An Investigation into All Electric and Hybrid Aircraft

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ABSTRACT

This study was an investigation into the feasibility of all-electric aircraft (AEA) and hybrid electric aircraft (HEA), including an analysis into the available technologies. AEA and HEA could dramatically reduce the aviation industry's contribution to global CO_2 emissions. There are several additional benefits of producing AEA/HEA aside from obvious environmental impacts. These include reduced thermal and acoustic signatures. Findings confirmed that due to the limitations of existing technologies, AEA with performance levels on par with current aircraft are not feasible in the short to medium term. HEA are feasible, with large potential gains found across a range of aircraft classes. A detailed analysis was carried out investigating the key factors affecting the relative performance of HEA when compared to existing conventionally powered aircraft.

KEYWORDS: *Electric, Hybrid, Aircraft*

1 INTRODUCTION

The aviation industry has recently greatly increased its awareness of environmental concerns. This mentality shift has arisen from environmental legislation, including the European Flightpath 2050 and the Strategic Research and Innovation Agenda (SRIA). This targets a 75% reduction in CO_2 per passenger kilometre. This is relative to aircraft from 2000, a highly ambitious target. 2035 was another target for SRIA setting out a 60% reduction in CO_2 emissions per passenger kilometer for all aircraft entering service in 2035 [9]. Other legislation includes Vision 2020 and AGAPE 2020, these split emission targets into several sectors: Airframe, Propulsion and Power Systems (PPS), where this paper focuses, Air Traffic Management (ATM) and airline operations. These set target reductions in CO_2 emissions per passenger kilometre of 50% and 38% relative to 2020 respectively [10].

The recent Channel crossing of the Airbus E-fan has greatly raised awareness of the potential of AEA. Based on this increased publicity and also recent developments in technology, an investigation was undertaken to assess the feasibility of AEA. Battery and fuel cell technology were evaluated, with each system having its' benefits. Electric propulsion relies on electric motors (EMs) to power fans and propellers. Therefore, it cannot directly replicate jet powered aircraft. Electric propulsion can in theory power alternative aircraft of a similar scale to jet aircraft, albeit typically at a lower cruise velocity. This lower cruise velocity arises from the use of fans and propellers (due to the inability to recreate a jet engine only using electrical energy). These have a lower efficient Mach number as they must avoid the fan/propeller tips from going supersonic. Due to the limitations of electrical power systems, namely low energy density, the primary focus of this paper was on smaller aircraft classes. This paper contains sizings for light aircraft (two seaters) up to small regional aircraft (approximately 50 passengers). A full list of the classes and source aircraft can be seen below:

- Light Aircraft: Cessna 172 Skyhawk
- General Aviation (GA): Cessna 310
- Business: Beechcraft Super King Air 300
- Regional: ATR 42-320

Previous studies have shown potential fuel and energy savings for hybrid aircraft, however these studies typically investigate the benefits at greatly increased energy densities compared to current technology. These studies also suffer from large weight increases, despite the 500-1000Wh/kg battery energy density values [5,6]. This is due to the large mass of batteries required, due to their substantially lower energy density than conventional fuels (~13000 Wh/kg). Similar studies were carried out using fuel cells, again finding that weight increases reduced the performance of the aircraft [7].

This study focused on comparing alternative propulsion systems to those in existing aircraft, carrying over the majority of their parameters, "retrofitting" a hybrid or all-electric propulsive system. Key parameters of the alternative PPS were then analysed to investigate at what battery energy density (Wh/kg) and motor power density (kW/kg) they matched or exceeded the CO_2 emissions and energy usage of their conventional source aircraft.

1.1 Batteries

There are several different types of batteries; these are differentiated through the components used in their construction. The main focus of this paper will be lithium-ion and lithium-polymer batteries. These batteries feature some of the best energy densities, whilst maintaining good lifetime characteristics and suitable operating conditions. An issue with battery power is the limited lifetime of the batteries, this is measured in cycles and is typically under 1000. Over the lifetime of the aircraft, several sets of batteries will be consumed. Subsequently, the cost of the batteries and their required maintenance could be a significant factor in battery selection. The disposal of these batteries could also generate environmental and economic concerns.

Unfortunately, battery capacity is a complex issue and altered by several factors. These include the operating temperature and history. The performance of a battery declines over time, but is also affected by both the charging and discharging rate and level. Ideally the batteries should be stored at or above 40% of capacity.

$$t = \frac{Rt}{i^n}\left(\frac{C}{Rt}\right)^n \tag{1}$$

A key consideration when sizing a battery based power system is the Peukert relation [2] where C =capacity, Rt = Rated time, i =current, n = battery parameter, t = time. Subsequently, the higher the power draw, the smaller the effective capacity of the battery and vice versa. As such, it may be worth over-sizing the battery system to utilise this effect in a beneficial manner. Although the extent of this is dependent on the n rating of the battery, typically around 1.3, although the ideal battery would have an n rating of 1. Modern batteries experience negligible drop in output voltage until almost fully discharged [2]. One key aspect to batteries is the form of output power, all batteries generate direct current (DC). Therefore, the aircraft needs to have a DC motor, or an alternating current (AC) motor coupled with an inverter. One potential concern is whether battery technology is stagnating. Current peak values of 260 Wh/kg (reported in the Airbus E-Fan) are not dissimilar to the expected plateau of 300 Wh/kg in the long term [1].

Lithium air batteries are a key area of research. This is due to the high theoretical specific energy of approximately 12 kWh/kg [14], not dissimilar to most hydrocarbons, kerosene for reference is 13 kWh/kg. There has also been some investigation into other metals such as Magnesium, Aluminium, Sodium and Calcium. Whilst these batteries have great future potential, their current capabilities, particularly in terms of lifetime and reusability mean the technology is not yet sufficiently developed to be considered for these applications. Their estimated production readiness is 2030 onwards. Another developing technology is lithium sulphur batteries, offering theoretical energy densities five times greater than lithium-ion and have been proven at energy densities of 500 Wh/kg [12]. Unfortunately, lithium sulphur batteries are not commercially viable yet at this point in time.

1.2 Motors

There are two main branches of electric motors, differentiated by the current received. They are Direct Current and Alternating Current. DC motors typically use brushes at the commutator, with the motor rpm controlled by the current. AC motors use the alternating current to continuously propel the shaft, with the speed controlled by the frequency of the AC. DC motors suffer from poorer efficiency (80-

85%), poorer reliability and greater mechanical wear. AC motors also have a greater power to weight ratio. However, AC motors do require an inverter, this adds weight and complexity. Due to these factors, the best set up is generally dependent on the aircraft size and class.

Currently the best commercially available motors for this application are brushless direct current motors (BLDCs). These motors are highly efficient, traditionally with an efficiency >90%. They also have a substantially higher power to weight ratio than the other motors researched, mass produced motors have power densities in excess of 2.5 kW/kg [11]. One of the key benefits of a BLDC motor is the speed control aspect. The speed, measured in revolutions per minute (rpm), for brushed DC and AC motors is dependent on properties of the electrical system, current and frequency respectively. BLDC motors utilise an electronic speed controller to adjust the rpm of the motor. These factors combine to make them the most sensible motor for our application and are thus used for this analysis.

2 HYBRID & ALL ELECTRIC AIRCRAFT SIZING

In order to investigate the feasibility of hybrid aircraft, a sizing algorithm specific to hybrid and electric aircraft was developed. Whilst the structural aspects of this algorithm are identical to those for conventional aircraft, the power system differs greatly.

One of the potential benefits of AEA and potentially hybrid aircraft is the ability to utilise distributed propulsion, facilitating powered lift and a greatly improved L/D ratio. However, this would require re-optimisation of the aircraft, therefore outside the scope of this investigation. Without the benefit of distributed propulsion this system is dramatically less attractive. The additional weight of the generator(s), makes the layout seen in Figure 1 the most efficient option in this scenario. It is worth noting that several papers use this layout [3] and still retain the function to generate electrical power from the turboshaft using the electric motor. This saves on the additional weight of the generator and also minimises packaging requirements.

As the aim of this paper was to provide a comparison between conventional aircraft and AEA / HEA, the sizing script (flowchart found in Figure 2) was tested using a conventional propulsion system, then compared to the existing aircraft. The results did have some discrepancies, but were within 25% and as the sizing methodology was used for all comparisons the absolute comparisons here were deemed acceptable in accuracy. Empirical aircraft weight fractions were built up and tailored to aircraft class [8]. These equations were used for the following components: wings, tail, empennage, landing gear, fuselage, nacelle, engine, fuel system, avionics, flight control, electrical system, furnishings and the pressurisation and air conditioning systems if required.

The propulsive system sizing varied depending on how the hybrid system was designed. There were two main options, similar to the methods seen in literature, either providing a certain percentage of the power through the electric system, or, alternatively, sizing the turboshaft engine for a particular stage of flight and cover the remaining power through the electric system. The former requires a smaller motor, however requires greater electrical energy over the duration of the flight. The latter is very power intensive, but dependent on the stage of flight selected, greatly reduces the energy demand.

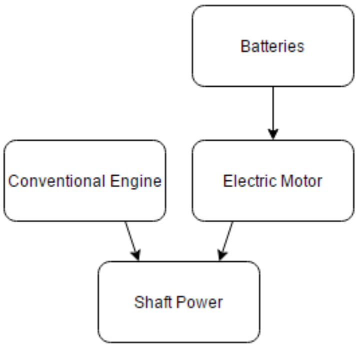


Figure 1: Direct Hybrid Layout

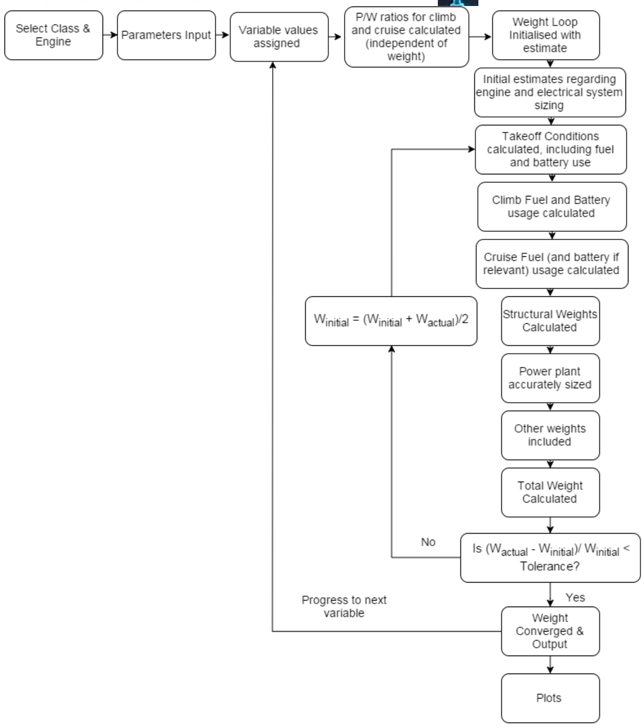


Figure 2: Weight Estimation Script Process

The electric motors were sized using a linear power to weight relationship, a reasonable assumption based on available motors. The specific power is one of the key variables investigated in this paper. The battery system is sized based on the energy required and takes into account the Peukert effect.

This sizing is working on the assumption that a battery system can be tailored to meet the design power point for no extra weight, this is not guaranteed. However, system characteristics can be tailored by the cell arrangement and architecture. The maximum power output per cell is regulated by the maximum safe current and peak voltage a cell can supply, however combining cells in series and parallel can adjust these to meet requirements. Battery selection will be a vital part of producing a hybrid aircraft, however, as this is a purely theoretical study no specific battery has been selected. It is worth noting that the two different hybridisation methods will require dramatically different battery characteristics. The hybrid boost option requires a battery with a very high discharge rate as this allows the battery to deploy its energy over a short time frame. This feature is vital in this case as the hybrid system is only required for approximately 15 minutes, dependent on class. The power percentage option will need a battery with a much lower discharge rate, ideally optimised over a time comparable to the duration of the flight.

3 RESULTS

The default parameters trialed can be seen in Table 1. These values, whilst greater than currently available technology, are believed to be reasonable in the short to medium based on recent progression.

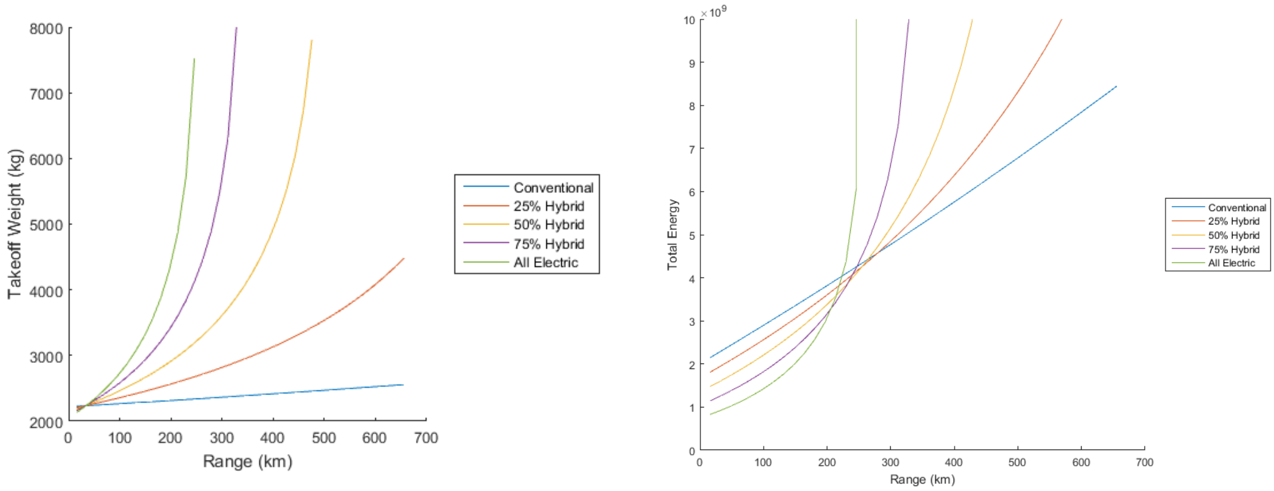
Table 1: Default System Parameters

Battery Energy Density	400 Wh/kg
Motor Power Density	10000 W/kg
N	1.1
Voltage	48V

3.1 Percentage Power Supplied and AEA

This section focuses on the proportion of power supplied by the hybrid system throughout the flight, with 100% being an AEA. This script worked on the percentage being both instantaneous and total, therefore the hybrid section did not favour any segment of flight. It was assumed that if the aircraft possessed a turboshaft engine this would power all ancillary systems. If the system was all electric, the batteries would have to supply the energy required by these systems.

The results for this section were highly range dependant. At low ranges, there were potential fuel savings across all of the trialled classes, with potential energy savings in the smaller classes. However, the range was dramatically reduced compared to the original aircraft, with fuel savings possible up to 460km, dependent on class. These results support previous AEA conclusions that short range flights are possible and can lead to environmental benefits, provided that the electricity used to charge the batteries is sourced renewably. The best classes were the Light and the General Aviation classes, conventionally powered by a piston engine. These classes showed a weight saving, in addition to potential energy and fuel savings at low ranges. Their turboshaft counterparts retained the energy and fuel savings, but without a weight saving at any range. The weight savings only occurred at ranges up to 50km. The energy savings for all levels of electrification were only valid up to 300km, beyond this point there were large penalties which grew exponentially.



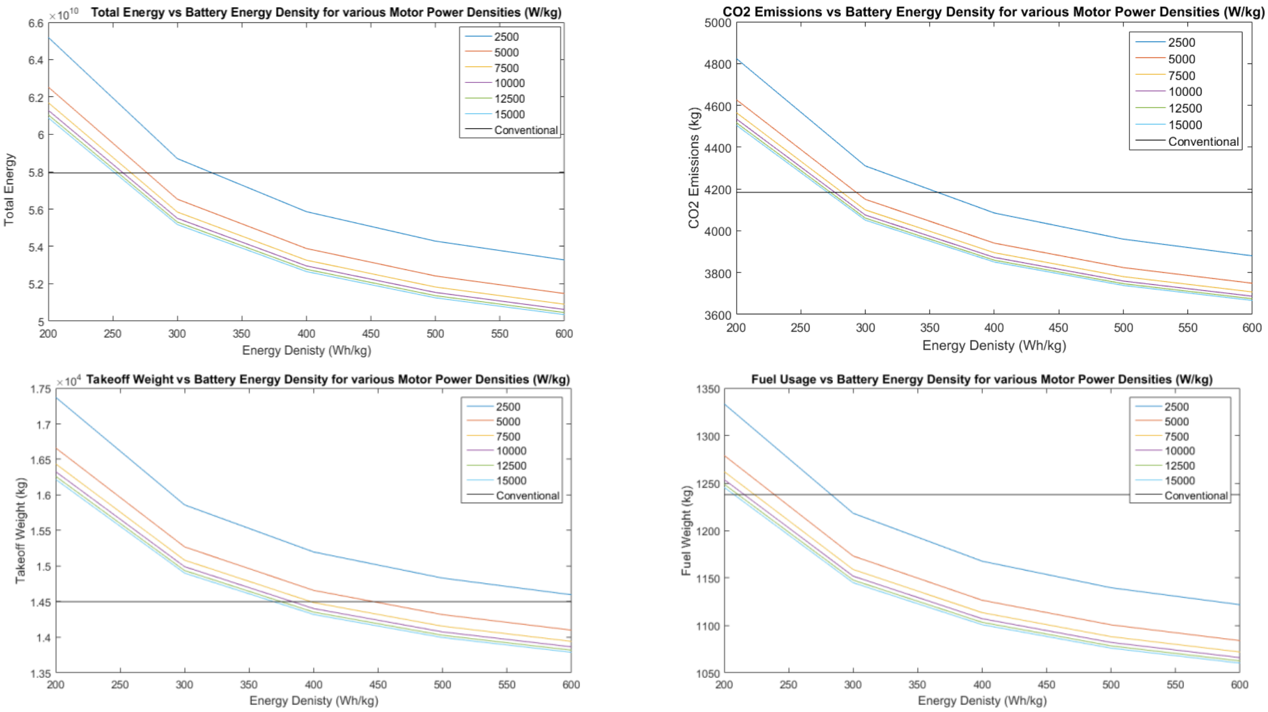
Figures 3 & 4: Takeoff weight and Energy Usage for a GA aircraft as affected by design range

3.2 Hybrid Boost

The conventional engine was sized to provide the required power at the start of the cruise phase of flight, with the electrical hybrid system providing the additional power required during the take-off and climb phases. This system became largely range independent due to the lack of change in the energy requirements during the take-off and climb phases.

All tested classes showed weight, energy and fuel benefits up to maximum aircraft range at the default parameters. Subsequently, the system parameters were varied to analyse the corresponding impacts. It is clear that the initial take-off weight is a key impact on fuel and energy usage, if the hybrid system can achieve a weight saving, or at least negligible weight increase, there are large fuel, energy and CO_2 savings to be found. The CO_2 values used were 410 g/kWh for electricity supplied (based on values for the UK National Grid [15]) and 260 g/kWh for Kerosene.

The full list of results can be found in Table 2. Due to the reduced power density of a piston engine compared to a turboshaft engine, aircraft with this engine option showed greater benefits and were subsequently tested with 1-6 kW/kg motors. The turboshaft options were hybridised with electric motors of a power density of 2.5-15 kW/kg. The 1 kW/kg motor option now achieves weight equivalence with an 800 Wh/kg battery system and requires 520 Wh/kg to reach energy equivalence for a piston powered light aircraft. The 6 kW/kg option in the same aircraft requires a much reduced energy density of 72 Wh/kg battery. The results for a hybrid piston powered GA aircraft are noticeably worse than the hybrid piston powered light aircraft results. The 1 kW/kg motor cannot achieve any weight, energy or fuel savings for any of the trialled energy densities. In contrast, the hybrid piston powered light aircraft can achieve all three. This is reflected across the other motor power densities, with increased battery energy densities required to achieve parity.



Figures 5-8: Regional Class Aircraft Hybrid Boost Results for Energy, CO_2, Weight and Fuel

The business class results are dramatically less positive for hybrid power than the GA results. All options are heavier than the conventional aircraft up to an energy density of 250 Wh/kg, but all options aside from the 2.5 and 5 kW/kg options achieved a weight saving at an energy density of 300 Wh/kg. The 5 kW/kg option required an energy density of 310 Wh/kg, whilst the 2.5 kW/kg required a value in the region of 605 Wh/kg. Whilst all motor options use more energy with batteries of 200 Wh/kg all except the 2.5 kW/kg option achieve an energy saving at 300 Wh/kg. The 2.5 kW/kg option achieves an energy saving at a battery energy density of 500 Wh/kg. It is a similar situation for fuel consumption, however the 2.5kW/kg option achieves a fuel saving at an energy density of 480 Wh/kg, 20Wh/kg less than the energy saving. A maximum possible fuel saving of 220kg, 18%, could be achieved.

At an energy density of 200 Wh/kg there was a minimum weight increase of 1700kg for a regional class aircraft, or 12% with a maximum weight increase of 2900kg, or 20%. These led to an increase in energy consumption by 5-12% motor dependent. This energy density also guaranteed an increase in fuel consumption by 0.4 - 7.7%. The majority of motor densities achieved weight neutrality at energy densities of 350 – 450 Wh/kg, however the 2.5 kW/kg motor required an energy density of 670 Wh/kg. Energy equivalence occurred at energy density of under 285 Wh/kg for all options aside from the 2.5 kW/kg option, this required 320 Wh/kg. All options achieved a fuel saving at a battery energy density of 300 Wh/kg.

These results show that for current available technology there are still large potential savings to be found, through implementing this method of hybrid boost. Across the range of classes, a motor density of 5 kW/kg and a battery energy density of 300 Wh/kg gave large fuel savings.

Table 2: Battery Energy density at which Property parity occurs (Wh/kg)

Aircraft Class & Engine	Property	Motor Power Density (kW/kg)										
		1	2	2.5	3	4	5	6	7.5	10	12.5	15
Light - Piston	Weight	800	115		90	81	77	74				
	Energy	520	107		85	77	74	72				
	Fuel	450	102		82	75	72	70				
Light - Turboshaft	Weight			280			151		131	123	119	116
	Energy			223			133		118	112	108	105
	Fuel			205			126		113	107	103	100
GA - Piston	Weight	-	151		113	100	95	92				
	Energy	-	146		112	99	94	89				
	Fuel	-	142		110	98	92	88				
GA - Turboshaft	Weight			452			205		173	160	154	150
	Energy			394			192		164	154	147	143
	Fuel			363			184		158	148	142	138
Business	Weight			605			312		269	252	242	236
	Energy			515			286		250	235	227	221
	Fuel			479			275		240	227	219	214
Regional	Weight			670			440		397	378	368	362
	Energy			311			252		238	232	227	224
	Fuel			275			228		217	212	207	205

The results summarised in table 2 were highly promising given the state of current technology. Electric motors that are currently commercially available possess a power density around the 5 kW/kg, whilst battery energy densities have reached around the 300 Wh/kg. For the aircraft classes tested, this combination always yields a reduction in total energy and fuel for all the tested ranges, even working at the modest 76% electrical system efficiency (again dramatically lower than assumed in many other research papers). Whilst always achieving fuel and savings, typically in the region of 4%, the take-off weight of the aircraft regularly increased. However, this weight increase is compensated by the increased efficiency. It is clear that for each given aircraft class there is a certain weight allowance for the electrical system. This explains the shape of the curves seen throughout this report, of the form y=1/x. Given this trend it is clear that when solving the paradigm of motor power density and battery energy density, their comparative weight fractions be taken into account. The GA aircraft system is power rather than energy dependent, subsequently minor changes in the motor power density lead to the largest percentage change in required battery energy density. The regional aircraft results demonstrate the antithesis of this. The regional aircraft is highly energy dependent, on account of having the highest climb energy percentage. Subsequently smaller percentage changes in the battery energy density lead to significant percentage changes in the required motor power density.

Another aspect evaluated was the battery charging time which is heavily dependent on the power supply. Currently battery electric vehicles can gain from utilising 'supercharging' networks which can charge at a rate of up to 120kW an hour. Applying this rate of charging gave times of approximately 20 minutes for light aircraft, 2.5 hours for GA aircraft, 10.5 hours for business class aircraft and approximately 26 hours for regional aircraft. These times were based on aircraft designed using the default electric system parameters. These times whilst clearly suitable for Light and GA craft, and potentially even business class depending on usage are insufficient for regional aircraft. In order to get a recharge time of under 3 hours the regional aircraft requires a charging rate of nearly 1.1MW per hour. One way of reducing this charging time would be to partially recharge the batteries during cruise utilising the maximum engine performance, however, this would reduce the fuel and environmental benefits.

4 SHORTCOMINGS & FUTURE WORK

Several simplifications were involved in the sizing script, this was deemed acceptable as the primary focus was not on absolute accuracy, but a reasonable estimate in order to compare the performance of the hybrid and conventional cases. Ideally, given additional time, the algorithm would be improved to give a more accurate estimation of the original aircraft weight. One weight fraction has currently been neglected from the hybrid sizing, whilst the weight of the wiring has been included, this does not include any additional insulation which would be required. Whilst this value is unlikely to have a dramatic effect on the weight it should be included to increase accuracy. Another key sizing area to improve is the empennage. The empennage was sized using average values and engineering knowledge, however, in order to accurately calculate its weight several further parameters needed to be known. Accurate tail sizing requires a full knowledge of the moments affecting the plane, in order to achieve stability and trimmability. Unfortunately, this data could not be easily found. This requires an aerofoil selection and knowledge of the aerodynamic centre among other parameters. One other key improvement to the sizing algorithm is related to the batteries. The battery weight is included in the weight used for the fuselage sizing equation, however this does not take into account the volumetric effect of the batteries. Whilst the weight may be accounted for, it is not guaranteed the physical size of the batteries can be located within the fuselage. A final key improvement relates to the PPS, whilst the assumption of using an EM and conventional engine to directly power one propeller is valid, there may well need to be additional gearbox fitted to ensure an efficient range of rpm is utilised.

Several conditions were not optimised, but instead averaged, or fixed using known values. During take-off a linear acceleration was assumed for simplicity and to calculate the time for takeoff. The climb conditions were not always working at the optimal rate as both the climb velocity and climb rate were pre-assigned. The cruise conditions were based on a fixed aircraft L/D and velocity. The largest source of error is likely to be the fixed TSFC values for each stage of flight, ideally this would be calculated based on throttle setting, Mach number and altitude [13].

Ideally, given the viability of the hybrid aircraft tested here, an entirely new aircraft design would be created to optimise the entire process. Creating a new aircraft from scratch will also increase the accuracy of all the other sizing components. A further improvement to be added to future algorithms would be to include a battery comparison section, which would allow several different batteries and their properties to be included. Such a comparison would evaluate the combined effect of:

- Energy density
- Voltage
- Peak current
- Lifetime performance
- Discharge rate
- N factor

Future research should encompass a full economic viability study into hybrid aircraft. This should include: initial cost, operating and maintenance costs and end of lifetime costs. Given the hybrid aircraft still requires a conventional hydrocarbon engine it is likely the initial costs will increase. This is due to additional components required, high grade electric motors and batteries and substantial wiring. The operating and maintenance costs are likely to favour the hybrid aircraft. The EMs should require dramatically less maintenance than a conventional engine, due to the increased simplicity of the design. The battery system is likely to be an enclosed system and require minimal maintenance. The operating costs should decrease through the energy and fuel savings. However, the battery lifetime and cost will be crucial as to assessing if there is a net operational cost benefit. The cost of removing and recycling the expired batteries will be a key factor in the complete economic scenario.

5 CONCLUSION

In conclusion, the dream of achieving an AEA still remains a distant one. Despite the improved power density of electric motors, the limited energy densities of electric power sources lead to excessive weight penalties for real life scenarios. AEA whilst novel, remain in the mire of short range proofs of concept of limited practical ability. The effective energy density of kerosene, even when operating in a 25% efficient engine, is 3215 Wh/kg. This value is over ten times the performance of current batteries commercially available. Whilst short term improvements in both electric motors and battery performance will increase an AEA's feasible range, it will still remain in the tens and hundreds of kilometres.

The results for hybrid aircraft are far more promising, depending on the method of hybrid implementation. The viability of the boost hybrid option is dramatically higher than that of the percentage hybridisation method. The hybrid boost option successfully achieved fuel and energy savings across all classes at the default variable quantities at maximum range. The hybrid boost is far more efficient than other hybrid options, as it focuses on the key benefit of hybrid power, namely the increased power density of electric motors when compared to conventional piston and turboshaft engines. The energy density of batteries remains such that they are still a poor replacement for kerosene, and subsequently not viable for long sustained energy output. As such the hybrid boost for take-off and climb is the ideal scenario, as it dramatically reduces the size and weight of conventional engine required, replacing it with a substantially lighter electric motor and the minimum quantity of batteries possible. The potential fuel and energy savings have several benefits. The reduced fuel consumption leads to fewer emissions and also a reduced fuel bill for the airline, which could be passed on to the customer through cheaper fares increasing global mobility. Under the rules of European Union Emissions Trading System (EU ETS), airlines are granted tradeable allowances covering a certain quantity of CO_2 emissions from their flights per year. A successful reduction in the CO_2 emissions per flight achieved through hybridisation, could subsequently allow the airline to increase the number of flights operated per year, whilst conforming to the ETS. A key benefit of the hybrid boost, which is more prevalent in this system than the percentage option, is the reduction of take-off noise. In the boost scenario the electric motor supplies up to 64% of the power at takeoff, this greatly reduces the combustion noise produced at take-off which is a key factor in take-off noise [4].

Unlike the hybrid boost option, the percentage hybridisation method struggled to achieve any fuel savings for ranges in excess of 30% of the maximum range. The percentage hybridisation system is still a long term development project, with short term technological improvements unlikely to be of the required scale to make a significant difference in the viability of this system. The battery energy density is the limiting factor, once viable to sustain a long range aircraft, there is likely to be dramatic energy and fuel savings. The AEA results clearly show that as soon as the weight converges to a finite value, there are noticeable energy savings to be found. However, these rely on a battery energy density far greater than currently feasible. With current and short term technology limitations, the only viable option is the hybrid boost scenario.

Overall, whilst AEA remain a pipe dream, there are substantial savings currently available from hybrid aircraft. Providing the hybrid system is correctly utilised, focusing on power rather than energy output, large fuel savings can occur. Current technology allows weight savings of up to 31.6%, dependant on aircraft class and engine type. For the aircraft tested there was a minimum 8.6% reduction in energy consumption and 8.9% reduction in fuel consumption. These sorts of savings could dramatically reduce global aviation CO_2 emission, whilst also contributing to significant decreases in running costs.

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