Conceptual Design of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept

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In this paper, a novel hybrid electric regional aircraft is presented that strategically locates multiple electric and hybrid electric propulsors to obtain aerodynamic benefits. This concept is called the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) aircraft. The use of the alternative propulsive systems coupled with their potential aerodynamic benefits presents modeling challenges for conventional aircraft analysis tools. These challenges are addressed by two methods that quantify the potential benefits of the PEGASUS concept. The results of both methods suggest that when compared to other hybrid electric regional aircraft, the PEGASUS concept has the potential to decrease the total energy required to complete a mission while also reducing the vehicle gross weight.

I. Introduction

Electric propulsion enables increased freedom to locate aircraft propulsors wherever a synergistic benefit can be achieved. Unlike conventional gas turbines, the scale invariance of electric motors with respect to efficiency and power-to-weight ratio allows this flexibility. In past years, NASA has proposed and studied different hybrid electric aircraft configurations with a goal to decrease operational cost, carbon footprint, and noise. In particular, Antcliff et al.[1] showed that the use of parallel hybrid electric regional aircraft has the potential to reduce operational costs by decreasing the total propulsive energy used. This paper builds on that work by presenting a year 2030 parallel hybrid electric aircraft concept that uses multiple propulsors in an attempt to provide synergistic benefits that could further decrease operational cost through lower energy required to complete a given mission. The proposed vehicle was given the moniker: the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) concept.

The PEGASUS concept is based on the parallel hybrid electric version of the ATR-42-500 aircraft discussed by Antcliff et al.[1] PEGASUS consists of parallel hybrid electric and electric propulsors located strategically to provide increased aerodynamic benefits. PEGASUS uses parallel hybrid electric propulsors at the wingtips to decrease downwash effects. Two electric propulsors providing additional thrust for takeoff and climb are located inboard on the wing. These propulsors are capable of folding mid-flight to decrease windmilling effects during cruise. Lastly, recent research suggests that adding a final electric propulsor to the tail of the aircraft will provide a benefit due to boundary layer ingestion.[2] To better envision the concept, an artist's depiction of PEGASUS is shown in Fig. 1.

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Figure 1. The PEGASUS concept.

The multiple propulsors, parallel hybrid electric propulsion architecture, and unique synergistic effects of the PEGASUS configuration present various modeling challenges. In this work, we propose two methods to perform the analysis. The first method (Method A) uses the Flight Optimization System (FLOPS)[3] as the main analysis component in a ModelCenter framework.[4] FLOPS is an aircraft design and analysis tool that has been developed at NASA Langley Research Center for over 30 years. It was designed to analyze conventional vehicles (e.g., gas turbine-powered aircraft) and it has no proper mechanism to handle hybrid electric propulsion systems. Method A is an extension of previous work done by Antcliff et al.[1] and contains workarounds to overcome some of the limitations of FLOPS. A second method (Method B) uses parts of different aircraft analysis tools to capture the different flight configurations and synergistic effects of multiple propulsors.

This paper discuss the PEGASUS concept and the two methods used for its analysis. Section II presents background information on the research that has led to the PEGASUS vehicle. Section III provides the details of the PEGASUS vehicle and its design assumptions. Section IV provides details regarding the mission requirements for PEGASUS. Section V covers both methods used to analyze PEGASUS. Section VI provides the results obtained by using both methods and Section VII presents the conclusions.

II. Background

Concept studies that are focused on the benefits of future vehicles require a current baseline vehicle for comparison. The current baseline vehicle selected for this study was the 48-passenger ATR 42-500, which was chosen based on a market and demand study.[5] Due to the complexities of the unconventional concept analyzed in this study, an intermediate, year 2030, hybrid electric baseline was also developed. The intermediate baseline used the conventional propulsion-airframe integration of the ATR 42-500, but replaced the turboprop engines with parallel hybrid electric propulsors. Only pertinent information regarding the intermediate baseline will follow; for more in-depth analysis and results refer to Ref. 1.

The development of the intermediate baseline required a thorough modification of the PW127E, the engine of the ATR 42-500, to a future hybrid electric version. Initially, this three shaft, two-spool engine was modeled in the Numerical Propulsion System Simulation (NPSS)[6] to match state-of-the-art (SOA) publically available data. Individual components of the engine were then upgraded in order to predict the performance of a PW127E-like engine in the year 2030. The performance of this engine model was then estimated over a range of altitudes, Mach numbers, and throttle settings. The standard power output for this engine is 2400 shp. Reduced power versions of the advanced engine model were also created at 1800 shp (25% electric), 1200 shp (50% electric), and 600 shp (75% electric). The estimated dimensions and weights of these parallel hybrid electric engines are shown in Table 1.

Table 1. Hybrid Electric Turboprop Engine Weights

Mechanical Design Parameter	SOA Turboprop 2400 SHP	Advanced Turboprop 2400 SHP	Advanced Hybrid Electric Turboprop Gas Turbine + Electric Motor		
			1800 + 600 SHP	1200 + 1200 SHP	600 + 1800 SHP
Turbine engine + Gearbox weight (lb)	1054	1010	819	626	410
Propeller system + Nacelle weight (lb)	782	781	766	752	737
Electrical system weight (lb)	-	-	135	270	405
Total engine weight (lb)	1836	1791	1720	1648	1552
Engine pod length (ft)	7.0	7.0	6.1	5.3	4.2
Maximum Propeller Diameter (ft)	12.8	12.8	12.8	12.8	12.8
Nacelle Diameter (ft)	3.3	3.3	3.3	3.3	3.3

A Multidisciplinary Design Optimization (MDO) framework capable of analyzing and designing hybrid electric aircraft was developed for the intermediate baseline. FLOPS allows two separate propulsion systems with different energy sources to operate during separate segments of the mission, but does not allow different energy sources for a single mission segment. Therefore, external analyses, including battery weight (W_{batt}) estimation, were coupled with the FLOPS mission analysis core to determine the performance of advanced, parallel hybrid electric vehicles. Figure 2 gives a graphical representation of this framework developed for the intermediate baseline, which is used as the foundation for the analysis of the unconventional PEGASUS concept.

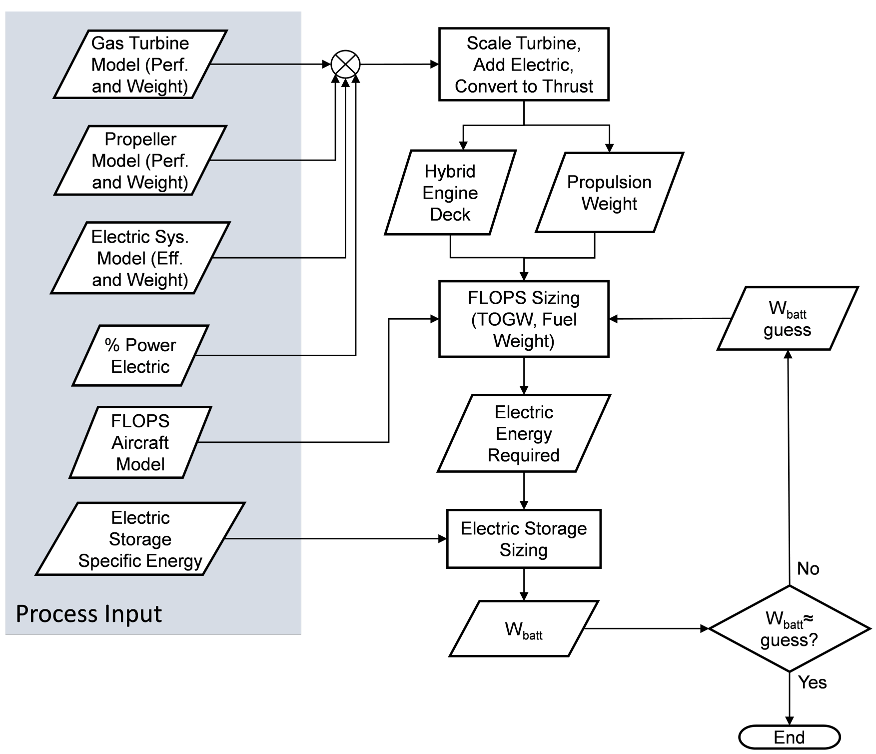


Figure 2. Multidisciplinary design optimization (MDO) framework for a parallel hybrid electric concept.

III. Concept Design

A. Parallel Hybrid Electric

In conceptual aircraft design, the predicted acquisition and operating cost of an aircraft concept can typically be directly related to the vehicle weight. Therefore, when considering alternative energy sources, comparing the specific energy (energy available per unit weight) across the different energy sources is a vital step in the design. Historically, Jet-A fuel has been the dominant energy source due to a specific energy of almost 12,000 Wh/kg. For comparison, the specific energy of the battery utilized for PEGASUS modeling is assumed to be 500 Wh/kg. There are, however, significant advantages of electric and hybrid electric aircraft that allow them to be viable options for commercial transports despite this disadvantage in specific energy. The most obvious of these advantages is reduced (or zero) NO_x and CO_2 emissions released during flight. However, a more compelling argument for electric and hybrid electric propulsion is how efficiently energy is transferred from energy source to propulsor. As shown in Fig. 3, parallel hybrid electric propulsion has the most direct path of any hybrid or turboelectric propulsion architecture and is unique in its ability to be powered by either an electric motor, a gas turbine, or a combination of both. The lowest efficiency option would be that of a gas turbine (∼40%) and the highest efficiency would be that of an electric system (∼93%). Any combination of the two would, therefore, result in an overall efficiency between these two values.

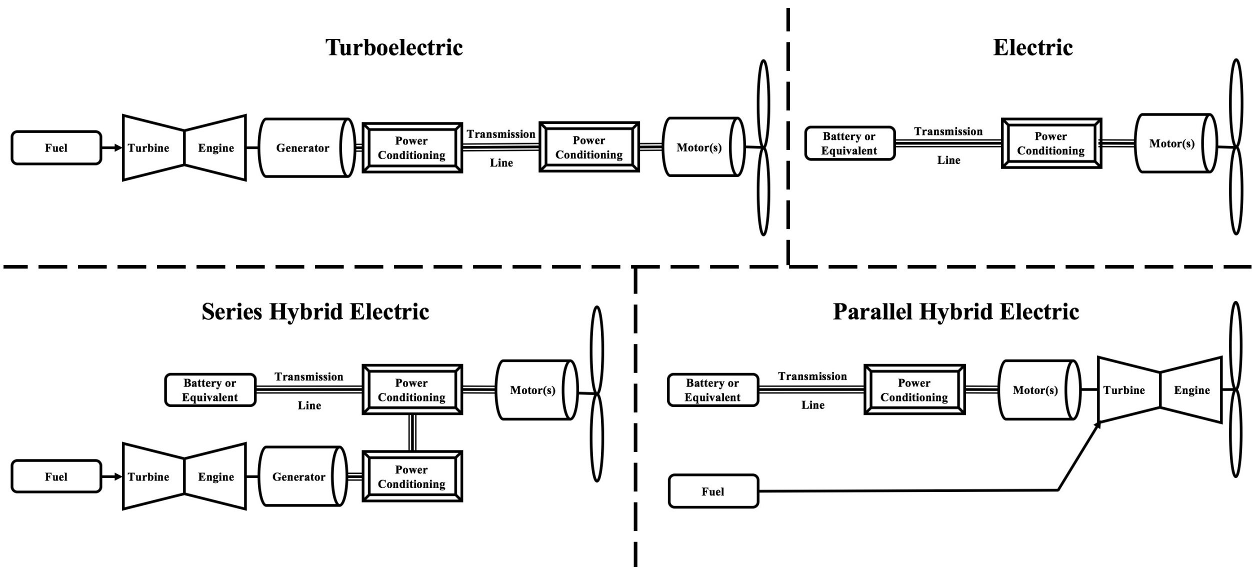


Figure 3. Turboelectric, series hybrid electric, parallel hybrid electric, and all electric propulsion architecture comparison.[7]

Both turboelectric and series hybrid electric propulsion architectures are burdened by the conversion of fuel to electricity. This conversion adds the complexity of a generator and additional power conditioning before reaching the propulsor. These extra steps create efficiency (and weight) penalties that reduce the overall efficiency of the system. This efficiency loss is important because it impacts the amount of energy, and thus energy cost, needed for a given mission. Despite the high volatility of fuel prices, fuel has historically been the highest source of operating costs for airlines.[8]

Specific energy versus overall efficiency is the main trade that must be considered in the design of electric/hybrid electric vehicles. Regardless of the range or size, the overall efficiency of the propulsion system will remain relatively constant. However, the weight of the vehicle is highly dependent on the range and the specific energy of the energy sources that are utilized. For electric or hybrid electric propulsion, the range must be minimized in order to reduce the impact of the heavy electric energy source. In the design of PEGASUS, we ensure that the range is no greater than what is needed to capture the majority of the airport origin and destination pairs as discussed in further detail in Section IV.

B. Propulsor Arrangement

A graphical representation of the PEGASUS concept in comparison to other concepts discussed in this paper is shown in Fig. 4. The ATR 42-500 served as the baseline vehicle for this analysis. Then, an intermediate baseline of two parallel hybrid electric propulsors with identical propulsion airframe integration was presented by Antcliff et al.[1] Lastly, this report discusses the synergistic propulsion-airframe integration (PAI) and operations of the PEGASUS concept. Synergistic PAI, discussed in the following sections, refers to sizing the wingtip propulsors and BLI propulsor for a given cruise point, then sizing the inboard propulsors for the remaining thrust needed to fulfill takeoff and climb requirements. Synergistic operations refers to lowering the design range to only what is needed to fulfill the large majority of future origin-destination pair trips, which will be discussed in further detail in the following section.

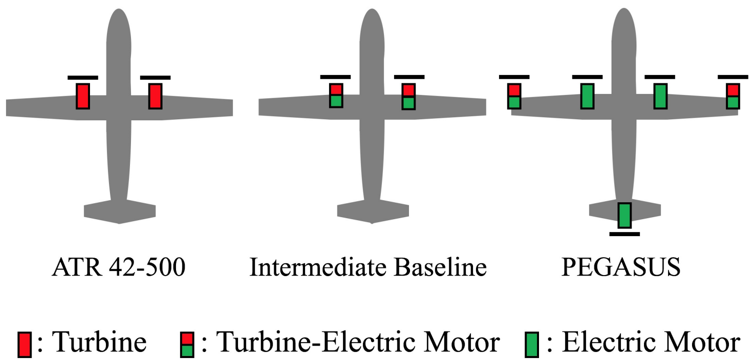


Figure 4. Baseline (ATR 42-500), Intermediate Baseline, and PEGASUS concept comparison.

C. Wingtip Propulsor

Snyder documented the use of end-plates and tip tanks to increase lift near wingtips and decrease the induced drag/downwash effects for low Reynolds numbers in 1967.[9] Snyder noticed that these benefits were severely limited at higher speeds. Therefore, he proposed a new solution: *"by placing the propellers which propel the aircraft at the wingtips... the rotational component of the propeller slip-stream is available for attenuating the wing vortex system."* The impact of this wingtip propeller slip-stream was quantified by Patterson as power reduction in relation to the cruise lift coefficient.[10] This quantification of the wingtip propulsor effect for a low aspect ratio, high cruise speed vehicle was compared to a study performed for the SCEPTOR project (or Maxwell X-57 concept), which is a high aspect ratio, low cruise speed concept.[11] Comparison of the two cases enabled an estimation of the potential power reduction for the PEGASUS concept as shown in Fig. 5. Wingtip propulsion integration takes advantage of the vortex flow field and results in an estimated 18 percent increase in effective propulsive efficiency for the wingtip propulsors on the PEGASUS concept.

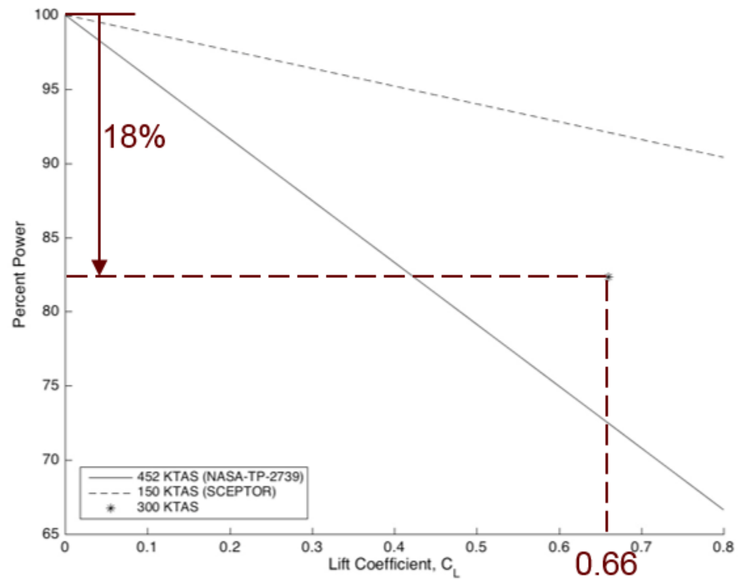


Figure 5. Percent power versus lift coefficient. With a C_L of 0.66, the wingtip propulsors on the PEGASUS concept can expect an 18 percent increase in effective propulsive efficiency based on previous wind tunnel data.

D. Folding Inboard Propeller

In the same Snyder report that introduced the use of wingtip propulsion, he stated that a *"feasible design configuration would be to adopt a four-engine design with two engines at the wingtips and two engines inboard."*[9] This would alleviate difficult trim and control characteristics that would arise during one-engine-out flight. However, the swirl of an operating inboard propeller creates non-optimal spanwise lift loading as shown in Figure 6. Thus, the PEGASUS concept allows for the inboard electric motors to be powered off and on as needed. This enables the wingtip motors to be sized for cruise with supplemental inboard thrust supplied for takeoff and climb or one-engine-out. Also, the inboard propellers can be folded when not in use to reduce blockage effects and overall drag.

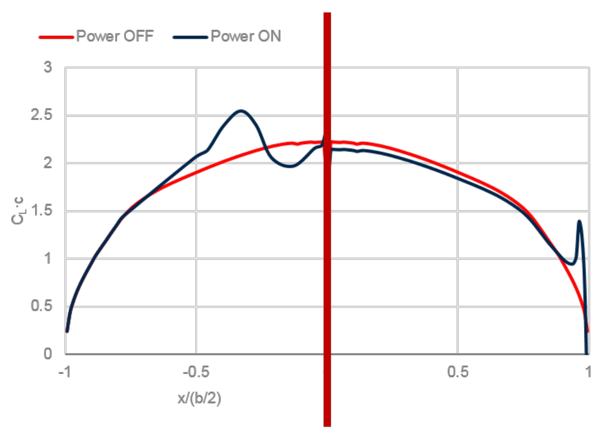


Figure 6. Simulated effects of wing-mounted propellers on lift distribution. The effect of inboard propellers (left) and wingtip propellers (right) on the lift distribution of the LEAPTech wing.[12]

Folding propellers are common in sailing yachts, model airplanes, and small motor gliders. They were introduced for future advanced electric propulsion aircraft concepts in 2014 as a part of the LEAPTech study,[12] and are currently being developed for the X-57 Maxwell concept. Based on analysis of these studies, removal of inboard turboprop propulsion effects results in a 10% reduction in the induced drag.

E. Boundary Layer Ingestion (BLI) Propulsor

It is known that ingestion of the wake of a ships, torpedoes, and missiles by a propulsor reduces the amount of power needed for propulsion. For aircraft, boundary layer ingestion (BLI) is less beneficial because the wake is spread out across the wings, empennage, and fuselage. However, Smith found that there is still a significant benefit from using boundary layer ingestion, especially as the propulsor decreases in size.[13] This was further substantiated by Welstead and Felder[2] in 2016 where they state that if 50 percent of the fuselage boundary layer is captured, over 70 percent of the momentum deficit can be recovered. Therefore, a small propulsor can be arranged at the aft fuselage to reaccelerate only the slowest moving air. Hardin et al.[14] concluded that boundary layer ingestion could provide on the order of 10 percent improvement in effective propulsive efficiency in the 2030 timeframe.

IV. Mission Considerations

A. Design Range

The PEGASUS concept is not only unconventional in propulsion-airframe integration, but in its design range. In a year 2030 transportation demand study by Marien,[5] the Transportation System Analysis Model (TSAM)[15] was used to predict the trip distance distribution for regional trips ($<$ 900 nautical miles) between airports in the United States. Marien found that 50 percent of the predicted regional trips have a distance of 200 nautical miles or less and 90 percent of the predicted regional trips have a distance of 400 nautical miles or less (see Fig. 7). With this in mind, we developed the mission requirements for the PEGASUS aircraft. The concept was designed to fly a 200 nautical mile mission with all-electric propulsion and a 400 nautical mile mission with hybrid electric propulsion.

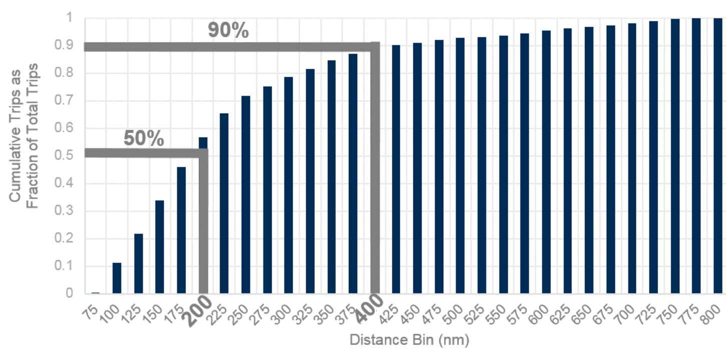


Figure 7. Regional jet and turboprop cumulative trip distribution versus mission range.

B. Mission Profile

A total of five propulsors will be used on this aircraft: two parallel hybrid electric wingtip propulsors, two inboard all-electric propulsors, and one BLI all-electric propulsor (as shown in Fig. 4). The only difference between the all-electric and hybrid electric missions will occur at the wingtip where the hybrid electric propulsor will solely use electric power on missions less than 200 nautical miles. For both the 200 and 400 nautical mile missions, all five propulsors will be used for takeoff and climb. Then, the inboard propulsors will be powered off and folded for cruise leaving the wingtip and BLI propulsors to provide efficient thrust for the aircraft as depicted in Fig.8.

Figure 8. A rendering of the PEGASUS concept with folded inboard propellers.

C. Hybrid Electric Reserves

The FAA has set regulations that determine the reserves needed for Instrument Flight Rules (IFR) conditions in Title 14, Section 91.167.[16] These regulations state that you must have enough fuel to complete the flight to the destination airport, fly from that airport to the alternate airport, and fly after that for 45 minutes at normal cruising speed. The alternate airport distance used by ATR for the published performance of the ATR 42-500 (our baseline) was 87 nautical miles. An alternate airport distance of 87 nautical miles added to 45 minutes at 300 knots yields a reserve requirement of around 300 nautical miles in comparison to the maximum design range of the vehicle. Reserve requirements create an interesting problem for electric and hybrid electric aircraft that are currently only viable with a low design range.

It is possible that future technologies, such as weather prediction enhancements, could lead to a relaxation in the reserve requirements. However, there is still a question of what energy source would be best suited for this additional mission requirement. Current battery technology limits utilization to 80 percent of the full charge; if more than 80 percent is used, then the lifespan of the battery is severely shortened. Therefore, the reserve mission should not be designed to utilize this remaining 20 percent of the battery energy or a battery swap would be recommended practice every time the design range is exceeded. Even with low overall efficiencies, gas turbines using Jet-A fuel (with a specific energy of almost 12,000 Wh/kg) will undoubtedly be the lightest power/energy combination available in 2030. Therefore, the wingtip gas turbines on PEGASUS were over-sized to enable the full reserve mission to be completed solely on fuel. Even with the large increase in gas turbine size and weight, this was the solution that saved the most weight overall.

V. Method Development

Two methods were considered to analyze the PEGASUS concept. Method A extends the use of well accepted and computationally efficient conventional design tools to capture the potential synergistic benefits. Method B attempts to avoid some of the modeling limitations inherent in the use of conventional tools by using a flexible framework that combines customized analysis tools.

A. Method A

The following are some of the current assumptions and computations required. The design of this method was partially driven by some of the features and limitations of FLOPS.

The propulsion system and the handling of the five propulsors (three propulsor classes) is one of the most important considerations. The PW127E-like engine in the year 2030 (discussed in Section II) was used as the reference engine and was adjusted appropriately to cover the three different propulsor classes. The first step involves the sizing of the wingtip and aft propulsors given a cruise thrust sizing point. Based on the PW127E-like engine deck mentioned in Section II, the sizing point is given by:

$$\begin{aligned}
\text{Mach} &= 0.5 \\
\text{Altitude} &= 20,000 \text{ ft} \\
\text{Thrust} &= 1320.8 \text{ lbs} \\
\text{Power} &= 1603.6 \text{ shp}
\end{aligned}$$

The percent of total power for the wingtip propulsor provided by the gas turbine ($\%_{GT}$) as well as the thrust distribution between the wingtip (WT) and aft propulsor at cruise are inputs that are used to determine the power required for the wingtip and aft propulsors at the cruise condition. These are given by $P_{WT_{\text{cruise}}}$ and $P_{\text{aft}_{\text{cruise}}}$ respectively. A propulsion sizing parameter is used to define the propulsive efficiency at a given operation point,

$$r_{PT} = \frac{P}{T} \tag{1}$$

where the power is given by P and thrust is given by T.

When placing the main source of propulsion at the wingtip, the one-engine-out yawing moment must be taken into consideration. This methodology assumes that the PEGASUS one-engine-out yawing moment, $C_{n_{\text{req, PEGASUS}}}$ is not allowed to exceed the yawing moment of the ATR 42-500, $C_{n_{\text{req, ATR42}}}$. This consideration is shown below:

$$C_{n_{\text{req, ATR42}}} \geq C_{n_{\text{req, PEGASUS}}} \tag{2}$$

$$\left[\frac{(T_{n_{\text{req}}} + D_{ewn})l_e}{qS_{\text{ref}}b}\right]_{\text{ATR42}} \geq \left[\frac{(T_{n_{\text{req}}} + D_{ewn})l_e}{qS_{\text{ref}}b}\right]_{\text{PEGASUS}} \tag{3}$$

where the thrust required by the propulsor is given by $T_{n_{\text{req}}}$ and the length between the propulsor and the centerline is given by l_e. Then, assuming a similar wing span, b, reference area, S_{ref}, dynamic pressure, q, and drag of engine when non-operational, D_{ewn}, this yields:

$$(T_{n_{req}} \cdot l_e)_{\text{ATR42}} \geq (T_{n_{req}} \cdot l_e)_{\text{PEGASUS}} \tag{4}$$

This limits the amount of thrust that is placed at the tip propulsor. The thrust at the wingtip for different Mach, altitude, and power conditions is given by:

$$T_{\text{WT}} = \min\left(\frac{P_{WT_{\text{cruise}}}}{r_{PT} \cdot e_{WT}}, T_{n_{\text{req}}}\right) \tag{5}$$

where r_{PT} is a function of Mach, altitude, and power and e_{WT} represents the efficiency factor at the tip. The thrust of the aft propulsor is also calculated at multiple Mach and altitude conditions based on the sizing point at cruise.

$$T_{\text{aft}} = \frac{P_{\text{aft}_{\text{cruise}}}}{r_{PT} \cdot e_{\text{aft}}} \tag{6}$$

Lastly, the inboard propulsors are utlized at low and slow conditions when additional thrust is required. The inboard thrust is computed using the following equation:

$$T_{in} = T_{req} - T_{WT} - T_{aft} \tag{7}$$

The fuel flow, thrust, and power at different Mach and altitude conditions for the three propulsor classes (five propulsors in total) are combined to generate a single "engine deck" that is fed to FLOPS. All the components of the model were linked together by using ModelCenter. The entire methodology is shown in Fig. 9. This methodology uses the all-electric mission (see section IV) to provide the initial sizing of the batteries. The initial battery size is used to update the component weights and is fed into the hybrid electric mission analysis. This process is repeated until the weights have converged.

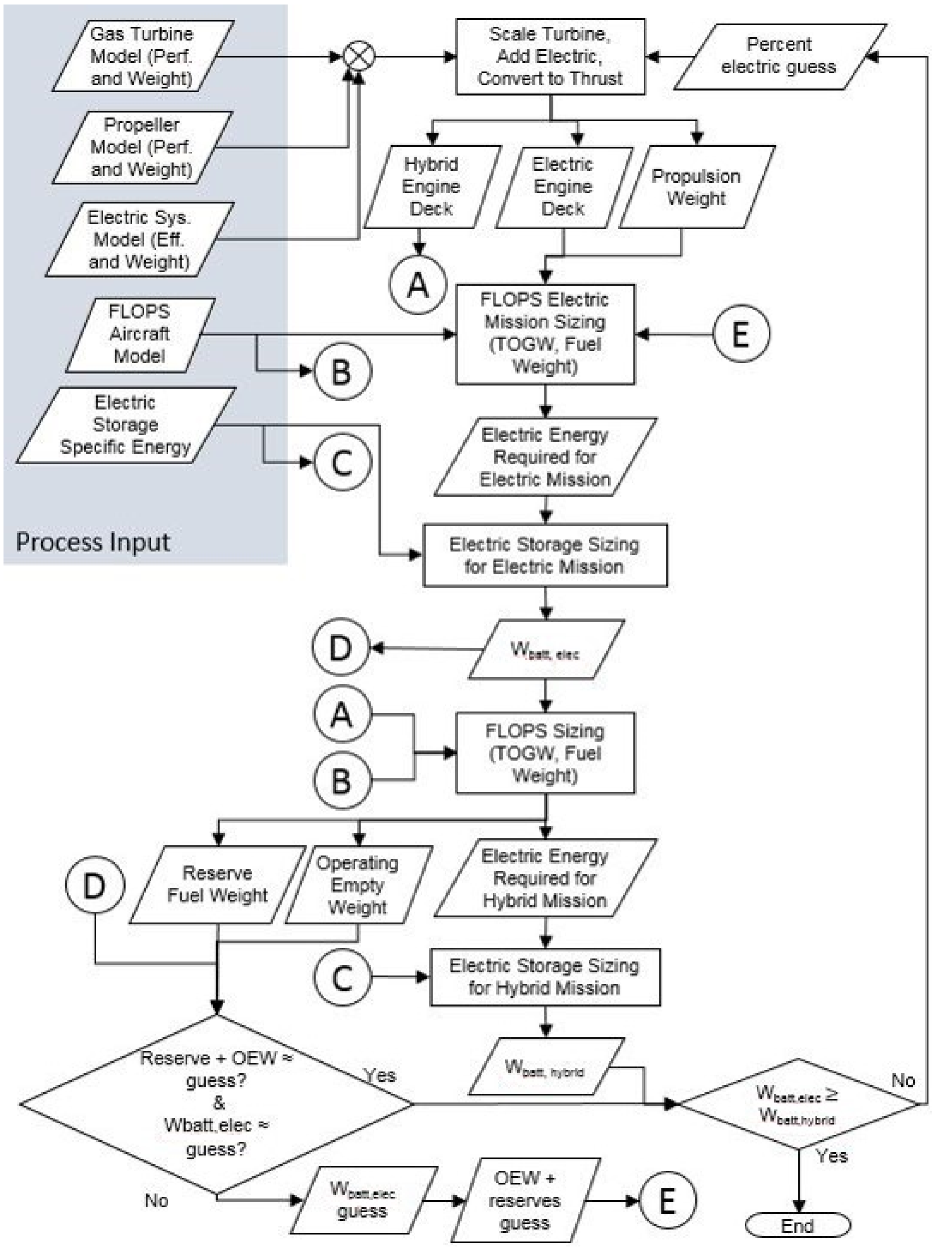


Figure 9. Method A multidisciplinary design optimization (MDO) framework for the parallel hybrid electric concept where takeoff gross weight is given by $TOGW$ and operating empty weight is given by OEW.

B. Method B

This method expands Method A by addressing some of the limitations observed with FLOPS. Method B entails a mixture of different analysis tools to provide a flexible method capable of sizing each propulsor independently. This capability enhances the analysis and expands the design space considered by Method A.

Method B consists of three different modules: mission analysis, aerodynamics, and weight sizing. These modules are coupled together by using the Python scripting language. The mission analysis module can handle different propulsion systems working independently. Capristan and Welstead[17] discussed in detail the characteristics of this module. The Python-based SUAVE[18] aircraft analysis tool was used to provide the aerodynamics needed by the mission analysis module. Finally, FLOPS provided the operating weight of the aircraft because its weight estimation capabilities have been extensively used to size vehicles similar to the ATR-42-500 aircraft.

The OpenMDAO framework[19] was used to handle the sizing process (analysis and optimization). The vehicle is sized to minimize the takeoff gross weight or total energy used by varying the wing area, the percent of power at the wingtip provided by the gas turbine, and the design point thrust for the three propulsor classes. The use of these five design parameters expands and explores the design space in more detail while decreasing the number of assumptions used in Method A. Table 2 highlights the major differences between Methods A and B.

Table 2. Main Differences in Methods A and B.

	Method A	Method B
Engine deck approach	Mission oriented	Propulsor oriented
Cruise conditions	Optimal (FLOPS)	Fixed
Cruise ceiling	300 ft/min	300 ft/min (all propulsors on) 100 ft/min (tip and aft propulsors on)
Computational time per iteration	< 30 seconds	> 2 minutes

The following subsections discuss the differences provided in the Table above.

1. Engine Deck Approach

The main difference between methods is the formulation of the engine decks. Method A provides a single engine deck per mission. Each engine deck is tailored to represent a specific mission, dependent on the mode of operation, due to FLOPS inability to throttle different propulsor classes independently. Method B, on the other hand, allows multiple propulsors to throttle independently; thus, a larger number of operating conditions can be explored.

2. Cruise Conditions

As discussed in the previous sections, Method A uses FLOPS to analyze the aircraft. The mission analysis capabilities in FLOPS allow the user to quickly optimize the flight conditions (Mach and altitude) during cruise to minimize fuel or maximize range. In contrast, the mission analysis approach used in Method B is not able to provide optimum flight conditions during cruise unless an external optimization process is used.

3. Cruise Ceiling

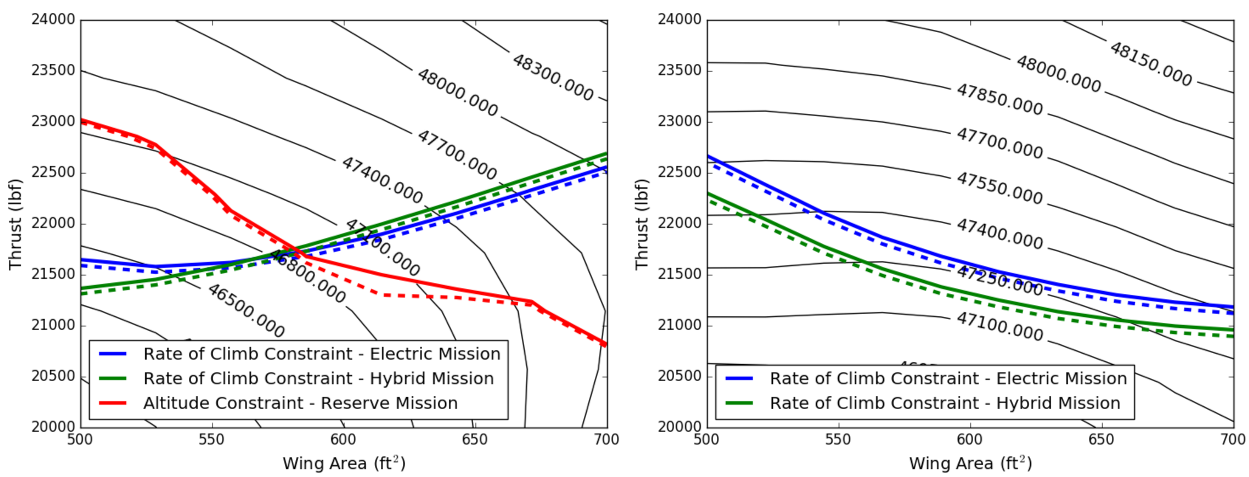
The cruise ceiling has been defined as the altitude at which the maximum rate of climb for the aircraft is 300 ft/min. This definition is easily applied to aircraft that are designed to operate with all engines providing thrust during cruise. A question arises regarding the applicability of this definition when the aircraft is designed to have certain propulsors completely off during cruise as in the case of PEGASUS. Methods A and B consider the cruise ceiling as an operational constraint, but due to modeling assumptions, they differ on how this operational constraint is implemented.

The engine deck used in Method A is designed to ensure that at cruise the inboard propulsors are off and folded, decreasing drag penalties due to non-optimal spanwise lift (see Section III). For this reason, the maximum thrust at cruise inferred from the engine deck is less than the actual maximum thrust capability of the vehicle. This has a direct impact on the cruise ceiling determination (altitude where maximum rate of climb equals 300 ft/min). Method A ensures that at cruise PEGASUS can climb 300 ft/min with the inboard propulsors off and folded. In contrast, Method B is not limited to a simple engine deck with a single mode of operation having the inboard motors turned off during cruise. This method identifies that the maximum thrust happens when the inboard propulsors are at full power. Therefore, Method B assumes that at cruise the aircraft should be able to climb at 300 ft/min with all engines at full power, and 100 ft/min with the inboard propulsors off (service ceiling).

VI. Results

A. Direct Comparison of Methods A and B

In order to assess the differences between Methods A and B, we compared the changes in gross weight when changing the maximum sea level thrust of the total propulsion system and the wing area. For this comparison, Method B was adjusted to emulate the same modeling limitations found in Method A (one engine deck for the entire propulsion system). This gives us a starting point with which we can directly assess if there are large discrepancies between the methods; Fig. 10 shows this comparison. The solid lines denote the thrust and wing area combinations where the constraints are active. The area under the dashed lines indicates the region where the constrains are not satisfied. In this figure, the green and blue lines represent the rate of climb constraint at cruise (>300 ft/min) for the hybrid and electric missions, respectively. The red line indicates the altitude constraint for the reserves mission (>2,000 ft). The reserve mission altitude constraint is only applied to Method A because FLOPS selects the altitude that will minimize the amount of fuel used, whereas Method B uses a fixed cruise profile.



(a) Method A

(b) Method B tools to emulate Method A

Figure 10. Method B tools used to simulate modeling constraints in Method A (one engine deck for all propulsors) with contours showing the takeoff gross weight. Constraint lines include electric mission rate of climb at cruise (blue), hybrid mission rate of climb at cruise (green), and reserves altitude (red). The dashed line next to the solid lines indicate the area where the constraints are not satisfied.

The results in Fig. 10 indicate that the methods have different behaviors due to the fact that they use different aerodynamic and mission analysis modules. In fact, the mission analysis methodology in Method A (FLOPS) is able to automatically select the appropriate cruise conditions to minimize fuel while meeting the rate of climb constraint, whereas Method B uses a fixed cruise profile (Mach and altitude). The characteristics of Method A are seen in the small difference in the rate of climb constraint for the hybrid (green line) and the electric (blue line) missions. On the other hand for Method B, the rate of climb constraints for the hybrid and electric mission are offset. This is due to the fact that the cruise altitude is not adjusted during the mission evaluation. This characteristic is also evident in the reserve mission altitude constraint (>2,000 ft) being active for low wing areas in Method A. The initial comparison highlights the importance of the rate of climb constraints and the reserve mission altitude in sizing the vehicle.

B. Potential Benefits

The vehicle was optimized using both methods in order to assess the potential benefits. The objective function selected was the takeoff gross weight. Method A has three design parameters: wing area, one thrust scaling parameter for all propulsors, and the percent of tip propulsor power provided by the gas turbine ($\%_{GT}$). Method B uses five design parameters: wing area, three thrust scaling parameters, one for each propulsor class, and the percent of tip propulsor power provided by the gas turbine ($\%_{GT}$). The cruise constraints for each method were discussed in Section V.B.3.

The optimum wing area for Methods A and B were 571 ft^2 and 549 ft^2, respectively. It is not possible to directly compare the propulsion system sizing due to the different modeling assumptions used in the methods. However, the total weight of the propulsion system with Method A was 3,955 lb. In contrast, the weight of the propulsion system using Method B was 2,421 lb. The percent of the tip propulsor power provided by the gas turbine is similar, 57 percent using Method A and 56.9 percent using Method B. The cruise rate of climb constraint was active in both methods and heavily influences the wing area and the propulsion system sizing. The biggest difference between optimizations is the size of the propulsion system. This was expected due to how the cruise climb constraint was implemented in the optimization (discussed in Section V.B.3).

Both methods show that the PEGASUS concept has promising advantages over previous concepts. Figure 11 shows the electric, fuel, and total energy of the intermediate baseline with a design range of 600 nautical miles compared with the PEGASUS concept at 400 and 200 nautical miles (hybrid and electric mission, respectively). The energy was normalized by mission distance to allow for direct comparison. The propulsion system design point was used to calculate the fraction of power from electric energy (percent electric in Fig. 11). The results of the PEGASUS concept for both Methods A and B show a substantial decrease in electric energy and fuel consumption per nautical mile. For the 400 nautical mile hybrid electric mission, Method A predicts a 27 percent decrease in the normalized total energy with respect to the intermediate baseline vehicle. Method B predicts a 39 percent decrease in the normalized total energy with respect to the intermediate baseline vehicle.

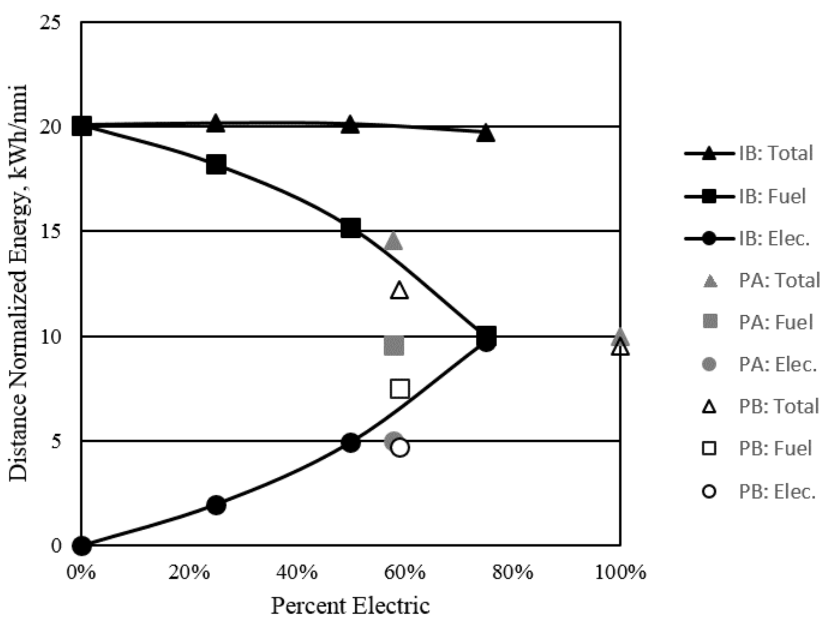


Figure 11. Distance Normalized Energy for the Intermediate Baseline (IB) and PEGASUS vehicle using Method A (PA) and Method B (PB). The distance is normalized due to varying design ranges: Intermediate Baseline (600 nm), PEGASUS Hybrid (400 nm), and PEGASUS All-Electric (200 nm).

Figure 12 shows the benefits of synergistic propulsion-airframe integration and operations in terms of weight. Both Methods A and B indicate similar weight reduction for PEGASUS when compared to the intermediate baseline. On average, Methods A and B estimate a 30 percent reduction in takeoff gross weight and a 20 percent reduction in operating empty weight.

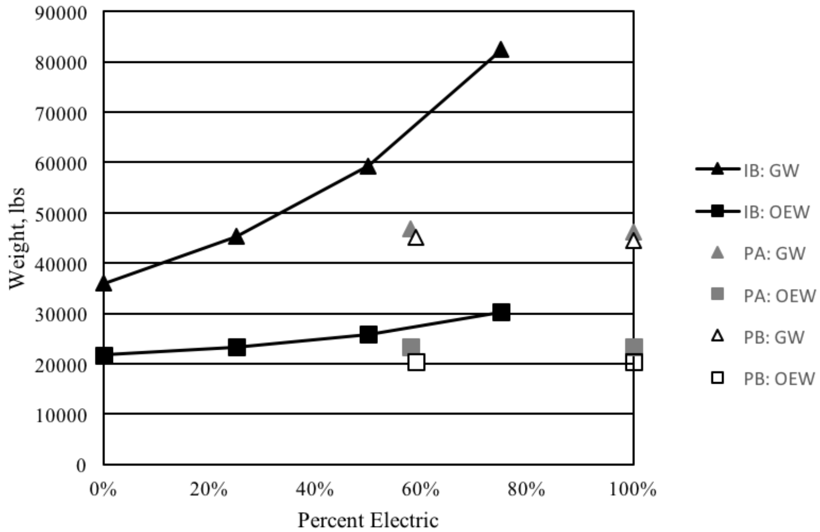


Figure 12. Gross weight and operating empty weight versus percent electric for the PEGASUS vehicle using Method A and Method B.

Building on the discussion in Section IV regarding reserves, for the 400 nautical mile mission of the PEGASUS concept, Method A estimates more fuel is needed for the all-fuel reserve mission than for the hybrid mission itself: 850 lb and 710 lb, respectively. Even when including the electric energy used during the mission, 44 percent of the total energy stored onboard is for the reserve mission. A similar result is obtained with Method B, for which the reserve mission uses 792 lb of fuel and the hybrid mission 554 lb.

VII. Conclusion

This study focuses on the design and analysis of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) concept. The PEGASUS concept was designed to fly a 200 nm electric only mission and a 400 nm parallel hybrid electric mission. The PEGASUS concept was analyzed with two methods to assess its potential benefits while addressing some of the modeling complexities due to the novel propulsion architecture.

The design space of the PEGASUS concept was evaluated using a FLOPS-based method (Method A) and a combination of parts of different tools integrated to overcome the analysis constraints observed in Method A. Results from both methods show that the constraint on rate of climb at cruise plays a crucial role in determining the proper size of the vehicle and its propulsion system. This is also true for the reserve mission. It was found that the reserve mission will have a direct influence on the size of the gas turbine used at the tip propulsor.

The discrepancies seen in the PEGASUS energy consumption with Methods A and B are primarily due to the different rate of climb constraints at cruise. The vehicle obtained with Method A is capable of a rate of climb of 300 ft/min when the inboard propulsors are off and folded. In contrast, the vehicle obtained with Method B is designed to be capable of a rate of climb of 300 ft/min with all the propulsors operating at full power and a rate of climb of 100 ft/min when the inboard propulsors are off and folded. Therefore, the wingtip propulsors sized with Method A are considerably more powerful than the ones sized with Method B. This extra power results in a larger propulsor weight. It is important to note that in Method A the rate of climb during the cruise segment (reserve mission) is an active constraint, and thus it sizes the percent of gas turbine at the wingtips. This is not an issue in Method B because the vehicle is still able to gain thrust from the other propulsion systems if required.

Total energy, fuel energy, and battery energy decrease significantly when the propulsors are arranged on the airframe to provide a synergistic benefit. In other words, high energy, and thus energy cost, savings can be realized when the scalability and flexibility of electric motors is exploited in the design of an electric or hybrid electric aircraft.

The weight increases associated with hybrid electric propulsion can also be mitigated. The PEGASUS vehicle during its hybrid mission and the intermediate baseline, at a slightly lower percent electric, have 31 percent and 65 percent higher gross weight, respectively, than the 0 percent electric or conventional propulsion baseline. Comparing the aircraft weight and mission energy results between the PEGASUS concept and the intermediate baseline hybrid-electric concept presents a strong case for electric and hybrid electric vehicles that are designed for synergistic integration and operations.

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