

Results for an Electrified Aircraft Propulsion Design Exploration

Ty V. Marien¹, Nathaniel J. Blaesser², Zachary J. Frederick³, Mark D. Guynn⁴, and Jason T. Kirk⁵

NASA Langley Research Center, Hampton, VA 23681

Kenneth Fisher⁶, Steven Schneider⁷, and Robert P. Thacker⁸

NASA Glenn Research Center, Cleveland, OH, 44351

Peter Frederic⁹

Tecolote Research, Inc, Santa Barbara, CA 93111

An electrified aircraft propulsion (EAP) design exploration study was performed to determine the impact of EAP technologies on a set of regional transport aircraft concepts. A range of aircraft sizes and types were assessed, including 18, 48, and 70 passenger turboprops, as well as 50 and 78 passenger turbofan aircraft configurations. A previous paper discussed the approaches, technology assumptions, and tools used to carry out the design exploration. The study team designed a series of baseline and advanced EAP aircraft concepts based on existing reference aircraft in the fleet. We then conducted a set of parametric trade studies on the EAP aircraft to better understand the design and performance implications of EAP. This paper documents results from the trade studies, including battery weight versus motor size, climb hybrid power versus cruise hybrid power, and range vs. battery specific energy. Assuming a 500 W-hr/kg battery specific energy, the turboprop aircraft demonstrated a significant fuel savings and modest energy savings. The turbofan aircraft demonstrated no fuel or energy benefits from electrification. In addition, operating cost results are presented on the most promising EAP designs. The cost analysis revealed that the EAP aircraft concepts were not competitive with their baselines, mainly due to the additional depreciation and interest cost for the much heavier and more expensive EAP aircraft.

I. Introduction

A design exploration study was conducted by NASA's Advanced Air Transport Technology (AATT) project focused on regional transport aircraft concepts that employ electrified aircraft propulsion (EAP). The study team developed EAP aircraft concepts with different sizes and propulsion architectures, explored design trades for the EAP aircraft, and determined the performance, environmental, and operating cost impact of EAP. In order to isolate the effects of EAP, we did not apply any other advanced propulsion or airframe technologies to the vehicles. The intent

¹Aerospace Engineer, Aeronautics Systems Analysis Branch, Member

²Aerospace Engineer, Aeronautics Systems Analysis Branch, Senior Member

³Aerospace Engineer, Aeronautics Systems Analysis Branch, Member

⁴Aerospace Engineer, Aeronautics Systems Analysis Branch, Senior Member

⁵Aerospace Engineer, Aeronautics Systems Analysis Branch, Member

⁶Aerospace Engineer, Propulsion Systems Analysis Branch, Member

⁷Aerospace Engineer, Propulsion Systems Analysis Branch, Member

⁸ Aerospace Engineer, Engine Combustion Branch, Member

⁹ Chief Scientist, Software Products and Service Group

was to understand the performance and design implications of applying EAP to a conventional baseline aircraft and to improve our tools where needed to support modeling of the EAP systems. We were not trying to demonstrate the maximum benefit for EAP in this study or design the most economically feasible EAP aircraft. We produced five parallel hybrid-electric aircraft designs: an 18 Passenger EAP Turboprop, a 48 Passenger EAP Turboprop, a 70 Passenger EAP Turboprop, a 50 Passenger EAP Turbofan, and a 78 Passenger EAP Turbofan. The same propulsion architecture (battery-powered electric motors provide additional shaft power to the turbine engines) was used for all the EAP aircraft concepts. The companion paper [1] documents the concept of operations, the engine/airframe modeling approach, aircraft sizing, mission analysis, and other key considerations and assumptions that were made for these aircraft designs.

For the main trade study in this design exploration, we parametrically varied the electric motor size and the battery weight for each EAP aircraft. For each battery/motor combination, we resized the EAP aircraft to meet the design mission range and determined the mission block fuel and block energy usage. Bigger batteries provided more energy and power for the mission but there was a significant weight penalty, which was compounded during the aircraft sizing. Bigger motors could deliver more power to the propulsors, but they needed to be compatible with the power available from the batteries and the propulsive power needed by the aircraft. We assumed a pack-level battery specific energy (BSE) of 500 W-h/kg, although we also ran cases with no BSE constraint to understand the upper performance limits of the aircraft. We also performed other trade studies. The power settings for the electric motors were varied parametrically for the cruise and climb segments. In many cases the electric motors provided significant excess power, allowing the turbine engines to be throttled back during climb or cruise, or enabling a higher rate of climb. With this trade study we tried to determine the most beneficial application of the motor power during the mission, in terms of fuel and energy usage. Finally, the trades between battery energy, battery weight, and range were explored. Mission range was varied parametrically with different values of BSE to understand the best operational ranges for these EAP aircraft.

As described in Ref. [1], we chose life cycle CO₂ emissions and direct operating cost plus interest (DOC+I) as the primary metrics for this study. The methods we used to calculate these metrics are detailed in that paper. The calculation for life cycle CO₂ emissions was based on the mission fuel and electricity consumption and was expressed as CO₂ equivalent (CO₂e). Using CO₂e enables other greenhouse gas emissions besides CO₂ to be expressed in terms of an equivalent amount of CO₂ based on their relative global warming potential [2]. The calculation for DOC+I required estimates of aircraft development, production, operating, and support costs. We chose the most favorable EAP aircraft designs, in terms of block fuel benefits, for a cost analysis to compare the DOC+I metric to the baseline aircraft.

This paper is organized into six sections. Section II describes the reference, baseline, and EAP aircraft models, Section III discusses the battery usage parametric study. Section IV contains the main battery weight versus electric motor size parametric study discussion. The mission range versus BSE parametric exploration is presented in Section V. The cost analysis results are contained in Section VI. Finally, the work and conclusions from the study are summarized in Section VII.

II. Study Aircraft Model Descriptions

The five EAP aircraft designs were based on existing reference aircraft. We modeled these reference aircraft using the Flight Optimization System (FLOPS) [3], a NASA aircraft sizing and synthesis tool. The turbine engines were modeled in the Numerical Propulsion System Simulation (NPSS) [4, 5] and then the engine performance decks were transferred to FLOPS. We applied different technology factors to the airframes and propulsion systems of the reference aircraft to create the baseline aircraft models, which all have an assumed common 2020 entry-into-service (EIS) date. These baseline aircraft were resized (wing, empennage, and propulsion system) to meet the same payload-range performance as the reference aircraft, assuming a constant thrust-to-weight ratio (T/W) and a constant wing loading (W/S). To create the EAP aircraft models, we modified the baseline aircraft designs to incorporate the volume of the EAP systems (if necessary) and then resized the wing, empennage, and turbine engines to meet the payload-range requirements factoring in the additional weight of the EAP systems. No additional technology factors were applied to the EAP aircraft airframes or turbine engines. The same T/W and W/S were used for the EAP aircraft as their respective reference and baseline aircraft. We required that the EAP aircraft were capable of completing the design mission without the EAP system operational (fuel-only mode), which represented a significant constraint in sizing the aircraft. This fuel-only requirement was expected to offer operational, safety, and certification advantages, but also might create significant weight penalties. Ultimately, the fuel-only requirement simplified the design requirements and allowed the study team to focus on the trade studies without getting side-tracked exploring any critical failure modes of the hybrid-electric propulsion system. We plan to remove the fuel-only requirement in a follow-on EAP

aircraft study. The vehicle modeling and sizing are explained more fully in the companion paper [1]. The reference, baseline, and EAP aircraft names are listed in Table 1.

Table 1 List of Reference, Baseline, EAP Aircraft

Reference Aircraft	Baseline Aircraft	EAP Aircraft
Embraer EMB 110P	18 Passenger Baseline Turboprop	18 Passenger EAP Turboprop
ATR 42-500	48 Passenger Baseline Turboprop	48 Passenger EAP Turboprop
ATR 72-600	70 Passenger Baseline Turboprop	70 Passenger EAP Turboprop
Embraer ERJ-145	50 Passenger Baseline Turbofan	50 Passenger EAP Turbofan
Embraer E175	78 Passenger Baseline Turbofan	78 Passenger EAP Turbofan

The general characteristics for the reference, baseline, and EAP aircraft are listed in Table 2. The airframe and propulsion technology factors applied to the baseline aircraft make them somewhat lighter than the corresponding reference aircraft and significantly improve the baseline aircraft fuel consumption. For each baseline aircraft, 16 variant EAP aircraft were modeled, corresponding to different combinations of battery weight and motor size, resulting in a total of 80 EAP aircraft designs. In Table 2, only two of the EAP variant aircraft are shown, corresponding to 1) the lightest battery and smallest motor and 2) the heaviest battery and largest motor. We sized the EAP aircraft in FLOPS with the requirement that the mission range had to be met using only fuel and with no battery power. We then performed the mission analysis for the hybrid-electric operations using the Layered and Extensible Aircraft Performance System (LEAPS) [6]. The performance of the EAP aircraft variants is discussed in Section IV, which contains the battery weight versus motor size parametric study results. We compared the performance of the EAP aircraft models only to the corresponding baseline aircraft, as the baseline aircraft share the same 2020 technology levels for the airframes and turbine engines (excluding the EAP system).

Table 2 Reference, Baseline and EAP Aircraft General Characteristics

	18 Passenger Turboprops				48 Passenger Turboprops				70 Passenger Turboprops				50 Passenger Turbofans				78 Passenger Turbofans			
	Reference	Baseline	EAP (Smallest battery & motor)	EAP (Largest battery & motor)	Reference	Baseline	EAP (Smallest battery & motor)	EAP (Largest battery & motor)	Reference	Baseline	EAP (Smallest battery & motor)	EAP (Largest battery & motor)	Reference	Baseline	EAP (Smallest battery & motor)	EAP (Largest battery & motor)	Reference	Baseline	EAP (Smallest battery & motor)	EAP (Largest battery & motor)
Operating Empty Weight (lb)	7,502	7,205	8,084	11,085	24,801	24,041	28,476	43,475	29,980	29,187	34,284	53,395	26,339	25,427	30,068	43,135	47,339	45,627	54,451	81,609
Maximum Fuel (lb)	3,072	2,850	3,433	5,994	9,959	7,923	5,287	8,503	10,321	8,299	5,968	9,687	9,202	7,380	8,197	10,562	20,785	17,283	19,300	26,186
Maximum Payload (lb)	3,457	3,457	3,457	3,457	12,043	12,043	12,043	12,043	16,498	16,498	16,498	16,498	11,359	11,359	11,359	11,359	22,487	22,487	22,487	22,487
Battery Weight (lb)	N/A	N/A	864	3,457	N/A	N/A	3,011	12,043	N/A	N/A	4,125	16,498	N/A	N/A	2,840	11,359	N/A	N/A	5,622	22,487
Maximum TOGW (lb)	12,105	11,506	12,826	18,538	41,005	39,175	43,772	60,087	50,706	48,861	54,143	74,780	46,275	43,743	49,082	64,113	85,517	81,304	91,514	124,122
Wing Area (ft ²)	312	297	336	488	586	560	625	858	657	633	701	969	551	521	584	763	783	745	838	1,137
T/W	0.416	0.416	0.416	0.416	0.435	0.435	0.435	0.435	0.387	0.387	0.387	0.387	0.328	0.328	0.328	0.328	0.339	0.339	0.339	0.339
W/S	38.8	38.8	38.8	38.8	70.0	70.0	70.0	70.0	77.2	77.2	77.2	77.2	84.0	84.0	84.0	84.0	109.2	109.2	109.2	109.2
Design Range (nm)	250	250	250	250	459	459	459	459	488	488	488	488	1,200	1,200	1,200	1,200	1,900	1,900	1,900	1,900

III. Battery Usage Strategy Parametric Study

The team conducted a parametric study to determine how to use the available battery energy most effectively during the EAP aircraft missions as the initial step in the larger study. The EAP study aircraft only used battery energy during the climb and cruise mission segments, so the most direct approach was to parametrically vary the throttle settings for the electric motors during those segments to find the best combination of settings. We modeled the EAP

aircraft propulsion systems with a new power control parameter called the Electric Power Code (EPC). The EPC was defined as the percentage of full electric motor power delivered to the turbine engine shaft. Due to modeling constraints, EPC was required to be constant during a mission segment but could be changed between segments. We varied EPC parametrically from 0% to 100% in 10% increments for both the climb and cruise segments, resulting in 121 throttle setting combinations. As EPC was parametrically increased, the turbine engine throttle settings were decreased in order to maintain the same overall power delivery at the propulsor.

Contour plots showing the effect of different EPC values during climb and cruise on mission block fuel and block energy for one of the 48 passenger EAP turboprop aircraft are presented in Fig. 1. The block energy consists of the energy from the block fuel plus the electrical block energy consumed by the propulsion system during the mission. The color contours are values of pounds of mission fuel (left plot) and megajoules of mission energy (right plot). The dashed contour lines are BSE constraint lines, representing the BSE that is required in order for the battery to store sufficient energy to complete the mission. Traveling along the 500 W-h/kg constraint line of each plot reveals that the block fuel and block energy values remain nearly the same at every point along the line. The cruise motor power varies between roughly 30% and 40% along the same constraint line, meaning that a battery with 500 W-h/kg BSE can only support operating the motors at partial power during the cruise segment because not enough energy is available to operate at full power. The key takeaway from these plots is the near perfect alignment of the fuel/energy consumption contours and the battery constraint contours. This indicates that the block fuel and block energy consumption is primarily a function of the total amount of electrical energy used by the motors and is largely insensitive to whether that energy is used in the climb or cruise segments. This result was seen consistently for the other EAP aircraft as well.

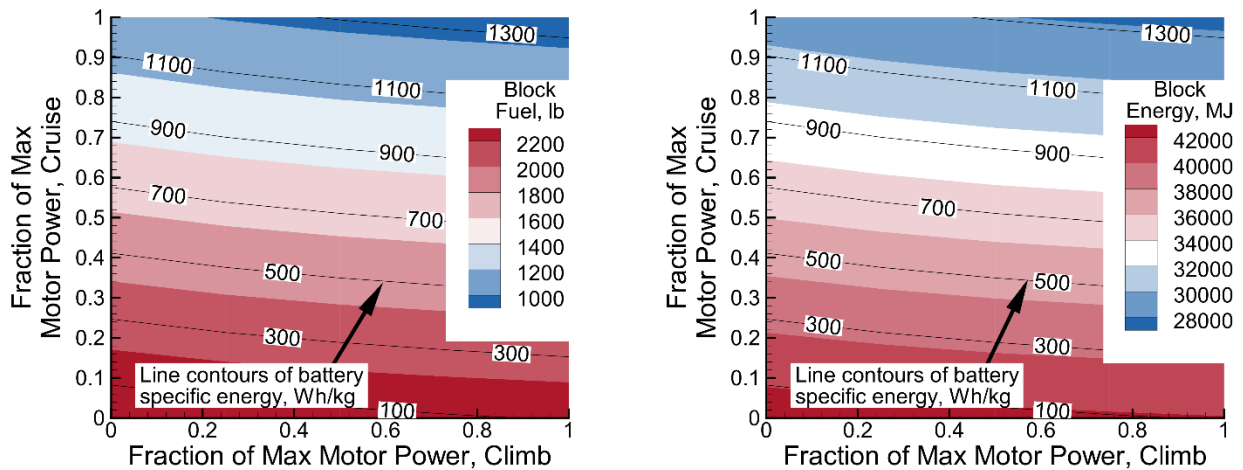


Fig. 1 Impact of climb and cruise hybrid throttle on block fuel (left) and energy (right) for one of the 48 Passenger EAP Turboprop aircraft.

IV. Battery Weight versus Motor Size Parametric Study

Each EAP aircraft consisted of 16 design variants with different battery/motor size combinations (a matrix of 4 battery weights and 4 motor sizes). These design variants enabled a parametric study to identify battery/motor combinations that produced the minimum block fuel, block energy, and life cycle CO₂e. We initially ran cases with no BSE constraint to understand the maximum benefit if battery energy is essentially unlimited. We then ran the same cases assuming a 500 W-h/kg BSE operational constraint. We selected the best battery/motor cases (with the BSE constraint) for a cost analysis to determine the effect of EAP on DOC+I, as discussed in Section VI.

We selected the battery weights used in the parametric study as a percentage of the maximum payload weight of the baseline vehicle. The largest battery weight was limited to 100% of the maximum payload weight. We required the EAP aircraft to carry the full payload weight plus the battery weight; battery weight was not traded for payload weight. For the four larger EAP aircraft (48 Passenger EAP Turboprop, 50 Passenger EAP Turbofan, 78 Passenger Turboprop, and 70 Passenger Turbofan), the motor sizes were limited to 1 MW. While larger flight certified motors should be possible at some point, most of the current development research is focused on 1 MW class motors or smaller. For these four aircraft, the four motor sizes selected were fractions of that maximum motor size. The 18

Passenger EAP Turboprop used a different strategy for selecting the motor sizes which was based on the desired amount of hybridization for the EAP aircraft. The motor sizes were determined as fractions of the sized EAP aircraft turbine engine SLS maximum power. This strategy was selected to limit the motor sizes within a useable range. This resulted in 16 different motor sizes being used for the 18 Passenger EAP Turboprop. The selection of the battery weights and motor sizes is discussed in depth in the companion paper [1]. Figure 2 is taken from that paper and shows the electric motor sizes used for the EAP aircraft in terms of percentage of the respective baseline engine's power.

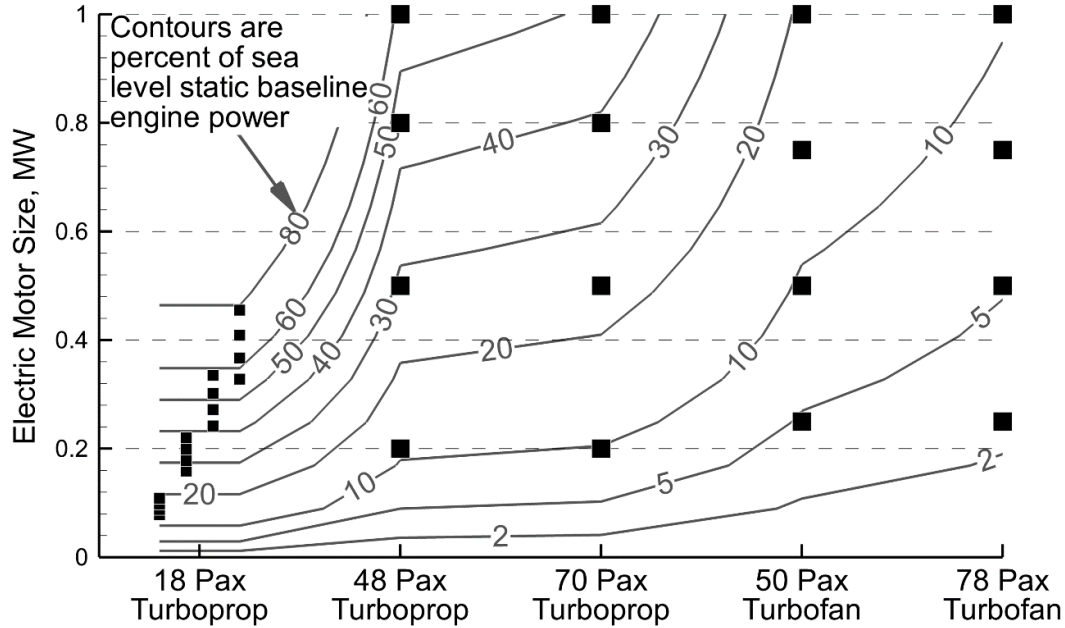


Fig. 2 Electric motor sizes for each EAP aircraft in megawatts and as a % of the baseline engine power

A. 18 Passenger EAP Turboprop Aircraft

The 18 Passenger EAP Turboprop presented a unique case because the power requirements were so much lower than the other EAP aircraft. As can be seen in Fig. 2, a much lower range of motor sizes was selected for this aircraft. A 16-case full factorial sweep was run with motor sizes of 12.5%, 25%, 37.5%, and 50% of maximum power of the EAP turbine engine in fuel-only operation, and battery weights of 25%, 50%, 75%, and 100% of maximum payload weight. For the initial set of runs, we determined the electrical energy required to fly the mission for the 16 cases, and then calculated the required BSE for the given battery weight. We then compared the required block fuel and block energy for each case to the baseline aircraft. The relative differences between the EAP designs and the baseline aircraft are shown in Fig. 3, in terms of block fuel (left plot) and block energy (right plot). Negative values indicate a benefit for the EAP aircraft. Each of the black squares represents one of the 16 parametric battery/motor combinations. In order to remain consistent with the results presented for the other aircraft, the motor power values are plotted in terms of the fraction of baseline engine power rather than the hybridization percentage of the EAP turboprop engine.

The overall trends in energy and fuel benefit were similar. There was a significant penalty as battery weight increased for all cases, as would be expected. Since the BSE constraint was not applied on these runs, the added battery weight did not provide additional energy versus lighter batteries. When the battery weight was held constant and the motor size increased, a benefit was seen for the smaller motor sizes. However, for the larger motors this trend was reversed, and there was a small penalty as motor size continued to increase. This trend reversal is due to in-flight limitations on the amount of electric motor power that can be used by these aircraft. It was found that the larger motors were capable of producing more power than was required for level flight in cruise. In these cases, the electric motors were operated at partial power to allow the gas turbines to remain at the minimum idle power (in-flight shutdown of the turbine was not allowed) while maintaining the required cruise thrust. Since the full capability of the larger motors could not be used in cruise, there was minimal additional benefit from the increase in available motor power to offset the additional weight penalty. The maximum block fuel consumption benefit for the EAP aircraft with no BSE constraint was 21.5% and the maximum block energy benefit was 10.1%.

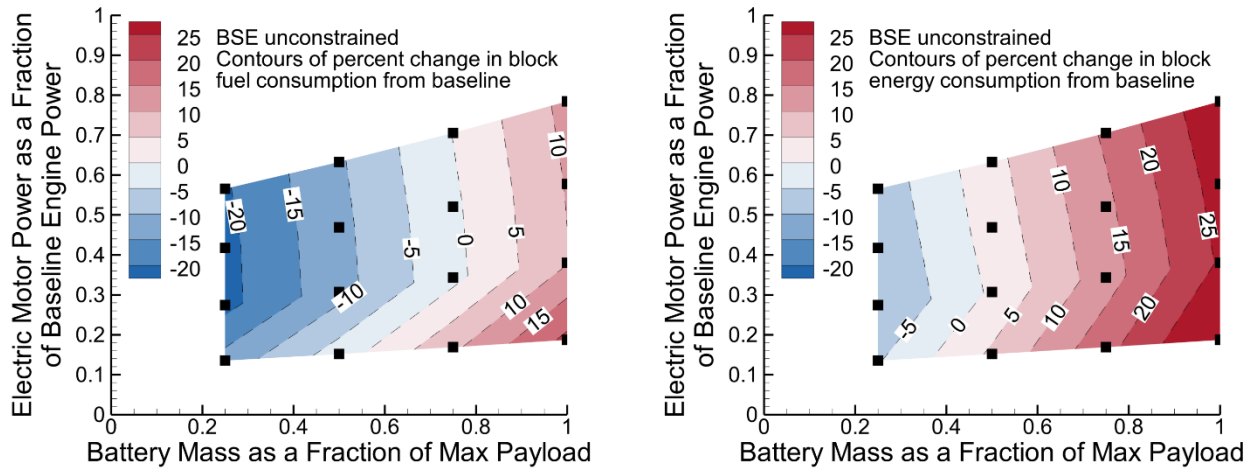


Fig. 3 Percent change in block fuel (left) and block energy (right) for the 18 Passenger EAP Turboprop compared to the 18 Passenger Baseline Turboprop (no BSE constraint).

We repeated the same set of parametric runs, but this time BSE was limited to a maximum of 500 W-h/kg. For each combination of motor and battery size, the electric power used in climb and cruise was set to ensure the 500 W-h/kg BSE constraint was not violated. In some cases, the maximum electric energy (with the motor at 100% power for all of climb and cruise) resulted in required battery energy densities lower than the technology target. We included these cases in the comparison, although they are penalized with a heavier battery than required. The results from these BSE constrained runs are shown in Fig. 4, which presents the block fuel and block energy benefits relative to the 18 passenger baseline aircraft as the previous figure. The minimum fuel consumption point was seen at a motor size of approximately 30% of the baseline power and a battery weight of about 50% of the maximum payload weight. In this region, the motor and the battery were well matched to the design mission to achieve minimum fuel consumption. The motor was the correct size to provide useful power to the turbine engine and to consume all the battery energy. For that motor size, a larger battery would have provided unusable excess energy during the mission. A smaller battery would have required the motor to be throttled back, meaning that extra motor weight would be carried with no benefit. Similarly for that battery size, a larger motor would need to be throttled back and a smaller motor would not use all the available energy in the battery. The best parametric case had 10.5% lower block fuel than the baseline aircraft. The block energy plot shows a much smaller potential benefit for the range of battery/motor combinations examined, with the smallest block energy values corresponding to the smallest battery/motor combinations. The best parametric case in terms of block energy was a 3% benefit for the EAP aircraft compared to the baseline.

The plots for life cycle CO₂e are not shown; however, the trends for life cycle CO₂e emissions are similar to those of block energy usage, since CO₂e is calculated using block fuel and block electricity. The best parametric case for life cycle CO₂e with a 500 W-h/kg BSE constraint enforced had a 5.2% benefit for the 18 Passenger EAP Turboprop compared to the baseline.

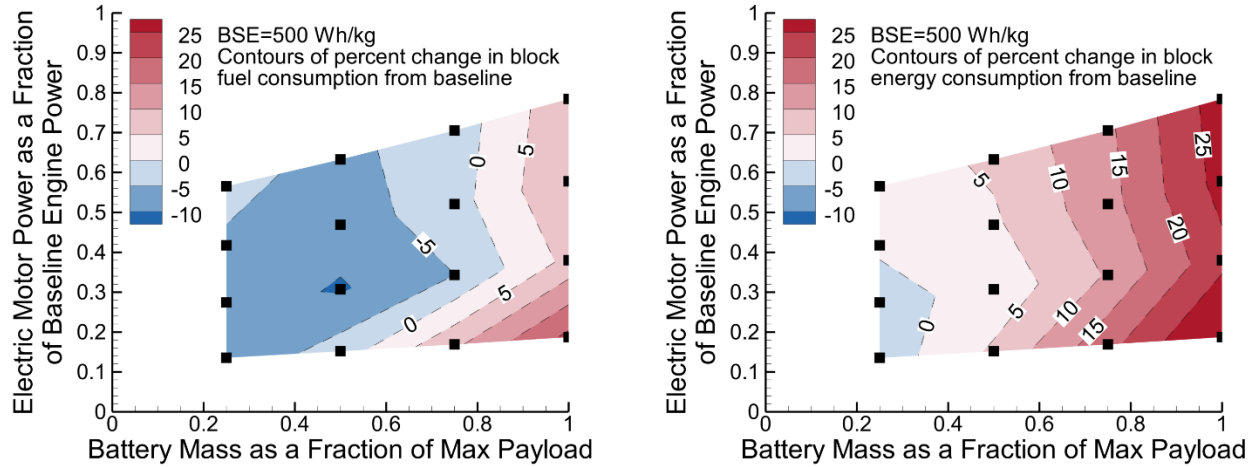


Fig. 4 Percent change in block fuel (left) and block energy (right) for the 18 Passenger EAP Turboprop compared to the 18 Passenger Baseline Turboprop (500 W-h/kg BSE constraint).

B. 48 Passenger EAP Turboprop Aircraft

The results of the parametric runs for the 48 Passenger EAP Turboprop are shown in Fig. 6. For this aircraft, we ran the 16-case full factorial sweep with motor sizes of 0.2, 0.5, 0.8, and 1 MW, and battery weights of 25%, 50%, 75%, and 100% of maximum payload weight. The plot on the left shows the percentage difference in block fuel between the 48 Passenger EAP Turboprop and the 48 Passenger Baseline Turboprop aircraft, and the plot on the right shows the percentage difference in block energy. No BSE constraint was placed on the 16 parametric cases for this initial set of runs. The fuel and energy benefits were maximized with high motor power (more electrical energy is used) and low battery weight (lighter batteries can carry as much energy as heavier batteries with no BSE constraint). Unlike the 18 Passenger EAP Turboprop, the largest motors did not produce more power than required in cruise. The maximum fuel reduction benefit was close to 60% and the maximum energy reduction benefit exceeded 30% for the lightest battery and largest motor. However, this battery/motor combination required BSEs exceeding 2500 W-h/kg, which would require revolutionary breakthroughs in battery technology. The same plots are shown in Fig. 6, with a 500 W-h/kg BSE constraint enforced. For the block fuel cases, there was a region where the largest fuel benefits can be seen. The battery/motor combinations in this area tended to have EPC values close to 100% for both climb and cruise. In this region the motor and battery were well matched so that the motor used all of the available battery energy and provided enough power to the turbine engine to provide a block fuel benefit. The parametric case with the best fuel consumption occurred at a battery weight of 50% of maximum payload weight and a motor power of 0.5 MW, resulting in a relative block fuel reduction of 9.1%. The best energy consumption cases for the 48 Passenger EAP Turboprop occurred at the smallest battery/motor size combinations. The best parametric case produced a block energy reduction of 3.8% compared to the baseline. The best parametric case for life cycle CO₂e had a 5.6% benefit compared to the baseline.

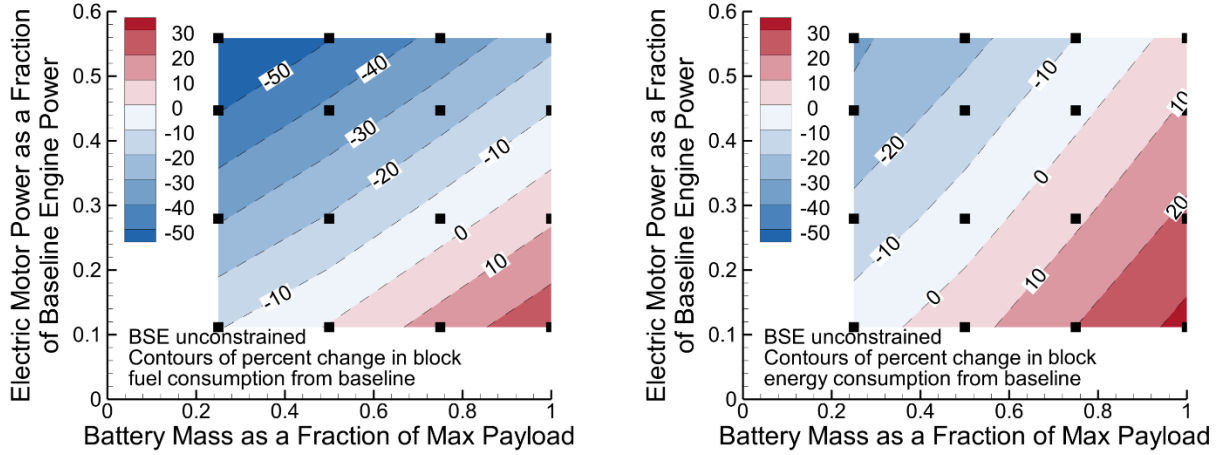


Fig. 5 Percent change in block fuel (left) and block energy (right) for the 48 Passenger EAP Turboprop compared to the 48 Passenger Baseline Turboprop (no BSE constraint).

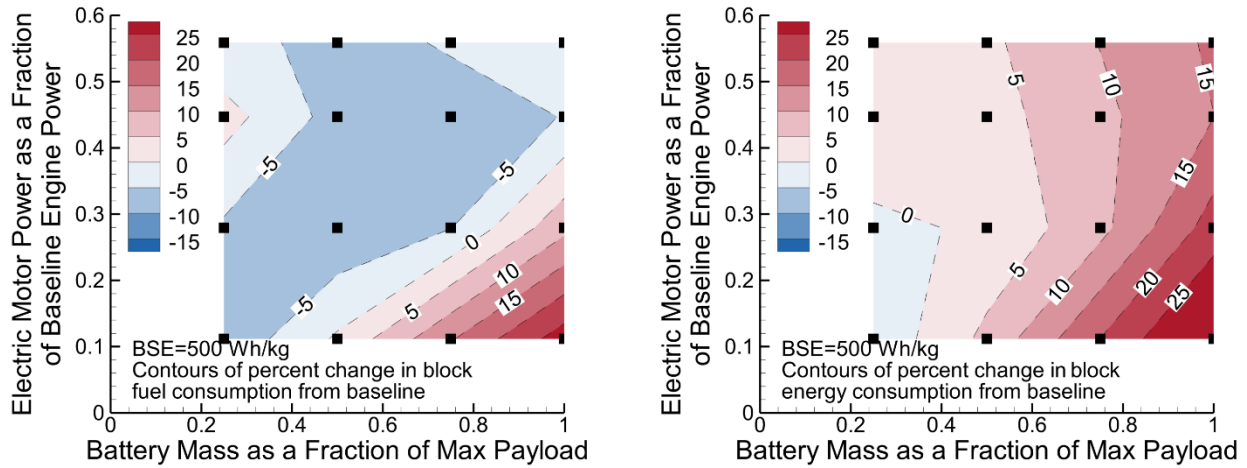


Fig. 6 Percent change in block fuel (left) and block energy (right) for the 48 Passenger EAP Turboprop compared to the 48 Passenger Baseline Turboprop (500 W-h/kg BSE constraint).

C. 70 Passenger EAP Turboprop Aircraft

The parametric results for the 70 Passenger EAP Turboprop aircraft are similar to those of the 48 Passenger EAP Turboprop. This should be expected, as the reference aircraft for the two EAP aircraft are the ATR 72-600 and the ATR 42-500. The ATR 72 is essentially a stretched version of the ATR 42 with slightly more powerful engines. Fig. 7 shows the percentage block fuel and block energy differences for the 70 Passenger EAP Turboprop compared to its baseline aircraft when no BSE constraint is applied. We used the same set of motor sizes as the 48 Passenger EAP Turboprop and used the same percentages of the maximum payload weight for the battery weights. The largest motor and smallest battery combination demonstrated very large block fuel and block energy benefits but required a BSE over 2000 W-h/kg. The block fuel and block energy results with the 500 W-h/kg BSE constraint applied are shown in Fig. 8. For the block fuel cases, once again there was a region of minimum fuel consumption where the EPC values were close to 100% for both climb and cruise. The best parametric case for fuel consumption occurred at a battery weight of 75% of maximum payload weight and a motor power of 0.8 MW, resulting in a relative block fuel reduction of 13.6%. The best parametric case for block energy consumption had a battery weight of 25% of maximum payload weight and a motor power of 0.2 MW, resulting in a relative block energy reduction of 3.3%. The best parametric case for life cycle CO₂e had a 5.5% benefit compared to the baseline.

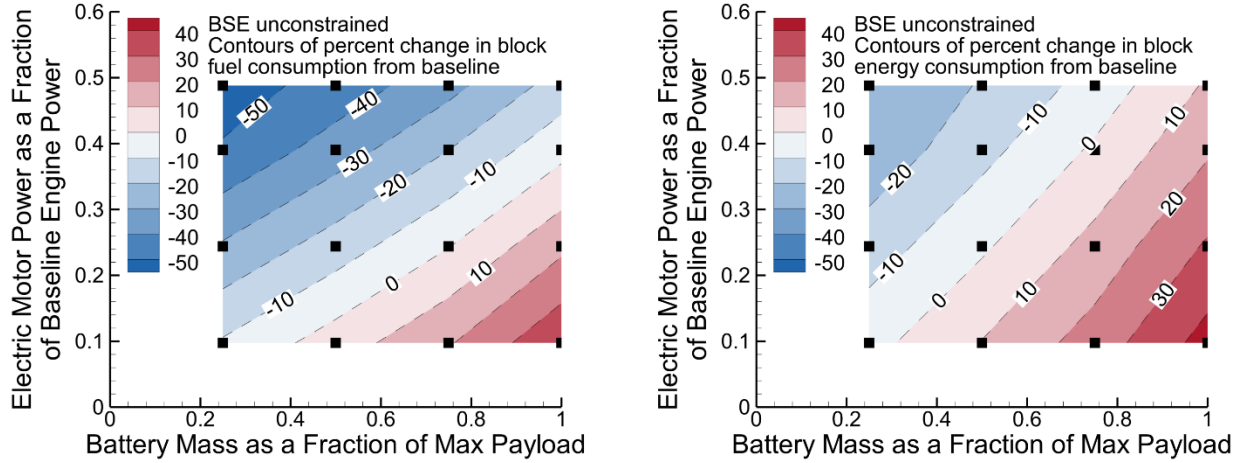


Fig. 7 Percent change in block fuel (left) and block energy (right) for the 70 Passenger EAP Turboprop compared to the 70 Passenger Baseline Turboprop (no BSE constraint).

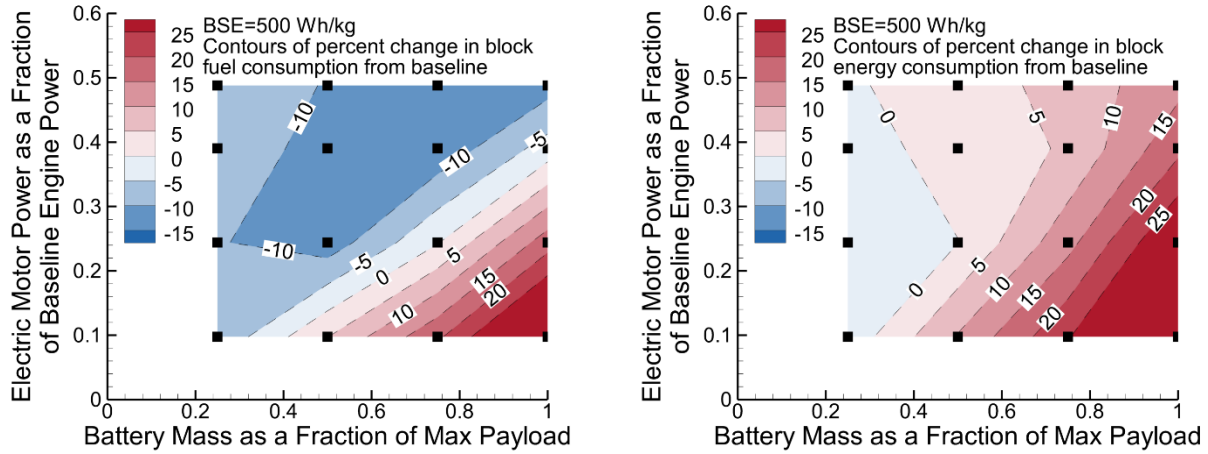


Fig. 8 Percent change in block fuel (left) and block energy (right) for the 70 Passenger EAP Turboprop compared to the 70 Passenger Baseline Turboprop (500 W-h/kg BSE constraint).

D. 50 Passenger EAP Turbofan Aircraft

The results of the parametric runs for the 50 Passenger EAP Turbofan with no BSE constraint are shown in Fig. 9. We ran the 16-case full factorial sweep with motor sizes of 0.25, 0.5, 0.75, and 1 MW, and battery weights of 25%, 50%, 75%, and 100% of maximum payload weight. None of the 16 designs demonstrates potential for a reduction in block energy consumption (fuel + electricity) compared to the 50 Passenger Baseline Turbofan. In other words, the hybrid system could not offset the increase in energy needed for carrying the battery weight, EAP systems weight, and the additional weight from the aircraft sizing, even without placing limits on the battery energy available. However, recall that even though the amount of available energy is unlimited, the amount of energy that can be used by the propulsion system is limited by the motor size. Six of the sixteen cases demonstrated a potential fuel consumption benefit, but all had associated BSE values well above 500 W-h/kg. The largest motor and smallest battery weight case required a BSE greater than 5000 W-h/kg to achieve a 17% fuel reduction. When a 500 W-h/kg BSE constraint was applied, there were no block fuel or block energy benefits for any of parametric battery/motor cases. The best block fuel parametric case showed a 7.1% fuel consumption penalty compared with the 50 Passenger Baseline Turbofan, and the best block energy case showed a 9.0% energy consumption penalty. The best case for life cycle CO₂e emissions is also 8.3% worse than the baseline aircraft.

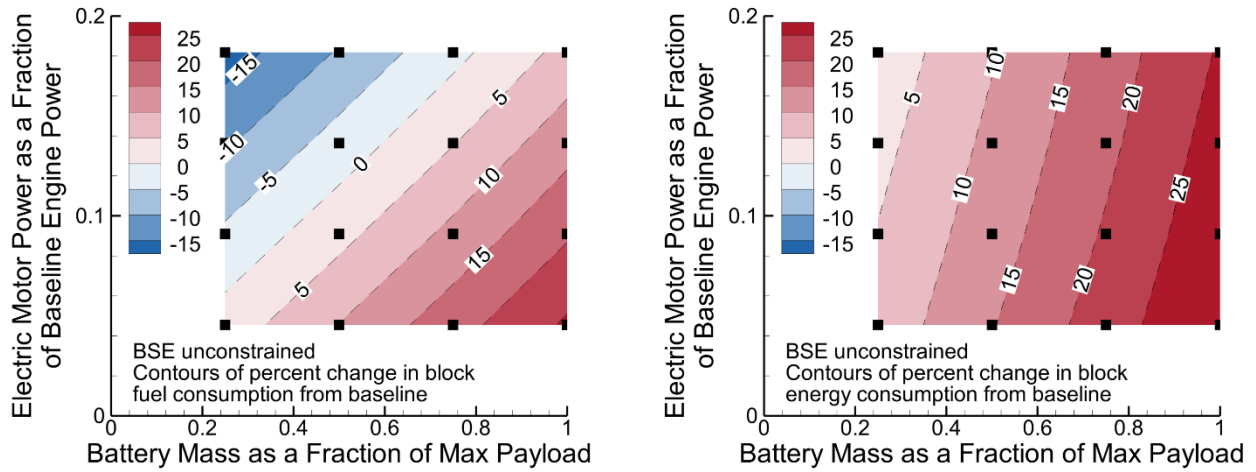


Fig. 9 Percent change in block fuel (left) and block energy (right) for the 50 Passenger EAP Turbofan compared to the 50 Passenger Baseline Turbofan (no BSE constraint).

These results show that the fuel and energy consumption of the 50 Passenger EAP Turbofan aircraft relative to its baseline was significantly higher than the EAP turboprops compared to their baselines. There are several likely reasons for this result. The turbofan engines for the 50 passenger EAP are larger and inherently more efficient than the turboprop aircraft engines, resulting in smaller relative improvements compared to the turboprops with the addition of EAP. Another factor is the percentage of hybridization applied to the different engines. For the 50 Passenger EAP Turbofan, a 1 MW motor is only about 20% of the baseline engine power, but for the 70 Passenger EAP Turboprop, it represents about 50% of the baseline engine power. For the unconstrained BSE cases, the higher percent hybridization resulted in larger benefits. Finally, there were more design issues encountered when incorporating the parallel-hybrid electric architecture into the turbofan engines versus the turboshaft engines. For the turboprops, we assumed that the electric motor would engage the propeller shaft via a gearbox, and that the variable-pitch propellers would be able to absorb the increased power provided by the motors without having to change the engine cycle design of the turboshaft engines. For the turbofans, the electric motors engaged with the low speed spool. We had to make changes to the engine cycle design to allow extra power to be delivered to the low speed spool while keeping the fan within reasonable operating limits. This design compromise is a likely source of the lower overall performance of the EAP turbofan compared to the EAP turboprops. The EAP aircraft propulsion system design and modeling are discussed in more detail in the companion paper [1].

E. 78 Passenger EAP Turbofan Aircraft

The 78 Passenger EAP Turbofan exhibits similar performance as the 50 Passenger EAP Turbofan when compared to its respective baseline aircraft. The block fuel and block energy consumption for the 78 Passenger EAP Turbofan with no BSE constraint are shown in Fig. 10. We used the same motor sizes and battery weight percentages of maximum payload that were used for the 50 Passenger EAP Turbofan. For this aircraft, the 1 MW limit on the motor size resulted in motors that were a significantly smaller percentage of the baseline maximum motor power than the other aircraft in the study. The maximum block fuel benefit was very close to the 50 Passenger EAP Turboprop, even with a more limited range of hybridization possible. Four of the sixteen cases demonstrated a potential fuel consumption benefit. However, each of these four cases has associated BSE values well above 500 W-h/kg. The 1 MW motor and 25% payload weight battery case required a BSE greater than 4000 W-h/kg to achieve a 10% fuel reduction. As with the 50 Passenger EAP Turbofan, none of the sixteen designs demonstrate a reduction in total energy consumption, even without a battery energy limit. When the 500 W-h/kg BSE constraint was applied there were no cases that demonstrated a block fuel or block energy benefit. The best-case block fuel consumption penalty was 7.5% and the best-case block energy consumption penalty was 8.9%. The smallest penalty for CO₂e emissions with the 500 W-h/kg BSE constraint was an 8.4% increase relative to the baseline.

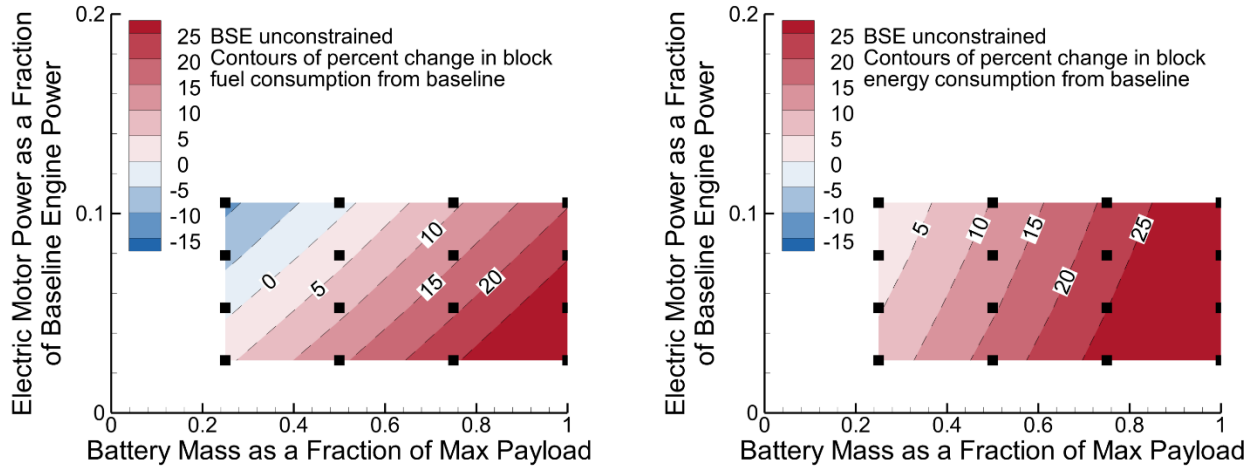


Fig. 10 Percent change in block fuel (left) and block energy (right) for the 78 Passenger EAP Turbofan compared to the 78 Passenger Baseline Turbofan (no BSE constraint).

F. Summary of Performance Results

A summary of results from the battery weight versus motor size parametric study is presented in Fig. 11. The best battery/motor parametric case is presented for block fuel, block energy, and life cycle CO₂e for each of the EAP aircraft assuming a BSE of 500 W-h/kg. These results are all independent of one another, so the best battery/motor combination for block fuel is not necessarily the same as the best combination for block energy or life cycle CO₂e. The EAP Turboprop aircraft all exhibited positive fuel and energy benefits when compared to their respective baseline aircraft for these individual cases. The EAP turbofan aircraft both exhibited fuel and energy penalties compared with their baselines.

The study team hoped that the analysis might show a trend in the effectiveness of EAP applied to different aircraft sizes. Unfortunately, the results in Fig. 11 do not appear to reveal any strong trends related to aircraft size. One reason might be the method for selecting battery weights and motor sizes. As previously discussed, the method for selecting motor sizes was not consistent for all the study aircraft. The EAP Turbofans and the two larger EAP Turboprops used fixed motor sizes that were intended to represent a realistic range of motor powers; however, these fixed sizes resulted in different ranges of hybridization between the aircraft. It is possible that the maximum benefit may not have been captured in the selected motor size range for every aircraft. The selection of battery weight based on payload weight may also have contributed to this problem. Although the methodology was consistently applied to all the aircraft, this meant that the battery weights for the smaller aircraft were significantly less than those for the larger aircraft. This shortened the amount of time the motors could operate at full power compared to the larger aircraft and limited the benefit that could be realized for a given BSE. Consequently, the ranking of these EAP aircraft in terms of relative benefit could change depending on the BSE level chosen. In future work, different strategies for choosing battery weight and motor power may be needed to see if any aircraft size trends can be identified.

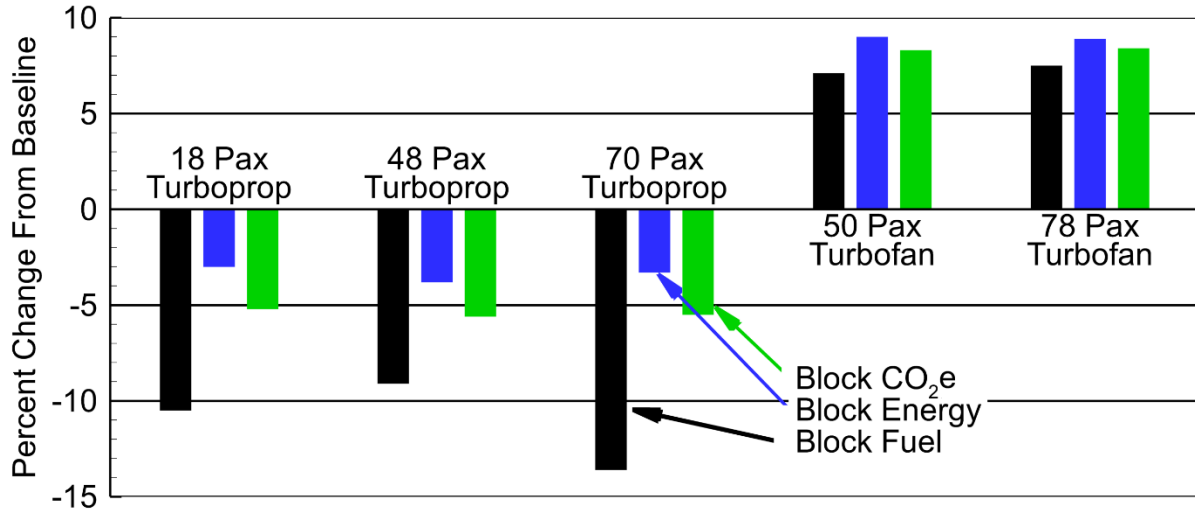


Fig. 11 EAP Aircraft Results for the Battery Weight vs. Motor Size Parametric Study With a 500 W-h/kg BSE Constraint

V. Mission Range versus BSE Parametric Study

The mission analysis for the EAP aircraft used in the previous parametric study assumed that each aircraft was flying the design range. For this parametric study, we evaluated several of the EAP aircraft while flying shorter missions at different BSE values. In general, shorter missions benefit the EAP aircraft because the energy requirements of the batteries are reduced. However, the analysis shows that there is a minimum range required to see a positive fuel consumption benefit. An example is shown in Fig. 12, for a single variant of the 78 Passenger EAP Turbofan aircraft. This figure shows a series of overlapping “v-shaped” curves that relate fuel consumption (relative to the baseline aircraft) and mission range for a set of BSE values. Starting at a 300 nm range, there is a fuel consumption penalty compared to the baseline aircraft because there has not been enough time in climb and cruise for the electrical energy used to offset the increased fuel consumption from the heavier EAP aircraft in the other mission segments. Increasing the range from this point greatly improves the relative fuel consumption performance until such point as the electric storage capacity limit is reached. Increasing the range further without using more electric energy than is available from the battery requires throttling back the electric motors (increasing fuel flow to the gas turbines) and the benefit of the hybrid system drops sharply. This gives a “negative peak” to the curves. The range at which this reversal occurs depends on the BSE, with higher BSE values allowing longer missions before the benefits start to drop. For example, if the battery has a BSE of 500 W-h/kg, the negative peak occurs at 400 nm (at this point there is a tiny fuel consumption benefit) and then there is a fuel consumption penalty almost immediately if range is increased from this point. Increasing BSE expands the portion of the aircraft range capability across which a fuel reduction benefit can be realized. If the BSE is 1000 W-h/kg, the fuel consumption benefit is positive after 400 nm, peaks at a 5% benefit at approximately 600 nm, and then decreases as range is increased until it is zero at approximately 870 nm. Also note that for a given BSE the mission range at which the greatest benefit occurs varies for each battery/motor combination, so each variant of the 78 Passenger EAP Turbofan would results in a unique plot.

The results of this study point to the importance of matching the battery capacity to the mission range. A given battery will provide a limited region of off-design ranges where the EAP aircraft will have better fuel consumption performance than the baseline. Having the ability to easily change the battery size on the EAP aircraft would help expand the envelope of off-design ranges where a fuel benefit is possible.

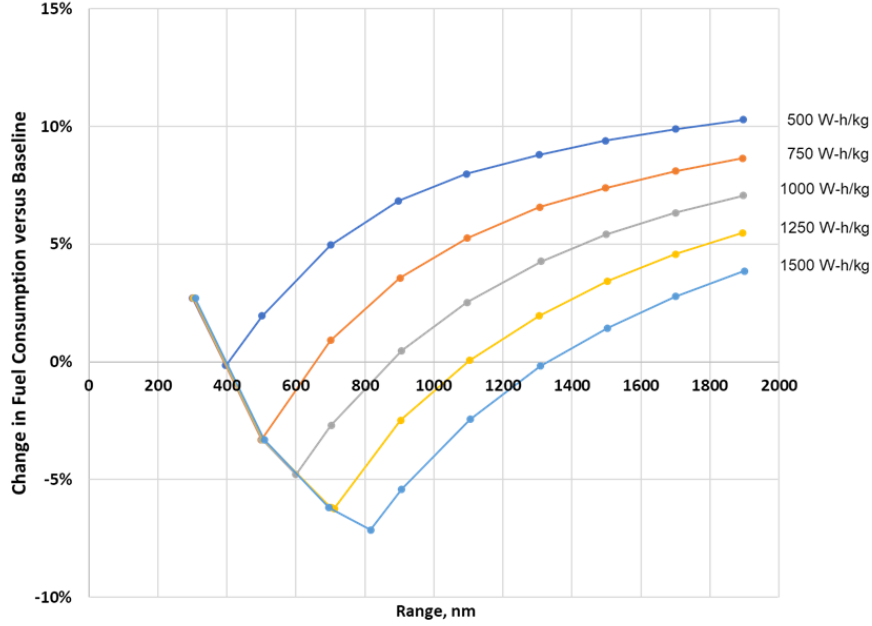


Fig. 12 Relative fuel consumption as a function of range and BSE for the 78 Passenger EAP Turbofan.

VI. Cost Modeling Results

We performed an operating cost analysis on the most promising cases, in terms of fuel and energy consumption, resulting from the battery weight versus motor size parametric study. The DOC+I calculation required estimates of aircraft development, production, operating, and support costs. The electrified propulsion cost analysis approach was based on a tool called the Probabilistic Technology Investment Ranking System (PTIRS) [7]. The cost analysis approach, tools, and assumptions are discussed in the companion paper [1]. The EAP turboprop aircraft each had two to three battery/motor combinations that received a DOC+I calculation, assuming a BSE of 500 W-h/kg. Since the EAP turbofan aircraft demonstrated performance penalties compared to their baselines with a BSE of 500 W-h/kg constraint, we reduced the mission ranges and increased the BSE values until there was a positive fuel consumption benefit, selecting BSEs of 1000 W-h/kg and 750 W-h/kg for the 50 Passenger EAP Turbofan and 78 Passenger EAP Turbofan, respectively. These BSE values required a jump in technology level for the batteries, and the design ranges were no longer comparable to the baseline aircraft, meaning the cost results between the EAP turbofans and EAP turboprops are not directly comparable.

An initial step of the cost analysis was to examine the difference in energy cost between burning jet fuel in a modern Brayton cycle engine and driving an electric motor with grid energy stored in batteries. Table 3 shows the difference in shaft energy cost between burning Jet-A fuel and consuming electricity stored in batteries. The electricity cost used was the 2020 U.S. average for transportation of \$0.10/kW-h, a pre-COVID-19 pandemic fuel cost of \$1.85/gal was used, EAP system end-to-end efficiency was consistent with our study aircraft (90.8%), and the specific fuel consumption for an ATR 72 aircraft was assumed. The resulting shaft energy cost for Jet-A fuel was 17 cents per kilowatt-hour (kW-h) versus about 9 cents per kW-h for power off the electrical grid. According to this analysis, the EAP system operation on a regional class aircraft should have a significant cost advantage compared to the turbine engine operation, in terms of shaft energy cost per kW-h. However, it is important to note that 1) the electricity cost is not negligible, 2) the realized cost savings is highly dependent on the split between battery power and turbine engine power for the EAP aircraft, and 3) the cost advantage for the EAP system needs to be very large in order to offset the additional acquisition costs for an EAP aircraft when compared to the baseline aircraft.

Table 3 Energy Prices Translated to Engine Shaft Energy Cost

	\$/gal	gal/lb	\$/lb	ATR-72 lb/shp-hr	ATR-72 \$/shp-hr	kW/shp	Shaft \$/kW-h
Jet-A (4Q2019)	1.85	6.71	0.28	0.47	0.13	0.75	0.17
					Grid \$/kWh	EAP system End-to-End Efficiency	Shaft \$/kW-h
Electricity					0.10	90.8%	0.09

As noted previously, cost analysis was conducted for multiple EAP aircraft in each class. The results for the cases with the lowest operating cost are shown for each EAP aircraft in Table 4. The same data is shown for the baseline aircraft flying the same economic mission for comparison. The PTIRS tool uses a probabilistic cost analysis, and the DOC+I values presented in the table are the 50% probability values. These results show that none of the EAP aircraft are expected to demonstrate a DOC+I benefit when compared to their baseline aircraft. There are several important factors which lead to this result. First, the EAP aircraft were sized to fly the design mission with their EAP system non-operational (fuel-only). Due to the resizing effect, the empty weight of the airframe (minus the EAP hardware) increased compared to the baseline aircraft. Furthermore, the additional weight of the EAP hardware, especially the batteries, is significant. In the end, the higher costs due to the larger empty weight, increased maintenance, and additional electricity cost vastly outweighed the modest benefits these EAP designs exhibited in terms of reduced fuel costs. This can be more clearly demonstrated by looking at the operating cost breakout of the 48 Passenger EAP Turboprop case in Fig. 13. The bar chart in this figure shows the relative benefit of each cost category compared to the 48 Passenger Baseline Turboprop aircraft. Fuel and Oil was approximately 2 cents per passenger mile less expensive for the EAP aircraft versus the baseline. This was the only cost category that showed a benefit. The maintenance cost for the non-EAP hardware was higher due to the higher empty weight of the EAP aircraft. The maintenance cost for the EAP hardware was dominated by the battery replacement cost. As discussed in the companion paper [1], it was assumed that the batteries require replacement after 3650 cycles. The additional electricity cost negates more than half of the fuel cost benefit for this aircraft. The next two categories are for the depreciation and interest costs associated with amortizing the higher purchase price of the EAP aircraft over a 20-year period. The depreciation and interest cost associated with the EAP hardware is the same amount as the fuel savings cost. However, the other cost components are dwarfed by the increase in depreciation and interest cost associated with the heavier airframe and larger turbine engines for the EAP aircraft. As seen in Fig. 13, compared to the baseline the manufacturer would have to invest an additional \$3.8 billion to develop the EAP aircraft, resulting in a \$10 million dollar higher minimum unit price for the EAP aircraft. The DOC+I breakdown for the other EAP aircraft show similar trends, especially for depreciation and interest costs.

Table 4 Study Aircraft Cost Inputs and Results

	18 Passenger Turboprops		48 Passenger Turboprops		70 Passenger Turboprops		50 Passenger Turbofans		78 Passenger Turbofans	
	Baseline	EAP	Baseline	EAP	Baseline	EAP	Baseline	EAP	Baseline	EAP
Economic Mission Range (nm)	250	250	459	459	488	488	500	500	500	500
Motor size (kW)	N/A	80	N/A	200	N/A	500	N/A	1000	N/A	1000
BSE (W-h/kg)	N/A	500	N/A	500	N/A	500	N/A	1000	N/A	750
Empty Weight, less EAP hardware (lb)	6,412	6,817	21,617	22,765	26,135	28,585	23,876	25,553	43,844	46,916
EAP hardware (lb)	N/A	964	N/A	3,290	N/A	8,947	N/A	4,257	N/A	7,596
Block Fuel (lb)	484	440	1,834	1,673	1,949	1,698	2,212	2,185	3,645	3,524
Block Electricity (kW-h)	N/A	157	N/A	496	N/A	1,358	N/A	1,045	N/A	1,531
DOC+I (\$ /seat-mile)	0.491	0.531	0.199	0.218	0.081	0.097	0.131	0.150	0.112	0.130

It should be emphasized that these cost results are for EAP aircraft models that were not specifically designed to maximize the cost benefits of EAP. Conservative ground rules were adopted in this study to understand the isolated impact of EAP on performance and cost. The cost results would likely look much different for an EAP concept that takes better advantage of that technology, includes other advanced technologies, and has less restrictive sizing rules. However, this cost analysis has been informative in that it shows the significant challenges in designing an economically competitive EAP transport aircraft. The biggest challenge appears to be limiting the acquisition cost, which is primarily driven by the growth in empty weight. Relaxing some of our more restrictive requirements, such as the fuel-only requirement, should contribute to limiting the cost growth, but it appears significant improvement will be needed in multiple areas to bring the operating cost down.

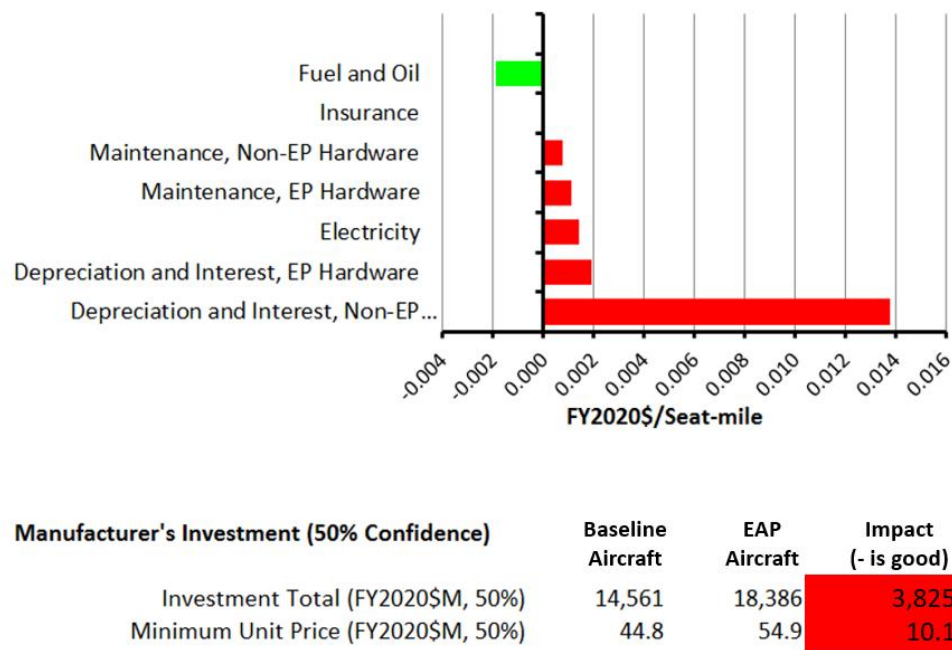


Fig. 13 Operating Cost Components of the 48 Passenger EAP Turboprop compared to the 48 Passenger Baseline Turboprop

VII. Concluding Remarks

The team conducted a design exploration study to understand the design and performance implications of applying EAP technologies to regional-class turboprop and turbofan aircraft. The intent was to perform a foundational study that would allow us to assess the impact of EAP isolated from other technologies while also improving our tools and understanding of EAP modeling challenges. Performance models were created for the EAP aircraft, ranging in size from 18 to 78 passengers, and for their comparable baseline aircraft. This paper documents the results obtained by conducting several design parametric studies and a cost analysis on these aircraft designs.

Our first study determined that the EAP aircraft fuel and energy consumption was relatively insensitive to whether the electric motor power was applied during climb or cruise. The main study was a parametric analysis of battery weight and motor size for each EAP aircraft. The best cases for the turboprop-based EAP aircraft demonstrated modest benefits in terms of block fuel, block energy, and life cycle CO₂e when compared to their baselines, assuming a BSE of 500 W-h/kg. None of the turbofan EAP aircraft demonstrated benefits for any of those metrics unless the requirements for BSE and mission range were relaxed. When the BSE constraint was removed, very large block fuel and block energy benefits were seen with the smallest battery weights and (generally) the largest motor sizes. However, the calculated BSE values associated with these benefits were often unrealistically large. We were unable to reach any definitive conclusions concerning EAP effectiveness on different aircraft sizes due to our battery/motor selection criteria combined with the BSE or mission range assumptions. Finally, a mission range versus BSE

parametric study determined that there was a minimum range required for our EAP aircraft to see a block fuel benefit. The BSE value determined the size of the envelope of mission ranges where a fuel benefit was possible.

We performed a cost analysis for the EAP and baseline aircraft to understand the effect of EAP on operating cost. This cost analysis showed that overcoming the additional cost and weight associated with the EAP systems will be challenging if EAP aircraft are to be economically competitive with conventional aircraft. However, there are some important caveats to note along with this conclusion. First, the EAP designs in this study adopted a conservative “fuel-only” mission requirement which affected the aircraft performance and cost. The impact of this assumption is not known at this point and will be explored in future work. In addition, the study was restricted to a conventional parallel-hybrid electric architecture. There may be more innovative designs that take better advantage of EAP. Finally, there are other factors not considered in this cost analysis which may tip the balance more in favor of EAP transport aircraft. If governments start tightening regulations of aircraft emissions, or if carbon taxes become common, or if the relative prices of fuel and electricity change significantly based on new technology or world events, EAP transport aircraft may start to look more attractive.

The team continues to investigate regional class EAP aircraft to improve our understanding and modeling of how EAP technology affects performance and sizing. A follow-on study is planned which will continue our design exploration for several of the EAP study aircraft. One of the main tasks will be to relax the “fuel-only” mission requirement to determine how much that affects aircraft sizing, performance and operating cost.

Acknowledgments

The Advanced Air Transport Technologies (AATT) project funded this research. The authors thank Jesse Quinlan and Bill Haller for their guidance.

References

- [1] Marien, T. V., Blaesser, N. J., Frederick, Z. J., Guynn, M. D., Kirk, J. T., Fisher, K. L., Schneider, S. J., Thacker, R. P., and Frederic, P., "Methodology Used for an Electrified Aircraft Propulsion Design Exploration," AIAA Paper 2021-3191, August 2021.
- [2] Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017," [Online]. Available: <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2017>. [Accessed December 2020].
- [3] McCullers, L. A., "Aircraft Configuration Optimization Including Optimized Flight Profiles," in *Proceedings of the Symposium on Recent Experiences in Multidisciplinary Analysis and Optimization*, NASA CP-2327, 1984.
- [4] Jones, S. M., "An Introduction to Thermodynamic Performance Analysis of Gas Turbine Engine Cycles Using the Numerical Propulsion System Simulation Code, Computing Systems in Engineering," NASA TM-2007-214690, NASA Glenn Research Center, 2007.
- [5] NPSS, *Numerical Propulsion System Simulation*, NASA: Consortium Software Package, Version 2.6, 2013.
- [6] Welstead, J. R., Caldwell, D., Condotta, R., and Monroe, N., "An Overview of the Layered and Extensible Aircraft Performance System (LEAPS) Development," AIAA Paper 2018-1754, January 2018. <https://doi.org/10.2514/6.2018-1754>.
- [7] Frederic, P., Bezos-O'Connor, G. M., and Nickol, C., "Cost Analysis Approach in the Development of Advanced Technologies for Green Aviation Aircraft," John Wiley & Sons, Ltd., Online, 2016. <https://doi.org/10.1002/9780470686652.eae1078>