Feasibility of a Solid Oxide Fuel Cell System Applied to Hybrid-Electric Regional Aircraft

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NASA's vision for the future of flight includes highly energy efficient aircraft that are environmentally friendly and have positive national economic impact. Although battery-powered electric aircraft are a viable alternative to reduce environmental impact, purely electric aircraft have drawbacks such as the low specific energy of batteries, which translates to an unfavorable weight scaling. Solid oxide fuel cell (SOFC) systems also have promise in providing environmentally friendly electrical power for new aircraft configurations at a higher efficiency than current methods, such as electrical generators. This study explores the use of the Fostering Ultra-Efficient, Low Emitting Aviation Power (FUELEAP) power system architecture for hybrid-electric regional aircraft. The FUELEAP power system utilizes a SOFC as part of a hybrid-electric power system architecture, enabling higher efficiency and specific power with a reduction in carbon and NOx emissions compared to state-of-the-art hybrid-electric SOFC architectures. The study includes comparisons of hybrid-electric power architectures and integration of the FUELEAP power system for two regional-sized passenger aircraft concepts. Results suggest that use of the FUELEAP power system as a replacement for onboard batteries in a hybrid-electric aircraft may provide up to a 50% reduction in the weight of the electric power and energy system for a typical regional aircraft mission.

I. Introduction

In recent years, NASA has been challenged to explore aircraft technologies that decrease emissions, reduce the dependency on carbon-based fuels, and increase efficiency [1]. Although electrification of aircraft propulsion may provide a path to reach these objectives, the required technologies have not yet matured to the level required to provide all onboard power for a transport aircraft. Near-term applications of electrification may utilize hybrid-electric or turboelectric systems to supplement the auxiliary power and/or engine power requirements. Current internal combustion powertrains for small aircraft only achieve an efficiency of approximately 35% [2][3], while larger powertrains can produce electrical energy at efficiencies above 50%. Due to the efficiency losses associated with turboelectric engines, different hybrid systems should be considered.

In order to overcome the challenge of efficiency loss, the power generation solution should utilize a system that can achieve the high power requirement by regional hybrid-electric aircraft, but with a higher efficiency than current turbogenerator methods, and for near term applications, ideally using fuel available at existing airports. Previous NASA research has used theoretical/future performance for fuel cell technology applications to transport aircraft [4][5]. The Fostering Ultra-Efficient, Low Emitting Aviation Power (FUELEAP) hybrid-electric architecture, utilizing a solid oxide fuel cell (SOFC) and battery with a gas turbine bottoming cycle, has demonstrated these higher efficieny performance capabilities at lower net energy outputs than required for a reigional transport vehicle and is used as the basis of this study [6]. This work aims to investigate the FUELEAP technology as a viable candidate to reduce emissions and the dependency on carbon-based fuels, while increasing the efficiency of the overall aircraft propulsion system. The FUELEAP architecture will be discussed in section II. Next, the methodology of the analysis and sizing will be explained in section III. The application of the FUELEAP architecture to two hybrid-electric regional aircraft will be presented in section IV. Finally, key findings from the current study and future work will be discussed in sections V and VI, respectively.

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II. FUELEAP Architecture Background

From 2016 to 2018, a hybrid-electric SOFC architecture, seen in simplified form in Fig. 1, was developed as part of the FUELEAP project, and a feasibility analysis was completed using a variant of NASA's X-57 "Maxwell" flight demonstrator as a reference platform [6]. This architecture has the benefit of using traditional fuels, while providing higher efficiency than typical turbo-generator solutions. Throughout the research, two different Design Analysis Cycles (DACs) were investigated for this power system, representing existing and near-term technology. A near-term technology option resulted in DAC 1. DAC 1 was designed around meeting the three FUELEAP feasibility goals of installed specific power greater than 300 W/kg, fuel-to-electrical efficiency greater than 60%, and continuous power greater than 75 kW, sufficient for primary power of light aircraft and secondary/auxiliary power for larger aircraft. DAC 1 leveraged lightweight, high-efficiency SOFC components in a hybrid-electric architecture. The pressurized fuel cell, with the addition of hot fuel and air recycle blowers, boosts the specific power to above the feasibility goals. However, there are reliability and maintainability concerns associated with state-of-the-art recycle blowers, which will require more development to meet the reliability goals for this configuration. The final DAC 1 architecture was designed to operate at a maximum continuous power of 120 kW (sized to X-57 motor requirements plus FUELEAP battery recharging during cruise) with a dry specific power of 302 W/kg. The electrical efficiency was 62%, relative to the lower heating value (LHV) of diesel fuel, at the cruise conditions of the X-57. It should be noted that these performance values include a 10 kWh battery with an energy density of approximately 150 W-h/kg.

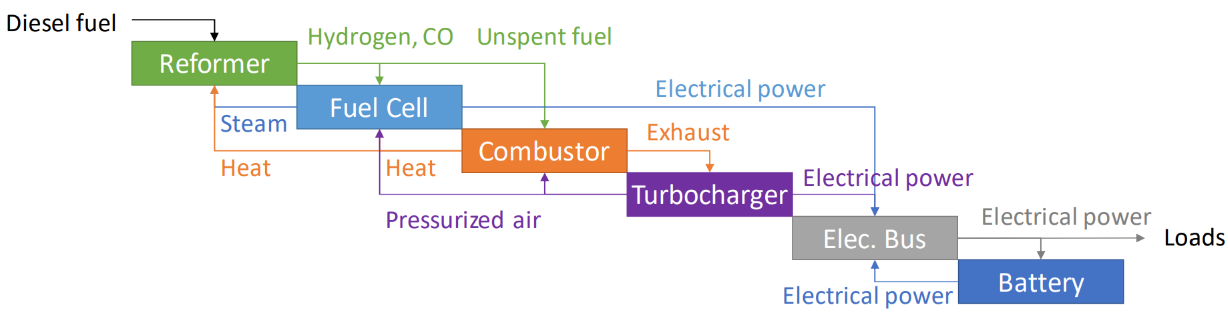


Fig. 1 Heavy-fuel, hybrid-electric SOFC power system architecture used for FUELEAP [6].

An investigation of SOFC configurations that could be implemented with current technology resulted in DAC 2. Although the DAC 2 architecture does not meet the aggressive feasibility goals, there is still promise in this configuration. DAC 2 utilizes a power system architecture similar to DAC 1. However, the hot recycle blowers are replaced with a series of heat exchanges and low-temperature blowers, resulting in a reduction in the overall efficiency. The final performance numbers at the maximum continuous power output of 120 kW were a dry specific power of 281 W/kg and an efficiency of 55%, relative to the LHV of diesel fuel, at cruise conditions for the X-57. The architectures of DAC 1 and DAC 2 with all components other than the batteries can be seen in Fig. 2. Although the overall system is different between DAC 1 and DAC 2, the fuel cell setup is similar, except for the operating voltage and the resulting performance. For this study, the number of stacks, banks, and cells in a stack will be changed in order to reach the required operating power and voltage. Detailed information regarding the trades performed on DAC 1 and DAC 2 and the integration of the FUELEAP architecture into the X-57 can be found in Refs. 6 - 8.

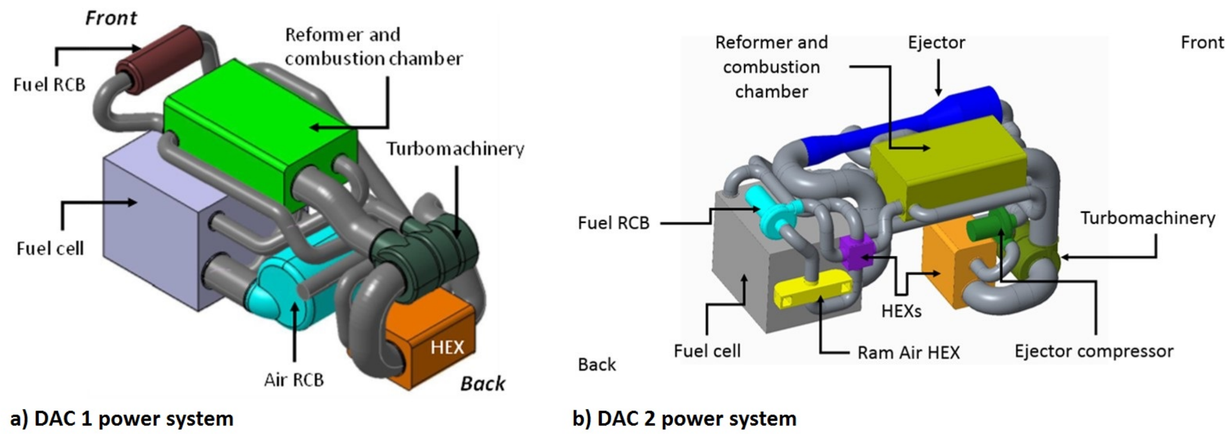


Fig. 2 DAC 1 and DAC 2 layout for X-57-F power system (HEX: heat exchanger, RCB: recycle blower) [6].

III. SOFC Sizing Methodology

Both the DAC 1 and DAC 2 architectures and performance numbers are used to perform feasibility studies for two hybrid-electric regional aircraft and assess whether current and near-term state-of-the-art FUELEAP technology can provide a vehicle level benefit. In Ref. 6, the system efficiency at a maximum continuous output power of 120 kW was provided for altitudes up to 20,000 ft at standard and hot day temperatures (see Fig. 3). For this study, the values are conservatively extrapolated to a cruising altitude of 25,000 feet. The resulting extrapolated efficiency values for DAC 1 relative to current density and altitude can be seen in Fig. 4. Additionally, Ref. 6 provided the efficiency as a function of system output power between 30-120 kW (25-100% load). These efficiencies will be used to determine the best configuration of voltage and current density at a specified altitude that results in the lowest dry weight of the system. The efficiencies are extrapolated to lower loads as well for fuel flow calculations in order to analyze low power requirement flight phases like descent. All values used in this study are for a standard day. A similar study could be performed with the lower power system efficiencies associated with extreme operating conditions.

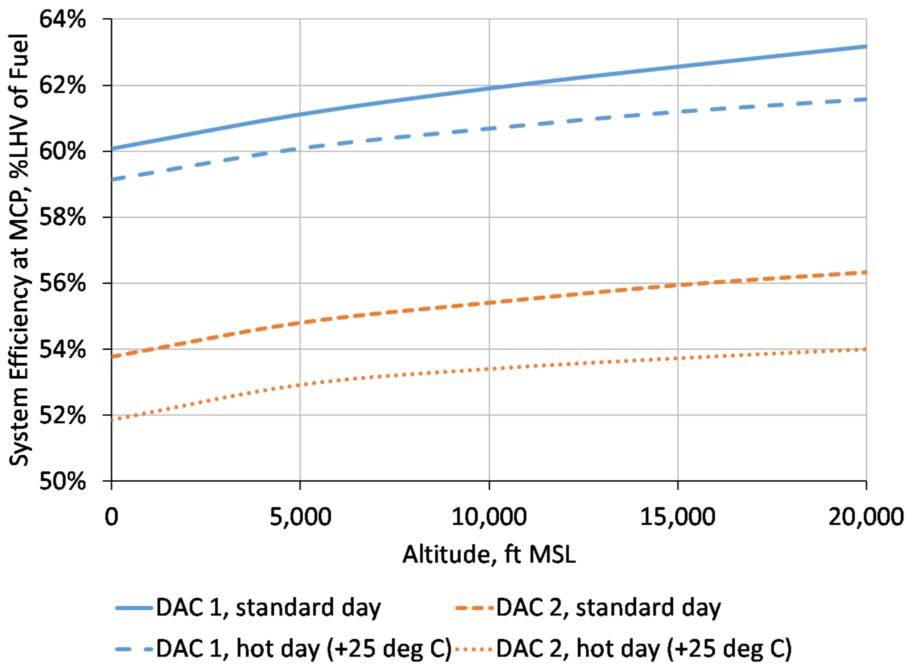


Fig. 3 Net power system efficiency vs. altitude for DAC 1 and DAC 2 architectures at MCP (120kW) [6].

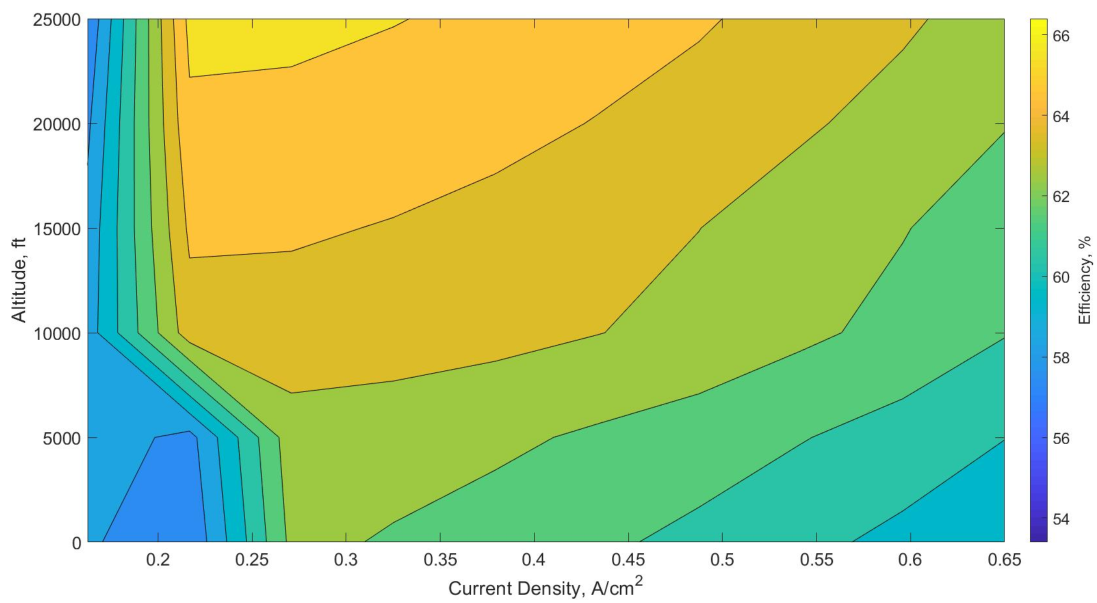


Fig. 4 Net power system efficiency variation with altitude and current density for DAC 1 architecture.

The FUELEAP power system will be reconfigured in such a way that cells with individual constant cell voltages and reactive areas may be added. The variables to obtain a given power will be the operating current density, voltage (number of cells), and altitude. It is assumed that high altitude voltage arcing will be dealt with via more detailed design of the system and, therefore, voltages of up to 2,000 Volts are considered. Current densities are limited to 0.65 Amps/cm^2 and altitudes to 25,000 feet. Banks and stacks can be altered by the number of cells and also the configuration (being placed in parallel and/or series) to achieve a specific voltage and current. These parameters will provide an efficiency of the system at a given altitude and power setting to drive the overall minimal dry weight requirement. Multiple solutions and configurations of the SOFC system may satisfy a given power requirement. In order to pick the best option, the solution selected is the one with the lowest overall dry system weight (fuel cell stacks, fuel cell additional components, and piping), while keeping in mind the voltage of each bank (efficiency lost in voltage/power conversion). The fuel cell component and piping weights are driven by a logarithmic equation fit to data on the FUELEAP system at different power requirements.

The efficiency of the system is mainly driven by the current density or loading of the system. Therefore, using the same range of current densities that were defined in the X-57 feasibility study, the efficiency of the SOFC system is extrapolated to different altitudes, creating an efficiency matrix based upon current density and altitude for a specified maximum power. For this study, the cell voltage remains constant throughout the flight, which is a conservative approach. The efficiency matrix does take into account the benefit of the voltage relief at lower power draws, which typically increases the efficiency of the overall system. The method used in this study may not provide the most efficient system, but it provides a conservative approximation of the fuel consumption and the weights of all required components in the SOFC system based upon a required power and altitude. The fuel weight for all phases is then calculated.

IV. Regional Aircraft Test Cases

A. Conventional Regional Aircraft Configuration Feasibility

Hybrid-electric aircraft may have difficulty matching the performance of traditional vehicles due to the current state of battery technology and the fact that, unlike traditional vehicles, the aircraft does not become significantly lighter throughout the flight due to fuel consumption. In addition, the batteries that are implemented in the aircraft will take up significant volume, which could result in a physically larger aircraft that may degrade mission performance. To assess the impact of these factors, NASA's FLight OPtimization System (FLOPS) [9] was used to conduct a trade study for a hybrid-electric ATR-42-like aircraft. The ATR-42-500 aircraft has a range of 716 nm with 48 passengers, at a maximum ramp mass of 18,770 kg [10]. For the trade study, the percentage of vehicle power coming from batteries, the battery specific energy, and the cruise mission range were varied in order to determine a gross mass. The results of these trades for battery specific energies of 250 W-h/kg and 400 W-h/kg, with an 80% depth of discharge limitation, are shown in Figs. 5 and 6, respectively. The plots show that even a small amount of hybridization can influence an aircraft's mass significantly. The specific energy of 250 W-h/kg approximately represents current technology; 400 W-h/kg is projected to be available in 5 to 10 years. For both battery specific energies at 10% hybridization, it is necessary to reduce the range in order to retain a gross mass similar to an ATR-42. Conversely, with a 400 W-h/kg battery the aircraft would need to be able to carry approximately 5,700 kg additional mass in order to achieve the same 700 nm cruise range as the ATR-42. With the 250 W-h/kg battery assumption, the vehicle sizing does not even converge for a 700 nm mission. Both of these plots showcase the need for increased development in battery technology prior to batteries being implemented as the main sources of energy for regional aircraft.

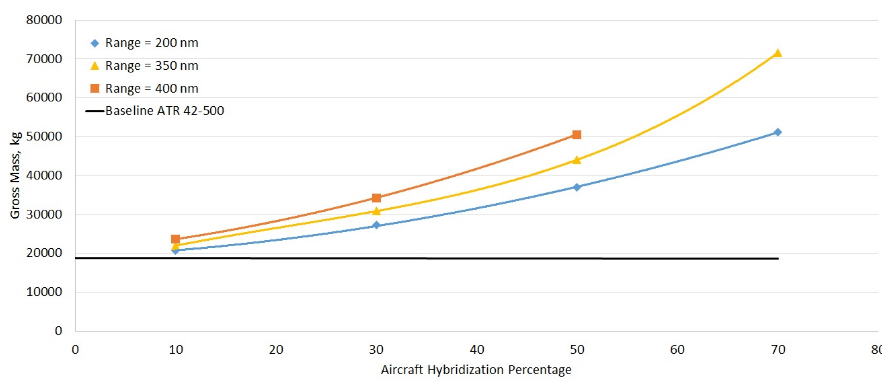


Fig. 5 Regional hybrid-electric aircraft with 250 W-h/kg batteries.

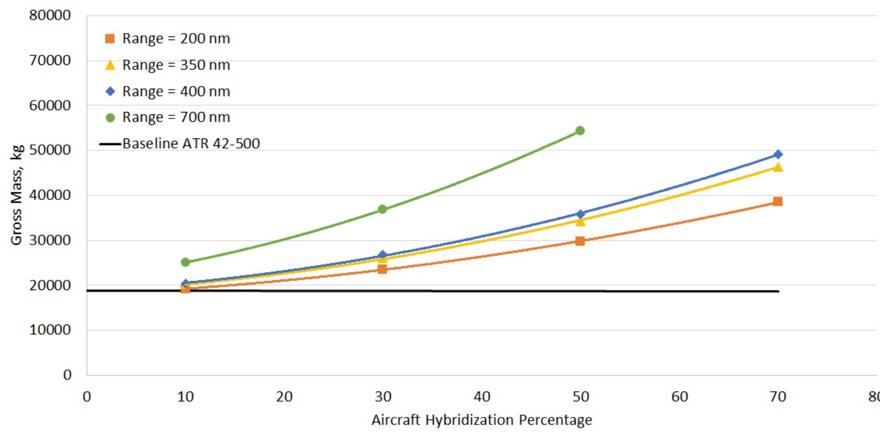


Fig. 6 Regional hybrid-electric aircraft with 400 W-h/kg batteries.

Since the hybrid-electric ATR-42-like aircraft leads to either reduced cruise range or increased gross mass, an alternative FUELEAP power system augmented version is also investigated. The mission profile and required electrical energy from the hybrid-electric ATR-42-like aircraft analysis above is utilized to perform this initial investigation. The electric power source mass (batteries vs. FUELEAP power system and fuel) is compared assuming a battery specific energy of 400 W-h/kg for ranges of 200 and 700 nm and different aircraft hybridization percentages. The 200 nm mission was selected based upon the results in Fig. 6, which indicate that the gross mass of the aircraft is minimally impacted for this range at a 10% hybridization percentage. This vehicle could potentially be designed without any configuration changes, aside from potential volume constraints, to the aircraft. The 700 nm mission is used in an attempt to match the traditional ATR-42 mission requirements. The aircraft hybridization percentage drives how much electrical energy is needed throughout the entirety of a mission. This comparison was completed for both DAC 1 and DAC 2 versions of the FUELEAP system. The results of the electrical power source mass comparison can be seen in Fig. 7. The differences between DAC 1 and DAC 2 are minimal for both missions. However, in comparison to the battery-only hybrid-electric vehicle, using the FUELEAP architecture provides at least a two-thirds mass reduction for both the 200 nm and 700 nm mission cases, excluding the 200 nm mission at 10% hybridization. Although there is minimal mass benefit from a FUELEAP architecture augmented hybrid versus a traditional hybrid with batteries for a short range regional aircraft, the benefit increases as range increases as seen in Fig. 8. In addition, because the energy requirement is driven by the baseline ATR-42-500 hybrid study, the results of the mass savings do not show the full benefit without a vehicle and mission iteration with the reduced gross mass. Comparing a 700 nm aircraft with 50% hybridization using batteries and the FUELEAP integrated architecture, using the FUELEAP architecture reduces the gross mass from 54,000 kg to 34,000 kg. Because the battery hybrid vehicle could not converge past 50% aircraft hybridization for high ranges, there was no electrical data to create a FUELEAP augmented vehicle, although it is assumed that the FUELEAP version could converge and reduce the mass even further.

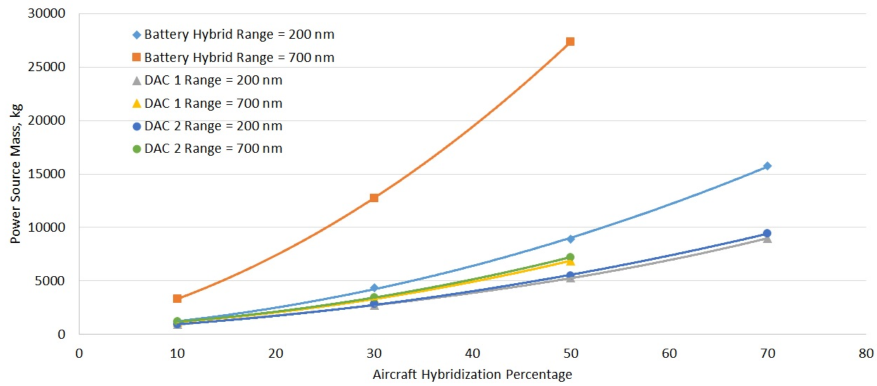


Fig. 7 Power source mass comparison of regional hybrid-electric aircraft with 400 W-h/kg batteries and FUELEAP.

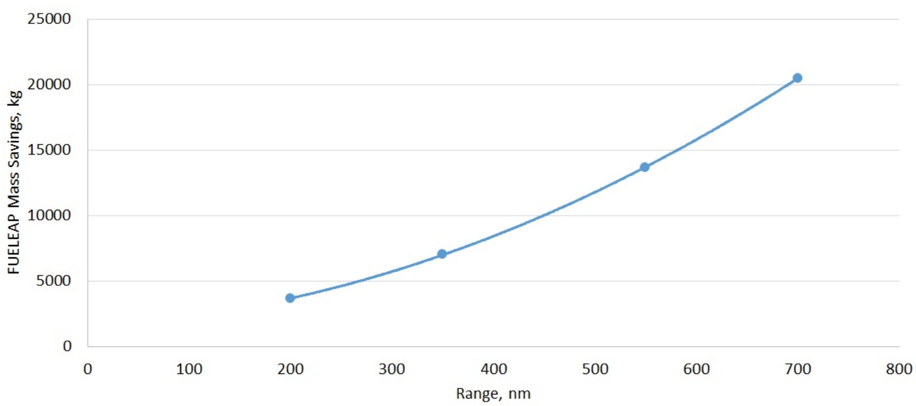


Fig. 8 DAC 1 mass savings compared to 400 W-h/kg batteries at 50% hybridization.

Neither the hybrid-electric battery nor SOFC configuration can overcome the specific energy advantage of a combustion engine burning jet fuel. However, the expected potential benefits from a hybrid-electric vehicle are in the areas of emissions and potential energy cost. A FUELEAP augmented aircraft has the potential to reduce the carbon and NOx emissions. The FUELEAP system produces electric power with zero NOx and, based upon higher efficiencies than a typical combustion design, can reduce carbon emissions. In an effort to qualitatively show the benefit of emissions, the fuel mass will be used as a comparison between a traditional ATR-42 and a hybrid-electric ATR-42-like aircraft with the FUELEAP architecture. The total fuel mass for the ATR-42 includes only the fuel required by the turbines for a specified range and is determined by FLOPS. For the hybrid-electric ATR-42-like aircraft augmented with FUELEAP, the total fuel mass is the sum of the turbine fuel from FLOPS and the required fuel for the SOFC determined by the electrical energy contribution of the system. However, as stated prior, the gross mass of the vehicle increases significantly and therefore fuel mass is not a fair comparison between the two configurations. In Fig. 9, two hybridization percentages can be seen for the hybrid-electric ATR-42-like aircraft using DAC 1. Both trends show an increase in fuel usage, regardless of range, which can be partially attributed to the increase in gross mass. For the 30% hybridization aircraft with DAC 1, the percentage of total fuel consumed by the SOFC ranges from 13% to 16%. Meanwhile, the SOFC uses 26% to 31% of the total fuel weight for the 50% hybridization aircraft with DAC 1. Although the mass increase is not offset by the efficiency of FUELEAP power system, the fractions of fuel consumed by the SOFC lead to a reduction in turbine fuel usage between 10% to 16% for the 50% hybridization aircraft and 2% to 6% for the 30% hybridization case, which can be seen in Fig. 10. With the benefit of zero NOx emissions from the FUELEAP architecture, the reduction in fuel usage for the turbine leads to a direct NOx emission benefit.

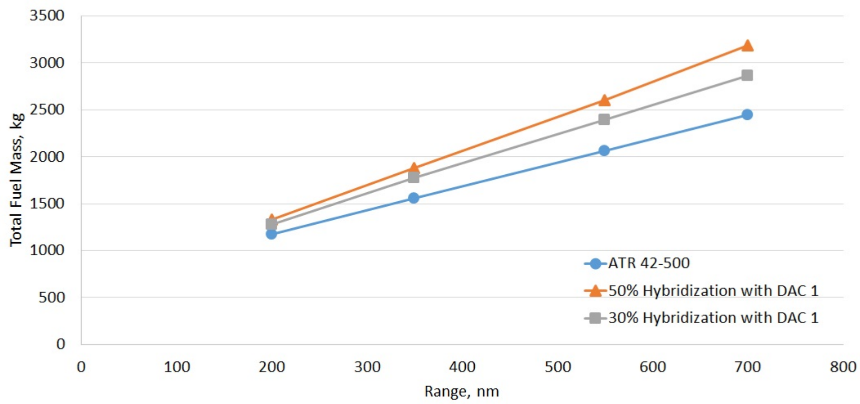


Fig. 9 Total fuel mass comparison for regional DAC 1 hybrid-electric aircraft and ATR-42.

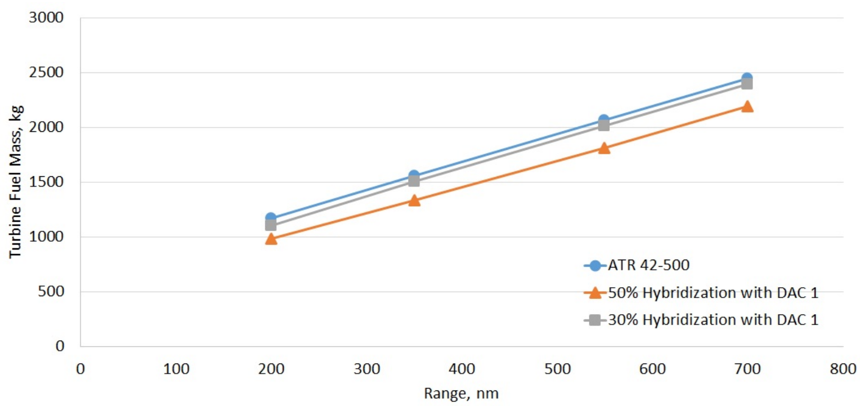
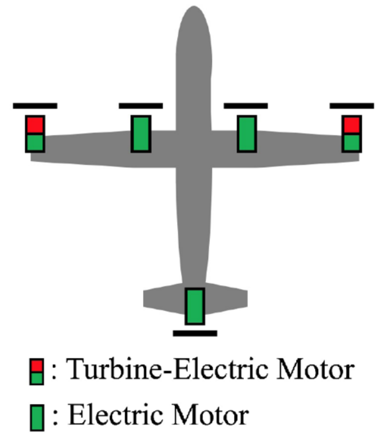


Fig. 10 Turbine fuel mass comparison for regional DAC 1 hybrid-electric aircraft and ATR-42.

B. PEGASUS Feasibility

The second vehicle selected for this study is the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) [11]. This vehicle uses multiple propulsors (as seen in Fig 11) that are located strategically to obtain aerodynamic benefits. Reference 11 provides a detailed description of the potential benefits of the PEGASUS vehicle and some of its analysis challenges.

(a) Artist depiction



(b) Propulsor configuration

Fig. 11 PEGASUS concept.

The PEGASUS vehicle has been designed to operate two missions using the same aircraft architecture. The first mission is a hybrid-electric mission and the second is an all-electric mission. The hybrid-electric mission has a 400 nm range and utilizes a combination of batteries and turbine engines using Jet A fuel. The all-electric mission is only 200 nm and the aircraft is powered solely by batteries. Both missions also include a reserve mission that is hybrid-electric, and therefore the all-electric mission will still have fuel. The available battery technology for PEGASUS is assumed to be approximately 500 W-h/kg [12], representative of an approximate 2030 entry-into-service date. In addition to using the projected, future battery technology, results assuming current battery technology of 250 W-h/kg are also investigated here. However, it should be noted that the baseline PEGASUS is not feasible for battery technology of 250 W-h/kg. For both specific energies, an 80% depth of discharge assumption is used. Each mission is broken into three flight phases: climb, cruise, and descent. Both missions are flown at a cruise altitude of approximately 20,000 feet. The sizing analyses also include a reserve mission. The initial integration of the fuel cell does not change the mission profile, aircraft architecture, or power requirements, only the source of the electrical power. Further iterations begin to change the percentage of gas turbine used and the wing area. The new FUELEAP power system-augmented PEGASUS concept also includes the same turbine engines as the original PEGASUS concept. In addition, the FUELEAP system is capable of providing the power necessary for the all-electric PEGASUS mission.

The feasibility of the FUELEAP power system being integrated into the PEGASUS concept will be determined based on the overall mass reduction of the concept, the reduction in overall energy usage without changing the mission, and the reduction in turbine fuel usage for eliminating NOx emissions. In the current configuration, the PEGASUS concept has a large portion of the mass dedicated to batteries in order to complete the all-electric mission. The SOFC system will be used to supplement the power provided by the batteries and turbines. Also, with the addition of the FUELEAP system, the hybridization of the wingtip propellers for the vehicle concept will change. For the baseline PEGASUS vehicle, 82% of the power generated by the wingtip propulsors come from the gas turbine, and 18% from the electric system. The inboard and aft propulsors are fully electric at all times. Meanwhile, the FUELEAP augmented PEGASUS vehicle uses a 50% split between electric and gas turbine on the wingtip propulsors and keeps the other three propulsors all electric. In this study, the FUELEAP power system design space ranges from 120 kW to 5 MW. These power levels span from a system able to be used as an auxiliary power unit (APU) to a system able to provide the majority of the takeoff power required for the all-electric mission. Any remainder of the required electrical power will be supplemented by batteries. For each FUELEAP power level and battery specific energy, the total power system mass, which includes fuel for the SOFC and turbines, batteries, and the SOFC system, is computed. This is calculated for only the DAC 1 architecture. The final iterated resultant power system masses for DAC 1 operating the PEGASUS hybrid-electric (400 nm) and all-electric (200 nm) missions, prior to minimizing energy consumption, can be seen in Fig. 12. Figure 12 show minimum points for both the current and projected future battery technology assumption sets. For the assumption of a 500 W-h/kg battery, DAC 1 FUELEAP augmentation lead to a minimum total power system mass with approximately 1.0 MW of power produced by the FUELEAP power system. For the assumption of 250 W-h/kg battery technology, the DAC 1 FUELEAP augmentation lead to a minimum total power system mass with approximately 2.0 MW of power produced by the FUELEAP power system.

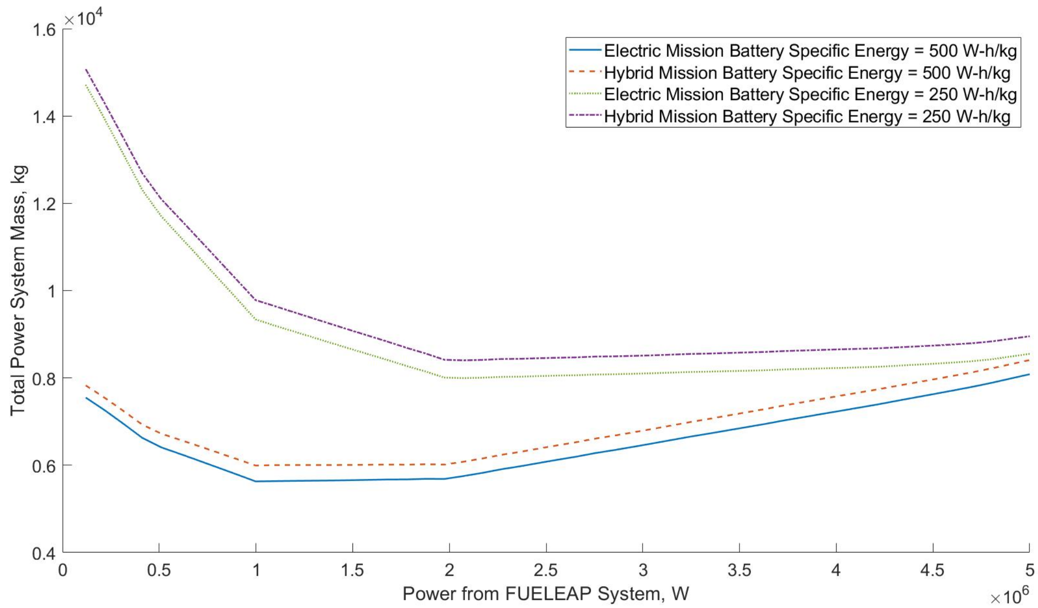


Fig. 12 Total power system mass for DAC 1 with varying power from FUELEAP.

Assuming a battery specific energy of 500 Wh/kg, at certain power design levels DAC 1 provides improvements in the overall power system mass for the current PEGASUS missions. It should be noted that the minimum total power system mass occurs at a lower FUELEAP power for the 500 W-h/kg assumption compared to the 250 W-h/kg assumption, and, therefore, the benefit of integrating the FUELEAP power system decreases with increasing battery technology. The FUELEAP power system's break-even point for the current PEGASUS vehicle occurs at both 400 kW and 3.35 MW, at which there would be no difference in weight between having only 500 W-h/kg batteries or the SOFC system plus fuel on board for DAC 1 operating both the hybrid and electric missions. However, it may be more beneficial to incorporate the higher power FUELEAP power system in order to capture a larger NOx benefit by reducing the needed turbine fuel. The breakdown of the masses for the final PEGASUS augmented with FUELEAP DAC 1 power system and the baseline PEGASUS vehicle are shown in Table 1 for the assumption of 500 W-h/kg for the batteries. Table 1 specifically shows the highest gross mass savings possible for the PEGASUS vehicle based upon the the 200 nm all-electric and the 400 nm hybrid-electric missions.

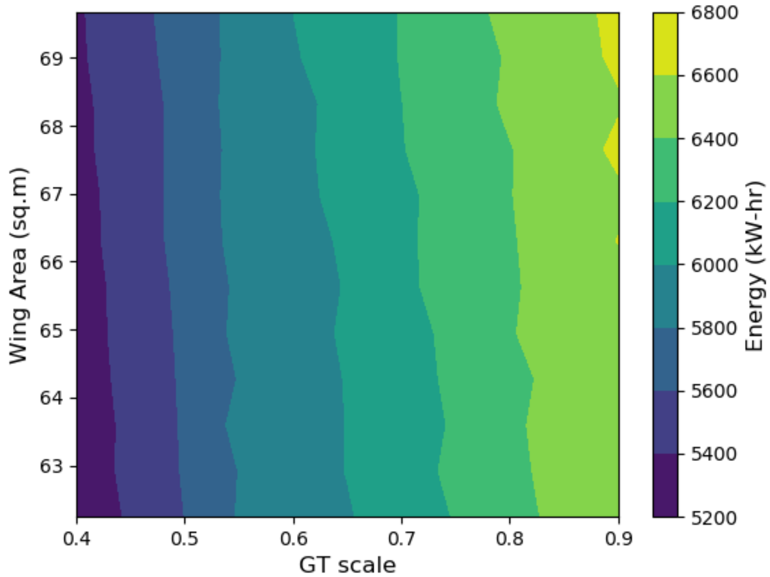
Table 1 Approximate PEGASUS Power System*Masses for Highest Gross Mass Savings

	Turbine Fuel Mass (kg)	FUELEAP Fuel Mass (kg)	Battery Mass (kg)	FUELEAP Power System Mass (kg)	Total Mass (kg)
Baseline PEGASUS Hybrid Mission	780	0	5,950	0	6,730
Baseline PEGASUS Electric Mission	368	0	5,950	0	6,318
PEGASUS FUELEAP DAC 1 Hybrid Mission	474	283	3,500	1,710	5,967
PEGASUS FUELEAP DAC 1 Electric Mission	218	198	3,500	1,710	5,626

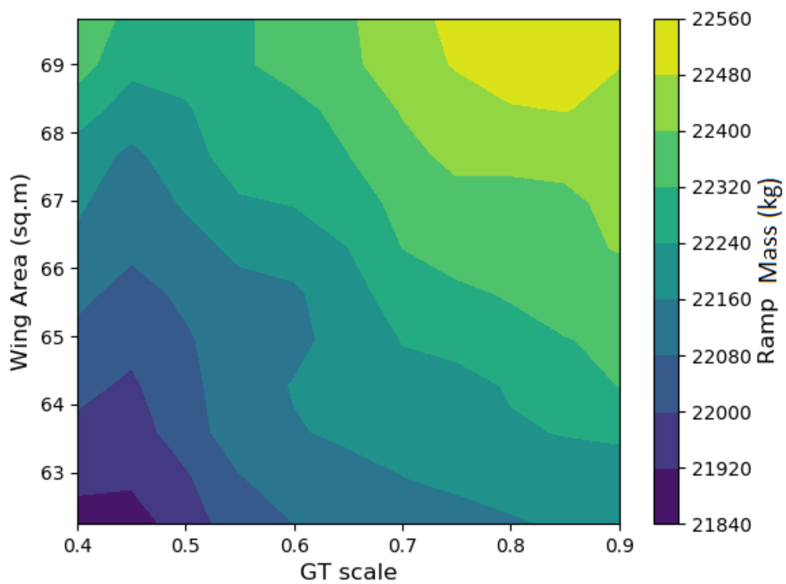
At first look, the total mass benefits of the FUELEAP augmentation appear to be minimal. However, the FUELEAP technology is estimated to be near-term (DAC 1), whereas the batteries are assumed to be 2030 technology. Using current technology, the PEGASUS battery system and overall vehicle would be significantly heavier as can be seen by the results obtained assuming a battery specific energy of 250 W-h/kg. The FUELEAP augmented PEGASUS also benefits from a decreasing weight over the course of the mission due to the consumption of fuel. Finally, there is a decrease in turbine fuel mass, which indicates a decrease in NOx emissions for the aircraft concept. Therefore, a new PEGASUS vehicle with FUELEAP should be designed and optimized for the design missions to take maximum advantage of the characteristics of the FUELEAP system.

In order to perform a more in-depth investigation of the impacts of FUELEAP on PEGASUS, a trade study was performed using a prototype of the Layered and Extensible Aircraft Performance System (LEAPS). LEAPS is a novel aircraft analysis tool currently being developed at NASA Langley Research Center [13]. LEAPS allows for the addition of the FUELEAP power system directly into the sizing and mission analysis. For the LEAPS analysis, FUELEAP inputs included the dry mass and a fuel burn matrix from the SOFC sizing analysis, which is based upon altitude, the LHV of Jet-A fuel, and power setting. The parameters that were varied for the analysis were the wing area and the level of hybridization for the wingtip propulsors, referred to as gas turbine scale or GT scale. For example, a GT scale of 0.80 means that the wingtip propulsor can get a maximum of 80% of its power from the gas turbine, with the remaining 20% from the electric motor. In this study, we used a configuration with a GT scale of 0.5, which is not feasibile with the baseline PEGASUS concept due to a wing loading constraint of 3.6 kN/m^2. This design space allows us to evaluate and refine the FUELEAP augmented PEGASUS vehicle. Figure 13 shows how energy and ramp mass change as a function of GT scale and wing area. The wing loading constraint of 3.6 kN/m^2 is included in the calculations for these plots, but due to the reduction in mass does not have an impact on the vehicle, and thus, does not appear on the plots. The results show that the sensitivities due to hybridization (GT scale) for the battery and FUELEAP combination are much less than for the battery system alone as seen by Capristan and Blaesser [14]. This is expected because the electric propulsion system does not depend solely on batteries but also uses fuel. Consequently, the energy used to complete the 400 nm mission increases as the hybridization decreases.

*Gas turbine masses are not included because they are kept constant. The FUELEAP DAC 1 power systems is designed to a maximum of 1.0 MW.



(a) Main mission total energy



(b) Ramp mass[†]

Fig. 13 PEGASUS concept with FUELEAP total energy and ramp mass results with a wing loading constraint of 3.6 kN/m^2.

[†]This figure shows a smoothed out contour of the ramp mass as a function of wing area and GT scale. The plot is noisy, therefore, smoothing out the results allows us to show trends.

V. Summary

This study investigated the feasibility of using the FUELEAP power system for two regional hybrid-electric aircraft. The integrated FUELEAP power system provided a mass benefit relative to both baseline hybrid aircraft. Specifically, there is a mass benefit from using FUELEAP for a hybrid ATR-42-like aircraft for levels of hybridization greater than 10% when battery specific energy is less than 400 W-h/kg. In addition, this benefit exponentially increases with the range of the mission at 50% hybridization. If battery technology improves past a 500 W-h/kg specific energy, the benefit of the FUELEAP architecture will decrease as seen from the PEGASUS study, in which the optimum power level for the FUELEAP power system decreased (and the dependency on batteries increased) when battery specific energy was increased to 500 W-h/kg. For the ATR-42 hybrid study, there was an increase in fuel usage. However, the increase in fuel weight can be attributed to the increase in gross weight for the baseline ATR-42. On the contrary, for the PEGASUS study, there was a slight decrease in the fuel usage for the 400 nm hybrid PEGASUS mission and a small increase of fuel for the 200 nm all-electric PEGASUS mission. Part of the increase of fuel weight to the all-electric mission can be attributed to a decreased GT scale between the baseline PEGASUS concept and FUELEAP augmented PEGASUS vehicle. For both the ATR-42 hybrid and PEGASUS study, the turbine fuel mass decreases, which shows a potential emissions benefit. The FUELEAP augmented vehicles have the potential to open up the design space of hybrid regional aircraft due to the reduction in overall mass. For the PEGASUS augmented with FUELEAP, the wing area and GT can be reduced creating more efficient cruise, leading to a new design space that can be explored.

VI. Future Work

With a baseline study of the FUELEAP augmented PEGASUS concept completed, further investigation with the FUELEAP system sizing integrated into the LEAPS optimization would be beneficial in order to have the capability to select the wing area and GT scale appropriately. Additionally, for a proper comparison of the fuel usage between concepts, an ATR-72 aircraft should be investigated at similar range constraints. With the comparison, emission studies should be performed in order to quantify the affects of integration of a SOFC onto a regional aircraft. In addition to having a benefit during flight, in terms of weight, the FUELEAP architecture has the potential to benefit taxi and ground support and, therefore, should be investigated for gate-to-gate operations. The study will also be expanded to investigate the feasibility of integrating FUELEAP with other configurations, including the Single-Aisle Turboelectric Aircraft with Aft Boundary Layer propulsion (STARC-ABL), which is a turbo-electric concept. The integration based upon physical sizes must also be taken into consideration. Based upon unit sizes of the cells in the SOFC, an estimated volume can be determined. However, the remaining components to the FUELEAP architecture do not scale linearly with power levels and therefore requires further investigation.

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