needs at all the airports, assuming that each airplane is going to refuel before departure. This data is also summarized in Table 3 for the ten FCHE busiest airports.



(a) North-east region (b) Midwest region



(c) Mountain region



(d) Puerto Rico and Virgin Islands

Figure 6. Hydrogen yearly estimates around main regions of interest for Scenario 2.

Table 3: Amount of necessary hydrogen at each airport.

Departure airport	No. of FCHE flights	Used hydrogen [t]
BOS	14173	298.412
ACK	6097	102.143
SJU	5756	92.848
STT	3532	57.054
HYA	3452	49.055
STL	3435	77.586
MVY	3127	52.695
BIL	2844	92.907
STX	2505	41.278
VQS	2272	34.919
LEB	2035	48.136

The total amount of hydrogen for the whole fleet amounts to 1548.7 t., while the total hydrogen production in the US in 2021 amounted to 110 Mt, and this would represent a small, yet significant fraction of it. The other open problem is whether the ability to refuel hydrogen will be available at all locations. For instance, hydrogen might only be available at the main hubs. This might limit the potential of FCHE adoption, contrarily to what was shown in Figure 4 (b), by the capability to replace the current flights.

2.5 Emission estimates

We analyzed the well-to-wake greenhouse gas (GHG) emissions of the four scenarios by integrating Aeronomie with GREET 2022 [21] . For hydrogen, we assumed it is produced through natural gas steam reforming, as it is the predominant method currently and is expected to continue being dominant by 2030 [22]. According to GREET, the resulting GHG emission factor is 95.5 gCO2eq/MJ. On the other hand, battery energy emissions account for energy production, transportation, and delivery using the U.S. electric energy production mix, resulting in 122.2 gCO2eq/MJ. Since GREET lacks data for AVGAS, we utilized the GHG emission index for jet fuel (89.0 gCO2eq/MJ).

As seen in Figure 7, Scenario 2 (FCHE) has the fewest equivalent GHG emission of all the studied cases, followed by Scenario 3 (AE) and Scenario 1 (HE). The Hydrogen fuel cell operated fleet only produces 43.5% of the total emissions when compared to the baseline, and approximately 57% of the AE and HE scenarios. In scenario 2 the GHG contribution of H_2 is 38.5% of the total emissions, the rest being fuel and electricity related life-cycle emissions. The AE fleet and the HE fleet GHG emissions are very close together, with AE contributing 75.7% of the baseline while HE accounts for 76.3%.

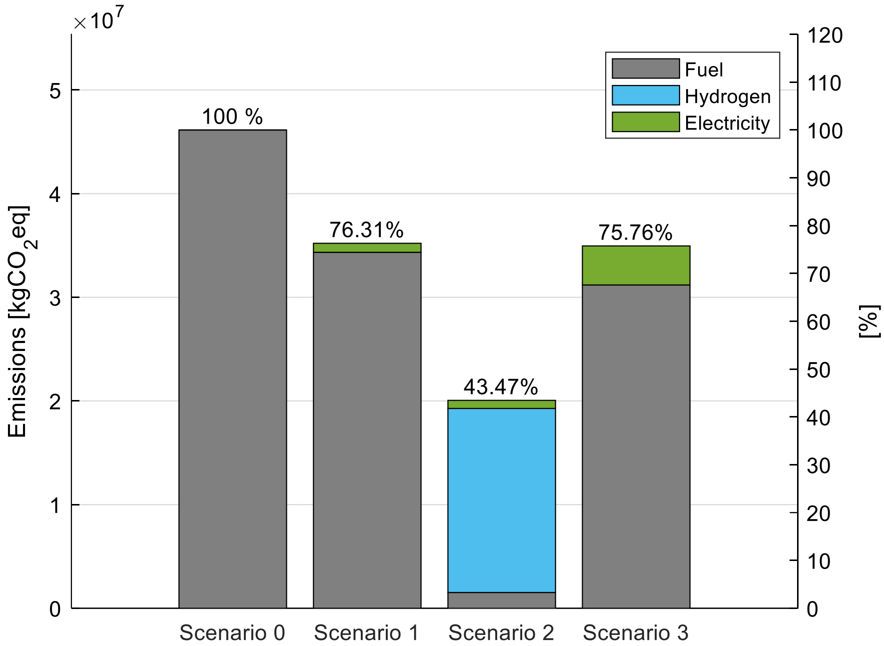


Figure 7: GHG emission comparison for the four scenarios.

Considering the goal of achieving net-zero emissions in aviation by 2050, it is evident that transitioning to new fuels or electricity, despite their higher current pollution levels compared to jet fuel, will yield significant benefits in terms of GHG reduction. Additionally, it is noteworthy that the current fleet of aircraft relies on AVGAS, which contains lead—a substance that has been associated with various health issues. Moreover, these aircraft often operate from small airports located near densely populated areas. The electrification of their powerplants, alongside strategies to regulate the thermal engine on hybrid-electric aircraft, can effectively reduce the sound exposure levels experienced on the ground and benefit local communities [1].

3. Conclusion

This paper analyzes the operations of a 9-seater small commuter aircraft featuring innovative propulsion systems such as AE, SHE, and FCHE on short-haul regional transport routes. In this paper, we detailed the technical specifications of the three retrofitted aircraft plus the original AVGAS-powered version. We also analyzed the flights operated with a current fleet of same or similar aircraft flown by a US regional airline. There were total of 74,951 flights recorded in 2022 by this airline, which were all less than 416 km long.

To reduce the fleet environmental impact, each flight was assigned to either one of the CONV, AE, SHE, FCHE options based on the aircraft range and the mission payload. The results show that electrified aircraft, even with their current limitations, have the potential to replace a significant portion of conventional flights and reduce GHG emissions. The HE and FCHE variants appear to be the most feasible replacements, while AE versions are limited in terms of range. Additionally, the GHG analysis signifies that even with current 'blue-hydrogen', FCHE aircraft can contribute toward significant reductions in emission for short-haul flights. The study also highlights the need for suitable refueling and charging infrastructure, which will need to be developed in parallel with aircraft electrification.

4. Acknowledgements

This report and the work described were sponsored by the U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) under the Energy Efficient Mobility Systems (EEMS) Program. The submitted manuscript has been created by the UChicago Argonne, LLC, Operator of Argonne National Laboratory (Argonne). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

All data used for this study is public. We declare no affiliation, sponsorship, nor any partnerships with Tecnam or Cape Air.

5. Copyright Statement

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