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Hybrid Electric Aircraft Propulsion Case Study for Skydiving Mission

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Abstract: This paper describes a case study for applying innovative architectures related to electrified propulsion for aircraft. Electric and hybrid electric propulsion for aircraft has gained widespread and significant attention over the past decade. The driver for industry interest has principally been the need to reduce emissions of combustion engine exhaust products and noise, but increasingly studies revealed potential for overall improvement in energy efficiency and mission flexibility of new aircraft types. In this work, a conceptual new type for a skydiver lift mission aircraft is examined. The opportunities which electric hybridisation offers for this role is analysed in comparison with conventional legacy type propulsion systems. For a conventional commercial skydiving mission, an all-electric propulsion system is shown as viable, and a hybrid-electric system is shown to reduce aircraft fuel costs and CO_2 emissions whilst maintaining conventional aero-engine operational benefits. The new paradigm for aircraft development which hybrid electric propulsion enables has highlighted significant issues with aircraft certification practices as they exist today. The advancement of aircraft design and production to harness the value of new propulsion systems may require adaption and development of certification standards to cater for these new technologies.

Keywords: turbo-electric; hybrid; aircraft; performance; simulation; propulsion; efficiency; utility; mission; modular; configuration; certification

1. Introduction

Recent advancements in aircraft propulsion technology are trending toward more electric propulsion and fully electric concepts. Over the past two decades, several key technologies for electrical power and drive systems have matured to the extent where the power and energy density has become suitable for certain aerospace applications and missions. The power density and reliability of electric motors and drive electronics have become viable, while projections on the advancement of battery storage energy density lead to industry-wide interest in aerospace electrical propulsion systems. However, studies of presently available electrical technology invariably conclude a deficit compared to traditional thermal engine propulsion for larger capacity transport missions due to the excessive battery weight. Today, there are already certain aircraft types and missions which favour electrical propulsion, but the limit is approximately two person-hours of flight time. This paper demonstrates how this same limit favours the skydiving mission under typical commercial conditions and provides an example of a new aircraft type.

The addition of electrical propulsion systems (EPS) for aircraft functionality is not solely based on overall efficiency considerations. The term "utility" is useful to consider as defined by "the state of being useful, profitable, or beneficial" [1]. A certain minimum aircraft efficiency is clearly necessary to perform the required mission, but a trade-off can exist against adequate utility. The value of hybrid electric propulsion (HEP) must be assessed according to the combination of efficiency and utility of an aircraft design to suit a mission and a market.

1.1. Skydiving Lift Mission

Skydiving is a popular aviation sport throughout the world. While the overall number of participants is relatively small compared to many other usual sports, there is a continuous popularity with hundreds of thousands of people active and approximately 1000 centres worldwide [2]. The United States Parachute Association alone recorded 36,770 members at the end of 2014 [3].

As compared to military parachuting operations, sports skydiving usually requires commercial operators or clubs to utilise converted general aviation and small commuter type aircraft to get participants to suitable jump altitude, typically up to 4000 m above ground level (AGL). The types in use for commercial operations are frequently four-seat to 10-seat aircraft, which include light aircraft and commuter category types. Examples of aircraft used include Cessna182, Cessna206 and 208, Piper PA-31, Pilatus PC-6, PC-12, LET410, and Twin Otter types, or similar piston or turbo-prop powered aircraft. As with any aircraft operation, the commercial viability of any choice is dependent on many factors such as the demand and utilisation, operating costs (maintenance, fuel), insurance etc. In many cases, the aircraft types which remain in service are aging legacy piston powered examples, typically between 20 and 50 years old, or the younger but more capital intensive turbo-props.

New designs suitable for this role are warranted but there are limited options in the market place. Apart from issues of safety with older legacy types which arise due to the demanding nature of the mission and loading cycle, the overall energy utilisation and resulting emissions are significant compared to the actual time spent engaged in the primary activity, free-fall and canopy time. Whereas the sport is partly centred on natural environment experiential quality, the process is highly energy intensive. The utilisation of more renewable green energy will reduce the carbon footprint [4] and offer reduced participation costs for the sport. A new clean-sheet design could yield operational, safety and environmental benefits.

Key technologies for electrical motors and power electronics systems have matured to the extent where the power and energy density has become suitable for certain aerospace applications [5,6]. Battery storage energy density is improving incrementally, but the future potential must be led by industry adoption of aerospace EPS which show viability even with modest battery performance. Studies of presently available aircraft electrical propulsion technology invariably conclude a deficit compared to traditional thermal engine propulsion for larger capacity transport missions due to excessive battery energy storage weight [7,8] and hence a limited payload-range. Therefore, little incentive exists to develop light commuter-class hybrid and electric aircraft, for existing and near-term markets.

A new design utility aircraft suitable for skydiving and freight roles has been proposed by Air Ute Pty Ltd. (Caloundra, Australia), as shown in Figure 1. This design features several notable design attributes which provide a compelling case for development due to extraordinary mission versatility and operational payload logistics. The skydiving role suitability is achieved according to fundamental market configuration needs, internal volume, exit door size, wing and tail layout etc. In addition, the aircraft will be highly suitable for freight and logistics roles with the capability of loading and carrying two airline transport containers. No current production aircraft in this size and category can load and carry the specified container. The aircraft itself will be able to be easily dismantled and packed into a standard "intermodal container" for ease of conventional transport by road, rail and ship, thus creating an ideal transport solution. This aircraft and its role make a very suitable baseline to consider as a candidate for a hybrid electric comparison.

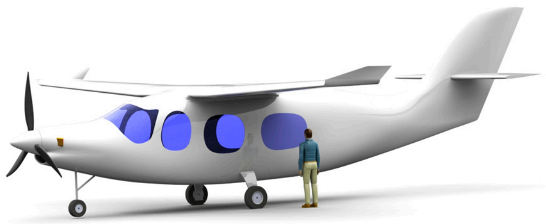

Figure 1. Conceptual prototype skydiver and freight role aircraft by Air Ute Pty Ltd. with conventional turboprop propulsion system.

1.2. Hybrid Electric Propulsion Suitability

Many examples of all-electric light aircraft are emerging with approximately two person-hours of flight time endurance. This makes a role as a primary trainer for example, where the mission involves carrying an instructor and student pilot for a 1 h mission, feasible for an EPS. However, a 1 h endurance is generally considered inadequate when translated into a maximum range for transport or commuter roles. Any future improvement in battery technology will be instantly adaptable to an aircraft already designed for to integrate battery electric drives, further improving efficiency, reducing costs, but also expanding role and mission suitability to new markets without requiring new design and manufacturing. However, the viability of currently and immediately foreseeable electrical propulsion technology must be shown in order to justify this new development.

The energy density of the battery must increase by at least a factor of five to yield a suitable range commensurate with ordinary present day conventional internal combustion engine (ICE) propulsion equipped light aircraft [7]. While new battery technology is envisaged to emerge in the future, improving the range and endurance possibilities while maintaining some key advantages of the EPS is presently made possible by use of combined hybrid systems. An aircraft using HEP can utilise the superior energy density of hydrocarbon fuel and the ICE over that of electrochemical battery storage, while maintaining many of the benefits of superior mechanical efficiency and reliability of pure EPS.

2. Materials and Methods

Analytic and simulation methods have been used to qualify and quantify the expected performance of the skydiver aircraft. The case study uses a numeric calculation tool based on flight mechanics applicable to given flight conditions. A parallel study using X-Plane simulation software was conducted to corroborate the findings, contrast detailed configuration examples and provide a convenient way to compare expected performance with a well-known legacy type.

2.1. Mission Profile

The role and mission profile of skydiver lift aircraft in commercial operations is known [9] to favour carriage of eight jumpers (loads), to a height of 4000 m AGL with a duty cycle of 3 to 4 loads per hour. A typical skydiving mission profile is shown in Figure 2. This implies a mission time (or endurance) of between 15 and 20 min, which when given the weight of the load and altitude required is shown below to yield an energy requirement within that available from current EPS technology.

However, such a system would require a complete recharge, or battery replacement after each mission. This concept is practically feasible, but we consider an alternative, the inclusion of an ICE element in a hybrid scheme to ensure reserve energy availability, redundancy and reduced battery re-charge or replacement frequency to avoid operating too close to hard limits of endurance without safety margins or reserves.

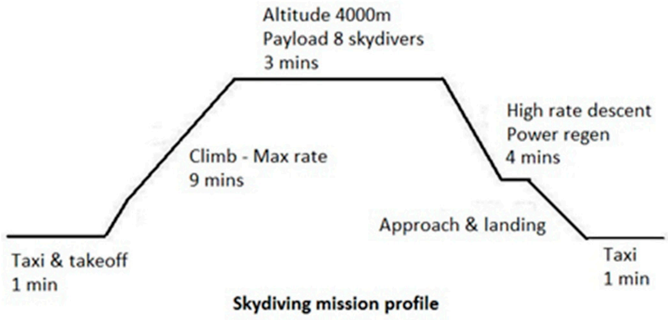

Figure 2. Typical skydiving mission profile.

A standard numerical simulation technique, taking candidate power-plant and aircraft aerodynamic performance parameters into account, has been used to obtain energy requirements for the given mission. By varying the ratio of installed power, and energy storage between EPS and ICE drive components, certain quantities such as battery weight, climb rate, fuel consumption and recharge rate for given technology constraints can be compared.

A typical HEP concept is shown in Figure 3. The aircraft may be designed to incorporate onboard recharging, or convenient battery exchange for rapid on turn around for next mission.

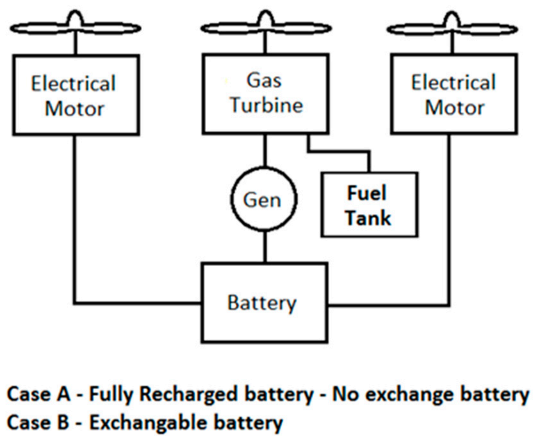

Figure 3. Hybrid electric propulsion architecture.

The hybridisation ratio or degree of hybridisation may be defined as the ratio of the electric motor (EM) to ICE power availability. A more useful metric is to consider the ratio of EM to total installed power, thus, $H_P = P_{EM}/P_{tot}$, where a fully electric aircraft could be considered as having a unity H_P, and a fully ICE powered aircraft an H_P of zero.

2.2. The Proposed Models

Case Study 1 uses an analytical model developed according to conventional aircraft flight mechanics for climb and descent performance. Parameters are included to vary the electrical system contribution for energy, power and mass through a range of hybridisation ratios. The critical outcomes are the required electrical system mass, including battery, and climb rate for the resulting gross weight. This yields the mission cycle time, and a case for viability when compared to current technology aircraft structural and aerodynamic limits for basic and useful load capability. The model aims to give qualitative and quantitative data related to mission parameters against the level of hybridisation.

The fundamental equation used to determine the climb rate, V_C for relatively small thrust-to-weight ratios is;

$$V_C = \frac{P_A - P_R}{W} \tag{1}$$

where P_A = power available, P_R = power required. If detailed knowledge of thrust available at various climb speeds and altitudes is known, then P_A is calculated as the product of true airspeed and the thrust component along the flight path. Alternatively, an estimate for P_A can be made as the product of propeller shaft power and the propulsive efficiency [10]. P_R may be estimated by the following formula [11];

$$P_{R\_minimum} = \frac{4\sqrt{2}C_{D0}^{1/4}}{(3\pi e R_A)^{3/4}} W\sqrt{\frac{(W/S_W)}{\rho}}$$

where estimates are required for C_{D0} the zero lift drag co-efficient, and e, the Oswald efficiency factor. R_A, the wing aspect ratio taken as 10 and S_W the wing area, 20 m^2 are given from the basic aircraft geometry while ρ the ambient air density varies with flight altitude according to a standard function. For the purposes of this analysis, C_{D0} assumed as 0.025 and e equal to 0.835. The significant variables when comparing across different propulsion installations are therefore only W, the weight which is the sum of the empty weight (including battery and nominal fuel) plus payload, and propeller efficiency. Using this technique, the direct effects of the propulsion system mass and propeller efficiency can be isolated and examined.

Figure 4 illustrates a conceptual prototype "Skybrid" hybrid electric skydiving aircraft based on the Air Ute development. In comparison to Figure 1, the nose mounted turboprop power-plant is augmented by two wing-mounted electric motor and propeller installations. This propeller layout is effectively the same as the rather simple and well established "tri-motor" seen in many types historically; however, new significant advantages of this distributed propulsion system using a hybrid electric scheme are available which ordinary legacy multi-engine layouts cannot offer.

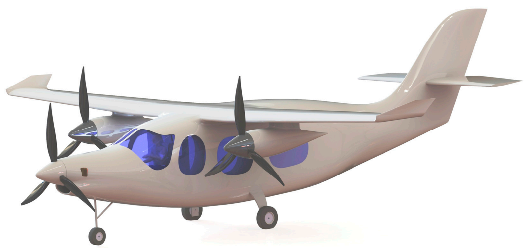

Figure 4. Conceptual prototype "Skybrid" hybrid electric skydiving/freight aircraft.

2.3. Mission Energy

The overall mission energy required is calculated from the following items:

- Potential energy requirements to climb;
- Drag energy expended in climb;
- Energy regeneration during descent.

It is noted that the drag energy expended during the descent phase of the flight can be considered to be fully regenerated from the potential energy gained during climb (a pure glide), and is a form of regeneration. However, for operational reasons, for non-hybrid, or very low proportions of electric propulsion, the ICE must be running during the descent. The aircraft must maintain the capability for re-routed flight profiles such as dictated by air traffic control, or events such as go-arounds, holds, or diversions. An ICE unit takes a certain amount of time to start and warm-up; therefore, it is typical and usually mandatory for the ICE to be running even during a full glide descent profile. The thermal efficiency of the ICE at flight idle is typically lower than at climb or cruise conditions.

Regeneration for hybrid electric propulsion can include energy derived from using the propeller as an air turbine during unpowered descent. Although the efficiency of the "wind-milling" operation is low due to the incorrect shape of the propeller as a turbine, and due to the Betz limit, it has been shown that between 5% and 40% [7,12] of the potential energy can be regenerated in this way. The resulting battery recharge quantity is very low, since much of the climb energy expenditure is not toward gravitation potential, but is lost as drag. However, the small gain comes with added benefits. For the skydiving operation, a rapid descent is necessary to allow improved cycle time. Ordinary aircraft descent rates are limited by the maximum permissible airspeed and deployable drag. Extra drag to allow steeper descent is usually afforded by the use of wing-flaps. Utilising the aircraft propeller as a turbine implies very high drag, this can enable very steep descent within certificated airspeed limitations.

Propulsion efficiency for propeller driven aircraft is determined by the design airspeed, thrust requirements and the propeller design characteristics. The primary design variables are the propeller pitch and diameter, and both must also suit the characteristics of the power-plant. Current technology aircraft have a very well-established design synthesis which can often yield a propulsive efficiency above 85% for specific flight conditions. In this case, there is not very much improvement available, but the implementation of hybrid electric components should aim to allow improvement to either the range of high efficiency throughout the flight profile, or a reduction in the complexity required to obtain the peak efficiency. For example, the addition of the EPS to the ICE can allow torque application characteristics which can eliminate the need for variable pitch propeller mechanisms, or allow larger diameter propellers without gear boxes, more suitable for high efficiency lower speeds [12].

Utilisation of EPS can provide more overall propeller disk area for a particular aircraft configuration, and thus improve propulsive efficiencies, particularly at lower speeds. Adding extra propeller disk area may be accomplished by adding EPS units, far more easily than adding extra ICE units, as shown by the concept illustrated in Figure 4. The mass specific power of the EM is presently comparable to the best ICE and is forecast to further improve in the near term while being orders of magnitude simpler in terms of parts count, manufacturability and a range of other attributes. The EM is extremely easy to mount on the airframe without significant structural or systems weight and complexity, these qualities are enabling many new aircraft designs both in concept and practice today. The provision of increased thrust, at lower airspeeds for a given aircraft mass implies that steeper climb angles are possible. In general, a steeper climb angle, at a lower airspeed can result in significantly reduced drag for a given climb rate. In particular, the induced drag decreases with the climb angle, and the induced drag is typically triple the value of parasite drag in climb configurations [11].

Aerodynamic efficiency improvements are also feasible by taking advantage of carefully integrated thrust characteristics which can reduce drag. Often a distributed propulsion (DP) scheme is used to provide powered lift capability in order to reduce the required wing area [13], or may be selected to ingest the turbulent boundary layer in order to reduce overall drag [14]. In this analysis, such advantages are not considered in depth, but remain as further potential for a conservative approach. Another item of propeller efficiency is related to the slipstream effect on the airframe components according to the location of the propeller. This appears to have a very significant influence and is discussed in further in this work.

2.4. ICE Limitations

For the skydiving mission, the maximum rate of descent for the aircraft is an important parameter, as it directly affects the mission cycle time. Several aspects of ICE installation can limit the maximum descent rate. The natural wind-milling characteristic of propellers can be a disadvantage. Depending on the ICE in use, piston or turbine, and the propeller type, fixed or variable pitch, the engine can be damaged if over-driven by the wind-milling propeller. This damage must be avoided by limiting the descent rate and airspeed.

Another limiting factor for conventional ICE powered aircraft descent is the behaviour of the ICE cooling system. Air cooled piston engines of the type very often used in current skydiving operations are particularly susceptible to shock cooling, caused by transition from high power settings at low airspeed to low power at high airspeed. This is the typical situation for aircraft in this role. Turboprop powered aircraft are less susceptible to shock cooling, but nonetheless, strict attention to temperature limits and variation must be observed.

2.5. Rated ICE Power

Internal combustion engine maximum output power is typically limited by any of three stress factors: pressure, engine speed (RPM) and temperature. The internal gas pressure developed during the operating cycle is dependent on the ambient atmospheric pressure but can be significantly modified by the nature of the engine mechanical systems. A maximum rating will usually be limited to a particular continuous operating time, and is typically given for a standard day sea level temperature and pressure.

A "naturally aspirated" piston engine's maximum power output varies with altitude due to the change in air density and therefore the amount of fuel which can be burned. A "forced induction" piston engine is fitted with a compressor to increase the density of the incoming air and is able to maintain full-rated power at higher altitudes. Gas turbine engines always feature a compressor and also have the potential to maintain full-rated power at higher altitudes.

Nevertheless, because the rated power of an engine is always limited by maximum stress, a compressor equipped type may need to be operated below its theoretical maximum power when at lower altitudes. The resultant power rating is termed "flat", when the available maximum engine power is constant up to some altitude. In this paper, a flat-rated engine is considered as having the same performance as a full-rated unit (at sea level) except that it maintains maximum rated power at altitude. Whereas the full-rated unit is assumed to lose power proportionally by the ratio of air density at altitude versus sea level. It is a notable attribute of EPS power-plants that they are not subject to output variation due to altitude, although thermal and RPM limits are still applicable.

2.6. Recharge Cases

Two particular HEP cases are analyzed and discussed in this work. This comparison shows advantages and disadvantages according to how the battery charging of a HEP aircraft should be managed.

Case A considers a hybrid electric aircraft propulsion system configured with a battery which is recharged using the on-board engine. Therefore, the aircraft can be fully self-contained and reliant only on consumable fuel, always maintaining a fully charged battery at the end of the mission. In this strategy, the ICE and EPS would provide power for flight but the duty cycles would be specified such that the ICE could always be capable of recharging the battery as required during the mission. An inevitable consequence of this strategy is that the electrical energy comes at the cost of the ICE efficiency, which is seldom better that 25%. Another problem with this approach is that the generator system capacity must be sized according to the engine as well as a time allocation based on the descent time. In the skydiving role, the descent time must be minimized to ensure high mission rates, and the electrical energy used from the battery during climb must be replaced during descent. The intent is to reduce the size and power of the ICE required for the mission, while retaining the capability for ICE-only operations independent of EPS storage. In addition, the cost and complexity of ICE units strongly favour the use of a single engine, and the accompanying EPS when in generator mode must then be sized to take the full ICE power. For a single ICE configuration, at higher H_P levels the power applied to non-ICE EPS units in climb will be significantly more than that able to be regenerated during descent. This adversely affects the recharge time which should be minimized as necessary to complete within the prescribed descent cycle time.

An inherent complication with "Case A" configuration is the sizing of the EPS equipment for efficient utilisation of ICE electrical generation. Clearly, a low H_P aircraft will have a lot of excess ICE power to recharge on descent, but also a low EPS capacity, whereas a high H_P aircraft would have a low ICE power available but a high EPS charging capacity and requirement. These factors will influence the viability of the "Case A" type for this mission.

Case B considers a hybrid electric aircraft propulsion system configured with a battery which is recharged by ground based sources. The battery can be removed and refitted easily such that the aircraft can resume operation for the next mission using a pre-charged exchange battery. It is shown that Case B is a superior system in terms of energy efficiency, direct operating costs and emissions, but may be significantly restricted in operational versatility. Nevertheless, the Case B system is presently feasible given current EPS technology, and will be ready for any and all improvements in battery storage technology over time which only improve upon original performance and utility.

3. Results

3.1. Hybrid Electric

Modelling has yielded results as presented later in this section which show that the full spectrum of hybridisation ratio is feasible right through to full electric operation for this aircraft type and mission.

The modelling for Case A indicates that the overall fuel consumption will increase if an on-board powerplant is used to recharge the battery during the operating cycle, using a conventional gas turbine unit. The specific fuel consumption for the preferred candidate type of ICE available, a gas turbine, turbo-prop or turbo-shaft unit is typically around 0.3 kg per kilowatt-hour [8]. While this type of engine has significant advantages in terms of mass specific power, approximately 4 kW per kilogram, and is a mature propulsion system within aerospace applications, significantly higher thermal efficiency would be required to make it viable for on-board recharging compared to ground based power sources. The application of electrical power to the aircraft, necessitates carriage of extra weight for batteries and power electronics, therefore the energy required for the flight is increased, unless efficiency is gained in either propulsion or aerodynamic efficiency. Nevertheless, the capability of configuring the aircraft for different missions using the EPS at certain H_P levels could find utility for some operators.

The modelling for Case B, indicates that HEP has the potential to significantly reduce emissions and direct operating costs for the flight operations.

3.2. Model Assumptions

The analytic model is based on standard flight mechanics run as a MATLAB tool. Without highly detailed analysis and wind-tunnel testing, certain assumptions on aerodynamic characteristics are required as input variables. The primary aerodynamic variable which must be estimated for this model is known as the Oswald efficiency factor (e). This is a parameter which expresses the total variation of drag with lift. It is sometimes called the span efficiency factor and would equal 1.0 for an elliptically-loaded wing with no lift-dependent viscous drag, for practical aircraft "e" varies from about 0.75 to 0.90 [15]. The other main variable which must be assumed for the model is the propeller efficiency. Again, values between 0.75 and 0.90 are typical [11] for the type of aircraft under consideration. Also, as noted below, the best propeller efficiency may be considered as dependent on the detailed aircraft configuration, with wing mounted propellers usually resulting in greater efficiency than a front fuselage mounted unit due to reduced slipstream "scrubbing". For the results below, an "e" value of 0.835 was used, and propeller efficiency varied between 0.75 and 0.85 respectively for the non-hybrid through to fully electric models assuming any EPS is accomplished by adding wing-mounted propellers. For intermediate H_P, the propeller efficiency was linearly scaled. Increasing H_P in this analysis implies increasing both the propeller area and the proportion assumed to be wing mounted and unobstructed by the fuselage. The battery mass required is calculated by a numerical iterative process taking into account the energy requirement according to the time required for climb at changing weight and drag conditions. The overall EPS mass is calculated using the proportion of installed power multiplied by the power density and is added to battery mass. The same technique is used to calculate the ICE mass in proportion to H_P to arrive at a take-off weight given the addition of sufficient mission fuel. Table 1, power system analytic model parameters, and Table 2, aircraft analytic model parameters, show the key parameters used in the analytical calculations.

Table 1. Power system analytic model parameters.

Component	Energy Density (Wh/kg)	Power Density (kW/kg)	Efficiency
EM	–	6	0.9
Power Electronics	–	6	0.9
Battery	200	–	0.9
ICE		4	0.26

Table 2. Aircraft analytic model parameters.

Aircraft Model	Installed Power (kW)	Empty Weight [1] (kg)	Payload Weight [1] (kg)	Oswald Efficiency Factor	Propeller Effciency
AUXX Conventional	670	2700	800	0.835	0.75
AUXX Hybrid	670	2700 + %EPS	800	0.835	Scaled
AUXX All-Electric	670	3500	800	0.835	0.85

[1] Weight given as mass in kilograms including nominal mission fuel.

Figure 5 shows the recharge time over-run for a "Case A" hybrid mission using a single ICE/EPS unit (single propeller). The "time over-run" is the amount of time the engine driven generator would be required to continue running on the ground after landing to recharge the battery. As the H_P increases, more battery energy is consumed for the climb, but less ICE power is available for both the climb and the descent phase. The practical H_P limit for Case A must lie somewhere before the knee of the curve, around H_P = 0.8. However, at the value H_P = 0.5, the over-run is 10%, which would represent a reasonable limit considering the ground handling and operational margins.

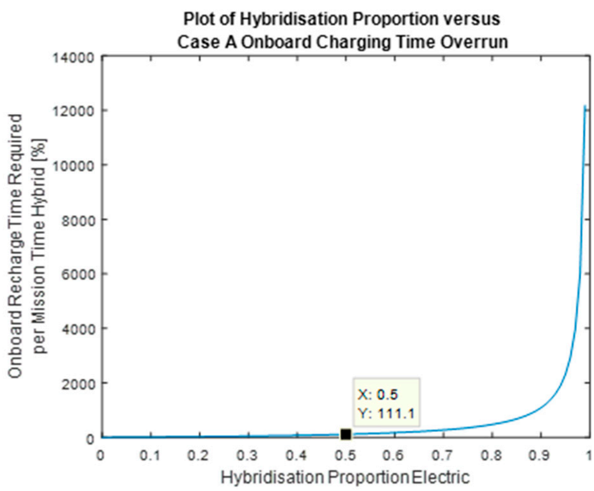

Figure 5. Hybridisation proportion vs. Case A charge time over-run; single EPS.

If multiple EPS units are used (three in this example), with a single ICE, the problem of recharge time becomes even more severe; as shown in Figure 6, where the useful H_P value is reduced to 0.25.

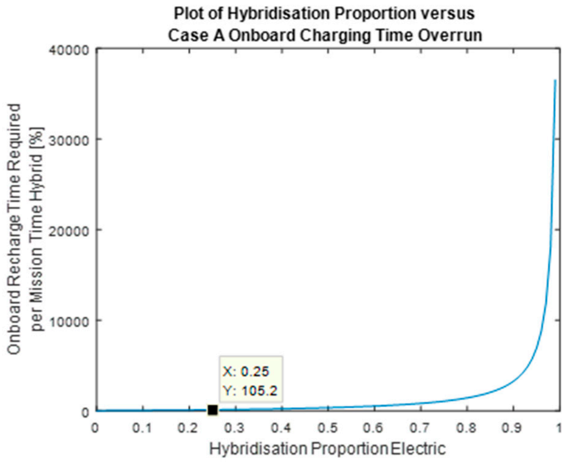

Figure 6. Hybridisation proportion vs. Case A charge time over-run; multiple EPS.

The problems inherent in Case A strategy in terms of mission cycle time are minor compared to the significant increase overall energy consumption. Figure 7 shows the mission fuel recharge requirements increase with increasing hybridisation ratio. That is additional recharge fuel is required to fully recharge batteries during a typical skydiving mission, based on a mission of duration 15–20 min.

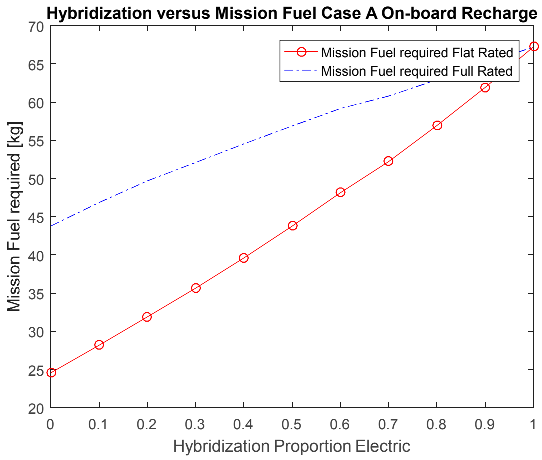

Figure 7. On-board ICE recharge mission fuel required, assuming no charge time limit.

In this case, a non-hybrid ICE-only system would use about 25 kg of fuel to complete the mission. For a flat-rated engine at the H_P value of 0.25, which as noted above would be the maximum for viable mission time utilisation, the mission fuel is increased by 40%. Clearly, the "Case A" strategy is counterproductive from a fuel consumption perspective, and shows why, historically, hybrid electric aircraft concepts were not considered useful. However, there are certain advantages which must be considered, and tend to favour hybridisation, such as those shown in the following sections. The justification of hybrid electric aircraft from the fuel consumption perspective is heavily dependent on any electric machine, propulsive and aerodynamic efficiency gains which can be made as well as the energy density of battery storage systems. Each of these factors are shown in literature to be advancing and have a positive development future [16].

The Case B type can include on-board recharging if desired, but the baseline is to replace and ground recharge the battery each mission. When battery recharging is conducted via ground based sources, renewable and green energy, with many wider societal and technical advantages can be utilised. This system guarantees the best emissions reduction and provides the best future utility potential as battery storage limits increase in the future.

If the presumption is made for Case B, where the battery is replaced or recharged without using the on-board ICE, the mission fuel required naturally tends to zero when the aircraft is solely electric powered ($H_P = 1$), as shown in Figure 8.

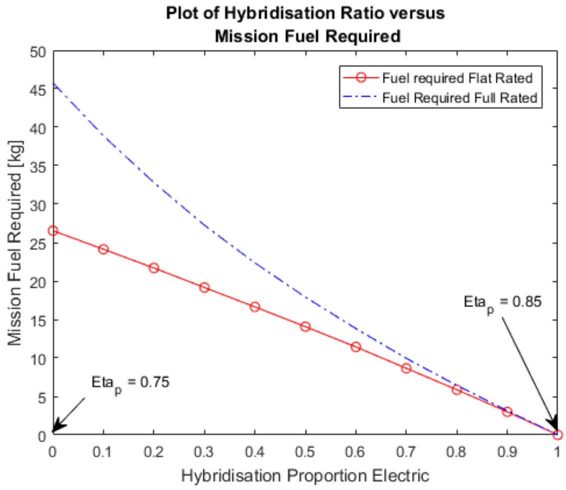

Figure 8. Skydive mission fuel required assuming off-board recharge.

The fuel required is nearly in proportion to the hybridisation for the flat-rated engine. In addition, clearly notable from Figure 8 is the difference between the flat-rated and full-rated engine type. The principle reason for the extra fuel required for the full-rated engine is the extra time required for the climb. This effect diminishes with increased H_P but would make hybridisation more favourable if use of a full-rated engine was necessary for any reason. The choice of hybridisation proportion can be made according to preferences for the energy source and hence emission characteristics, operating costs, weight or other operational characteristics. The fuel required reflects the direct operating cost of the mission as well as CO_2 and NO_x emissions. The overall energy required for the mission may increase for higher H_P because of the inherent electric energy source, distribution, conversion and storage inefficiencies. Carefully selecting the nature of the energy supply can easily reduce the cost and environmental impact. For example, converting the energy in coal to electricity to charge batteries via a conventional national grid for flight purposes is counterproductive to efficiency and emissions goals, but utilizing solar, wind or even nuclear energy sources can reduce the emissions. Nevertheless, the EPS system weight for a given flight will exceed that required for pure ICE operation, this translates to more energy being required to account for the higher drag due to increased required wing lift and more work done to raise the mass against gravity during the climb.

The Case B fuel consumption naturally favours this hybridisation model; however, the viability of using such an amount of electrical storage in terms of the aircraft structural and performance capability must be verified.

At the maximum H_P, the battery weight including a 20% margin amounts to 800 kg. This battery weight is considered feasible for an aircraft with a take-off weight of 4500 kg and a payload of 800 kg.

Figure 9 shows the battery weight implication for both the full-rated and flat-rated hybrid electric scenarios, while Figure 10 shows the effect on take-off weight.

The mission cycle time is naturally dependent on the best climb rate achievable, as well as the descent rate. For an identical installed propulsive power of 670 kW, the analytic model shows climb times for the range of H_P given the full-rated and flat-rated hybrid electric scenarios shown in Figure 11.

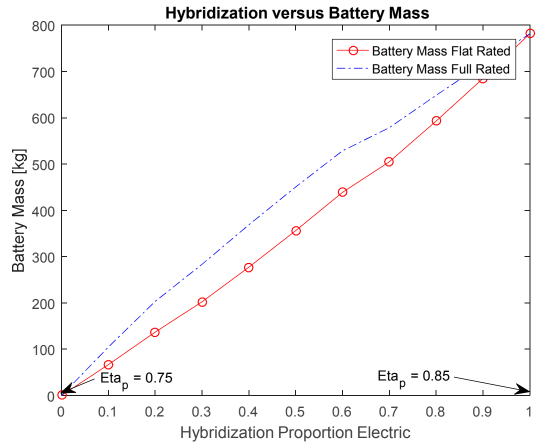

Figure 9. Battery mass requirements.

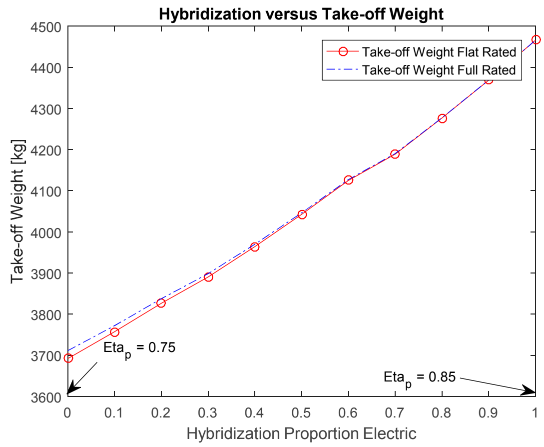

Figure 10. Take-off gross weight vs. hybrid proportion.

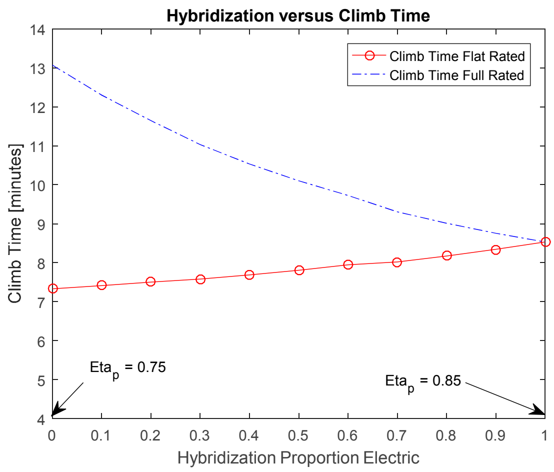

Figure 11. Time to climb vs. hybrid proportion for flat-rated and full-rated ICE.

The time to climb for a fully electric example is acceptable, and the improvement over a full-rated powerplant operating to the prescribed altitude is very significant.

The effect of propeller efficiency ($\mathrm{Eta_p}$) on the climb performance in this model is very sensitive. The foregoing examples used $\mathrm{Eta_p}$ values linearly scale from 0.75 to 0.85 on the H_P domain and show adequate performance. If the propeller efficiency is held constant (0.75 for example), and all other variables remain the same, the following plot of hybridisation versus climb time is produced shown in Figure 12.

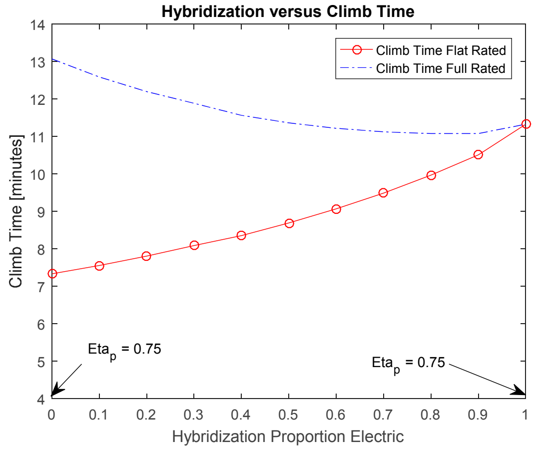

Figure 12. Time to climb vs. hybrid proportion given constant propeller efficiency.

In this case, the climb rate has decreased significantly with increasing H_P and would have negative implications for aircraft utility. This indicates the extreme importance of improving items of efficiency in order to enable hybrid electric propulsion systems to be viable.

Results obtained using the X-Plane simulation as detailed in the following section show a definite improvement in rate of climb for the hybrid models compared to conventional propulsion. The X-Plane models were configured at a constant H_P of 0.67. The analytical study shown above does not reflect such an improvement given the assumed propeller efficiency parameters, so it is of interest to see what change of propeller efficiency would yield results which concur with the simulation. The original propeller efficiencies used in the above calculations varied proportionally from 0.75 for a conventional non-hybrid using a single propeller through to 0.85 for a fully hybrid propulsion system using two additional wing mounted propellers. These numbers are arbitrary and reasonable assumptions, but a much more rigorous and comprehensive study of particular detailed designs would be necessary to improve estimates, or the flight testing of prototypes to verify real outcomes would be required. However, for the purposes of this study, a new set of possible propeller efficiency numbers can be conveniently input and the resulting performance calculated to find a match to the simulation. Figure 13 shows the result using a more extreme improvement of propeller efficiency terms through the domain of H_P. Figure 13 shows that the climb time has reduced by a similar amount as the simulation tool predicts.

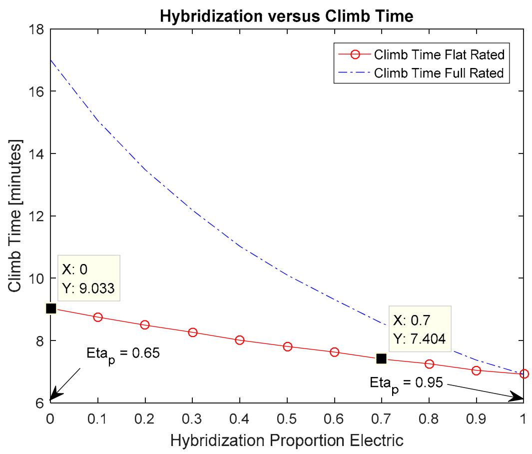

Figure 13. Time to climb vs. hybrid proportion at significantly improved propeller efficiency.

Table 3 shows the analytic results data from Figure 13, where the propeller efficiency assumed increases from 0.65 to 0.95 along the H_P domain, against measured times from X-Plane simulation flights. The times for each completely independent analysis method are now reasonably close, and the trend in changing to the distributed propulsion (three propeller) hybrid layout is very distinct. It is stressed that changes to the X-Plane model between the conventional and hybrid propulsion models created were the empty weight and the extra propellers and nacelles. The total installed power remained constant for both models.

Table 3. Calculated and simulated climb data.

Aircraft Model	Installed Power (kW)	Empty Weight [1] (kg)	Payload Weight [1] (kg)	Climb Time Analytic (minutes)	Climb Time Simulation (minutes)
AUXX Conventional	670	2400	800	9	10.6
AUXX Hybrid	670	3300	800	7.4	8.6

[1] Weight given as mass in kilograms including nominal mission fuel.

These results should be interpreted as trends only, as the input parameters are coarse estimates, however the underlying theory and technique for the analysis is based on fundamentals and well known properties. These trends reiterate that hybrid electric aircraft propulsion has many compelling advantages which can improve aircraft performance for particular mission requirements. These include:

- High power/weight (where battery storage capacity requirements are low);
- Ease of adding propeller area for any given installed power, allowing greater propulsive efficiency under particular conditions.

While at the same time reducing direct operating costs for energy.

3.3. All-Electric

From a survey of conventional aircraft types suitable for the skydiving mission as considered here indicates that a reasonable operating empty weight (the basic weight of an aircraft including the crew, all fluids necessary for operation such as engine oil, engine coolant, water, unusable fuel and all operator items and equipment required for flight but excluding usable fuel and the payload) [17], for this class of aircraft is approximately 2500 kg.

Calculating the required energy for the mission and using the lithium battery technology mass specific energy of approximately 200 Watt-hours per kilogram [7] and suitable allowances for other electric power system components yields a take-off weight within the maximum allowable for typical candidate example aircraft types. This calculation takes into account performance variations according to the power usage at any mass according to the installed components.

This result concurs with the fact that present state of the art all-electric aircraft such as Pipistrel "Alpha-Electro" are capable of carrying a payload of two people with a short endurance of 1 h in circuit climb and descent mission profile [18].

An all-electric skydiving lift aircraft has been found to be viable using current state of the art EPS technology from an aerodynamic standpoint given the condition that the battery is replaced or recharged for each mission. The primary parameter governing the aerodynamic viability is the weight of the battery required. In this case, given the short overall mission time, a battery mass is feasible which in addition to the payload is within the aircraft load carrying capability.

4. X-Plane Modeling

X-Plane is a flight simulation and modeling software tool available online and commercially. In this section X-Plane simulation was conducted to corroborate the findings, of the analytical analysis tool detailed above and to contrast propulsion configuration examples. Also provided is a comparison of expected performance with a well-known legacy type. The software can provide high accuracy simulation [19] and uses blade element theory according to specified geometry to integrate resulting forces, accelerations and consequent flight behavior. "FAA Certifications: X-Plane can provide Federal Aviation Administration (FAA)-certified simulation and vehicle models. This allows researchers to achieve high levels of confidence in simulation results" [20]. Three X-Plane models were developed to simulate relevant configurations of aircraft for comparison.

1. AUXX Hybrid Electric 1× 224 kW Turbo-Prop plus 2× 224 kW Electric Motors, Figures 14–16;
2. AUXX Conventional Single Turbo-prop 670 kW, Figure 17;
3. Cessna208 Grand Caravan equipped with 900 HP (670 kW) engine, Figure 18.

Figure 14 is a screenshot from X-Plane "Planemaker" software environment showing the AUXX hybrid aircraft model.

The Planemaker model is flown in the X-Plane simulation environment in the same way as any ordinary computer flight simulator. Aerodynamics are modeled using the physical features of the Planemaker mode,l including effects of wing sections, planforms, weight and balance etc. The AUXX Hybrid is shown in Figure 15.

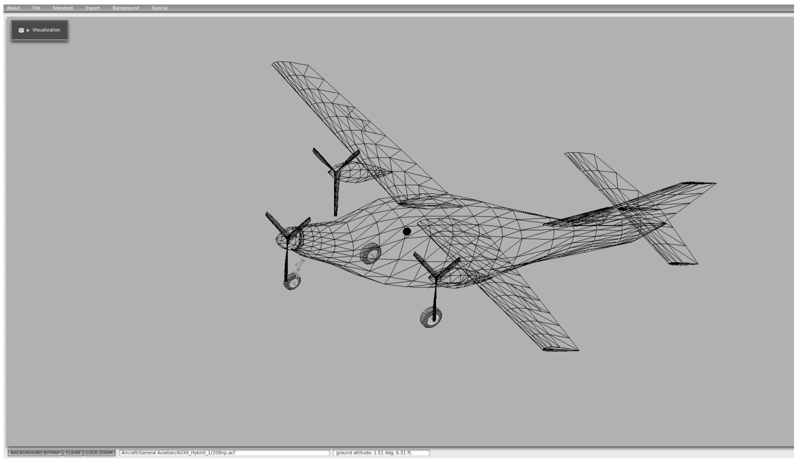

Figure 14. X-Plane "Plane-Maker" AUXX hybrid model.

Figure 15. X-Plane AUXX Hybrid unrendered model in simulation flight.

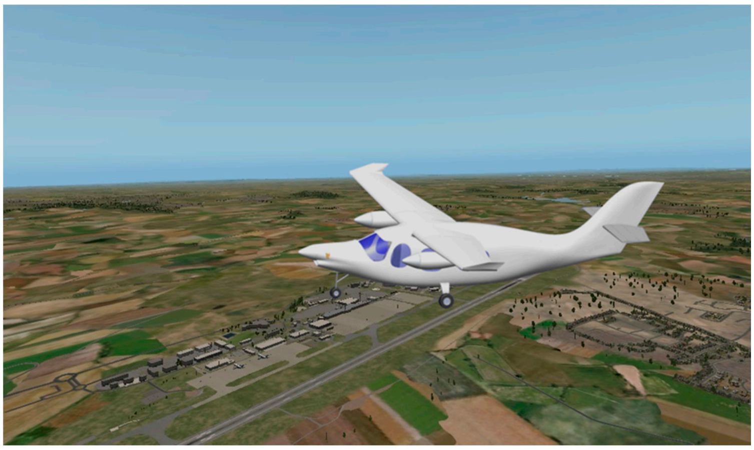

Figure 16. AUXX hybrid rendered model for X-Plane simulation.

Figure 17. AUXX conventional rendered model for X-Plane simulation.

X-Plane can generate well-rendered visual models by draping 2-D image files over a 3-D Planemaker-created aircraft, or by importing 3D graphic files. The aircraft model details rendered in this way do not affect the flight physics but are a useful cosmetic enhancement depicted in Figures 16 and 17.

Figure 18. X-plane C208 model in simulated flight.

In order to compare the performance of the AUXX models in X-Plane with an existing type, a Cessna 208 Grand Caravan model was employed. This model was modified to incorporate the same propulsion layouts as the AUXX but otherwise remained standard. The C208 model is shown in Figure 18.

Each model was flown in the simulator from take-off at maximum rate of climb to 4267 m (14,000 ft) altitude. The average climb rate was observed for each aircraft model. The flight simulator software includes a full "autopilot" facility which enables straight-forward and repeatable simulated flights. In this work, the autopilot setting maintained a given pitch and roll angle throughout the climb. The roll angle was set as close as possible to zero, while the pitch angle setting was decided through experiment to give best climb speed. It was noted that the indicated airspeed reduced slightly during the climb for all models, while the rate of climb steadily reduced as expected.

Of particular interest in determining relative performance and efficiency is the effect of propeller slipstream "scrubbing". "The part of the body, nacelle, wing or other airplane component which is directly located in the slipstream will experience a change in drag, called scrubbing drag. This effect can be "counted" as a change (increase) in airplane drag or as a change (decrease) in the installed thrust of the propeller" [21].

The AUXX design requirements result in a body with very large fuselage frontal area ratio of the propeller disk area compared to most similarly configured types. Although the fuselage is very well contoured, it inevitably has larger pressure gradients and wetted area contributing to drag, especially scrubbing drag, than comparative size and weight aircraft in the class which have much slimmer fuselages. Figure 19 shows the relative frontal cross-section area of the AUXX compared to legacy types.

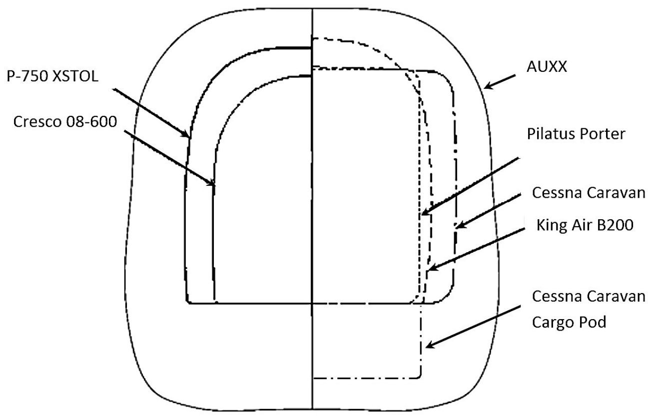

Figure 19. AUXX frontal area comparison.

The advantages of the conventional single front mounted engine configuration are clear and acknowledged in the design requirements. Commercial experience in the mission confirms that the operating and capital costs of twin engine (ICE) configurations must be avoided. It is also a known problem of light twin turbine powered aircraft that typical location of wing mounted engines places significant risks of uncontained turbine blade failure affecting the cabin [22].

However, the ability to locate electric motors and propeller units on the wings presents an excellent opportunity to improve the propulsive efficiency, by reducing propeller disk loading and scrubbing drag, while retaining the advantage of single front mounted engine placement. The electric motor is low temperature, low speed and low cost by comparison to equivalent power gas turbine equipment, thereby eliminating the gas turbine blade failure risk while providing an economical, higher-efficiency distributed propulsion installation.

Another advantage to be established in the simulation results is the performance of the electric motors at altitude. The X-Plane simulation uses a gas turbine flat-rated to 10,000 ft. Above this altitude, the maximum power available reduces in proportion to reducing air density. The electric motor power output remains constant with altitude.

The results for average climb rate of the simulated aircraft and key parameters are shown in Table 4.

Table 4. X-Plane aircraft simulation model parameters and climb rate.

X-Plane Aircraft Model	Installed Power (kW)	Empty Weight [1] (kg)	Payload Weight [1] (kg)	Average Climb Rate to 14,000 ft (ft/min)
AUXX Conventional	670	2400	800	1320
AUXX Hybrid [2]	670	3300	800	1620
C208 Conventional	670	2200	800	1550
C208 Hybrid [2]	670	3000	800	2150
Real Aircraft Data 850HP C208 [3]	635	2200	1800	* 1460 [4]

[1] Weight given as mass in kilograms including nominal mission fuel; [2] H_P = 0.66, 1× Front mount gas turbine plus 2× wing-mounted electric including battery and electrical components; [3] [23,24]; [4] * Initial rate at maximum gross weight.

These results show a clear trend of improved climb rate with the application of HEP at an H_P of 0.67 even with the necessary increase in weight. Since only the weight and the number and location of propellers was changed in the model, it has to be assumed the improved performance in simulation was due to increased efficiency.

4.1. Multi-Role

The analysis above was concentrated on the particular mission of high frequency climb and descent cycles with an assumption that the electrical propulsion battery would be changed out or recharged for each cycle. The feasibility of the mission is shown as viable with an attendant reduction in fuel consumption and, therefore, direct operating cost and emissions. However, varying the mission requirements for the in-service aircraft, perhaps for regional passenger transport or freight operation, will render the range and endurance inadequate when using any significant degree of hybridisation due to the limitation of current and near-term battery energy density technology. Such a reduction in role versatility is likely to prevent an operator investing in this new technology aircraft equipped with hybrid electric components. The benefits of the hybrid electric installation remain clear; the redundancy of including two separate propulsion systems, but without the problems inherent in conventional twin engine layouts; the possibility of utilizing non-hydrocarbon energy sources; the improved propulsion and aerodynamic efficiency etc. So, how can these conflicting objectives be resolved in order to allow the best future concepts to emerge?

4.2. Modularity

A solution to the problem is to introduce a new paradigm for aircraft propulsion modularity. Different roles and missions can be achieved using mixtures of basic component parts all designed to fit standardized interfaces. The concept is currently used for example on military aircraft external stores. A standard rack can carry a large variety of payloads, munitions, sensor pods, fuel tanks etc. For new propulsion, where a range of different hybridisation degrees, sizes of engine, battery packs etc., allow a variety of different performance outcomes, this concept can allow economic viability.

As an example, using the aircraft modeled above with a 223 kW ICE installed, and 447 kW of EM, we note that the effective range is severely limited. The battery size may be reduced to allow carriage of more fuel, but the remaining propulsive energy of the EM is then reduced, and the propulsive power of the ICE is inadequate for safe flight across all phases. In this case, removing the battery and installing a larger ICE to support electrical energy demands of the EMs would provide acceptable power and range, though at potentially lower propulsive efficiency due to the removal of the wing mounted propellers With some compromise in overall structural mass efficiency, it is a straight-forward engineering process to provide a firewall forward change-out of the ICE components. Such a task could realistically be achieved within minutes if the design were suitable. It may be useful for some missions to remove the EM units or fit different sizes etc. It is the capability in practice for such module interchange in the airworthiness and certification process which would currently cause the most delay. The legacy airworthiness and certification process was not designed for and is unfit for this type of approach, but just as that process was developed according to the requirements and constraints of the time, so a new system can be developed for new requirements and constraints.

An operator could invest in a set of components based on a standard fuselage and tail group. Various ICE, EM, and wing group parts suiting different missions could be interchanged as necessary for the best cost/performance outcomes.

5. Future Analysis

The aircraft concepts in this paper have been explored according to fundamental mission requirements and the constraints of propulsion technology. Future analysis will extend this approach into a whole of system design domain using advanced conceptual design methodologies to evaluate the performance attributes of these hybrid-electric propulsion concepts. It will approach this using an analysis based on conceptual design methodologies such as the concept design analysis (CODA) [13], quality function deployment (QFD) [25,26] , decision matrices (DM) [27,28] and value driven design (VDD) [29,30] approaches. The methodology will establish mission requirements and needs in relation to provisions for system performance, sustainability, certification, weight and cost metrics. Given that the system solution space may include hybrid combinations of ICE and EP configured in multiple multi-motor architectures, and/or operated to various battery charging strategies, it is likely that numerous potential concepts will result. One particular method used has been the application of general morphological analysis techniques [31,32] to evaluate various technology combinations and options. This is achieved using a concept morphological matrix approach which develops technology vectors which can be evaluated within integration requirements. Different concepts are therefore developed by combining various possible solutions exhaustively to ensure that a rigorous examination of the design space is conducted. Later steps in this methodology will therefore involve selection of the "best candidate" concepts, and optimization of the solution based on change propagation analysis [33–36]. This change propagation analysis method will also use matrix methods combined with various visualization techniques to assess the impact of changes resulting from HEP related aircraft modifications. This analysis methodology will assess the impact of change propagation on integration risk and evaluates technology readiness level. In addition, this methodology can assist in evaluating technical performance attributes, sustainability and value proposition of the HEP solution.

Safety and Certification

Commercially operated aircraft are subject to stringent certification and standards control. In many jurisdictions, skydiving lift aircraft comply to FAA Part 23 normal category standards. This category allows up to 5700 kg maximum take-off weight (MTOW) [28]. Aviation certification and standards and regulations often lag technological development and may become anachronous in view of disruptive technologies. Yet, the foundation of these processes remains vital to the ongoing safety of aviation and will not disappear. However, the adoption of conceptual design methodologies as described above provides a means to assess those certification requirements impacted by HEP aircraft modifications. This methodology would build on change propagation analysis techniques as described above. It is anticipated that this would a research project in its own right which would inform regulatory changes accounting for these new propulsion technologies and maintaining the salient hard-won safety principles developed over the past 100 years.

6. Conclusions

A novel aircraft design has been analysed as a case study to highlight the positive advantages of hybrid electric propulsion for aircraft. Whereas negative compromises of electric propulsion remain significant due to increased system weight compared to pure internal combustion alternatives, various efficiencies and advantages can be shown to allow overall performance improvement for particular missions and some new aircraft roles become viable only as a result of hybrid electric propulsion.

It has been shown how a short duration high power mission such as skydiving can use HEP equipped aircraft to reduce fuel consumption, and how even simply-configured distributed propulsion benefits the efficiency to offset the problematic aspects of increased HEP system weight.

The use of a hybrid electric propulsion system could yield a viable bridge between legacy certification standards and new evolving standards for fully electric aircraft. The way in which the traditional ICE is integrated with electrical components can provide enhanced performance as well as system redundancy. This changes the whole risk profile for the aircraft capital investment, development and operation. It is evident that more and more hybrid and electric aircraft concepts are emerging from small light sport types through to intercontinental heavy transport. It is inevitable that the new opportunities for aircraft design will result in a range of new types with technical and commercial viability, but requiring reform and advancement of regulatory and certification systems.

Many studies of electric and distributed propulsion for aircraft look at the opportunities which may only exist once significant further battery storage technology and other future EPS improvements take place. The study presented here exemplifies the fact that HEP technology can have utility in aviation today with current levels of technology. Moreover, the study shows that new aircraft developed using current HEP technology can lead progress, and will only benefit as future technology emerges, rather than being superseded.

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Author Contributions: Richard Glassock: Richard is a Research Fellow at the University of Nottingham Institute for Aerospace Technology. Richard wrote the body of the manuscript and developed the MATLAB and X-Plane modelling tools, as well as the 3D CAD models used in design development and illustrations for the case study aircraft. Michael Galea: Michael received his PhD in Electrical Machines Design from the University of Nottingham, UK. He is currently a Lecturer in Electrical Machines and Drives within the Power Electronics Machine and Control research group of the University of Nottingham. Michael reviewed the manuscript and provided input for all items regarding electrical systems. Warren Williams: Warren is a professional aeronautical engineer in private practice in Australia and is currently completing a PhD in Aeronautical Engineering. Future Analysis topics of Safety and Certification were contributed by Warren. Tibor Glesk: Tibor is a professional skydiver who has operated commercial skydiving centres around the world for 30 years. Tibor designed the conceptual requirements of the AUXX aircraft, owns and manages the design program. Tibor provided advice and feedback on all areas of commercial and operational requirements for the skydiving aircraft concept.

Conflicts of Interest: The aircraft used in this paper is subject to ongoing development projects toward commercialisation. Contribution from private project resources was limited to allowing use of data and figures. No funding, sponsorship or financial consideration of any sort was given.

References

1. Oxford University Press. (2017). Definition of Utility in English. Available online: https://en.oxforddictionaries.com/definition/utility (accessed on 20 July 2017).
2. Dropzone Inc. Where to Dropzone. Available online: http://www.dropzone.com/dropzone (accessed on 7 November 2016).
3. The USA Parachute Association. Who Skydives? Available online: http://www.uspa.org/facts-faqs/demographics (accessed on 7 November 2016).
4. European Commisson. *Europe's Vision for Aviation. Report of the High Level Group on Aviation Research*; Directorate-General for Mobility and Transport: Brussels, Belgium, 2011.

5. Gerada, C.; Galea, M.; Kladas, A. Electrical machines for aerospace applications. In Proceedings of the 2015 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Torino, Italy, 26–27 March 2015; pp. 79–84.
6. Galea, M.; Hamiti, T.; Gerada, C. Torque density improvements for high performance machines. In Proceedings of the Electric Machines & Drives Conference (IEMDC), Chicago, IL, USA, 12–15 May 2013.
7. Hepperle, M. *Electric Flight—Potential and Limitations*; NATO: Brussels, Belgium, 2014.
8. Specific Range Solutions Ltd. (2009, 2016). Parametric Specific Fuel Consumption Analysis of the PW120A Turboprop Engine. Available online: http://www.srs.aero/wordpress/wp-content/uploads/2009/03/srs-tsd-002-rev-1-pw120a-sfc-analysis.pdf (accessed on 10 November 2016).
9. Glesk, T. Requirements Document. In *Requirements Document*; Glassock, R., Ed.; Air Ute Pty Ltd.: Caloundra, Queensland, Australia, 2012.
10. Massachusetts Institute of Technology. Thermodynamics and Propulsion. Available online: http://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node86.html (accessed on 27 February 2017).
11. Phillips, W.F. *Mechanics of Flight*, 2nd ed.; John Wiley and Sons, Inc.: Chichester, UK, 2010.
12. Glassock, R. Design, Modelling and Measurement of Hybrid Powerplant for Unmanned Aerial Vehicles (UAVs). Master's Thesis, Master of Engineering, School of Electrical Engineering and Computer Science, Queensland University of Technology, Brisbane, Austria, 2012.
13. Pornet, C.; Isikveren, A.T. Conceptual design of hybrid-electric transport aircraft. *Prog. Aerosp. Sci.* **2015**, *79*, 114–135. [CrossRef]
14. Plas, A.P.; Sargeant, M.A.; Madani, V.; Crichton, D.; Greitzer, E.M.; Hynes, T.P.; Hall, C.A. Performance of a Boundary Layer Ingesting (BLI) Propulsion System. In Proceedings of the 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, USA, 8–11 January 2007.
15. Stanford University. (2009). Simple Performance Estimation. Available online: http://adl.stanford.edu/sandbox/groups/aa241x/wiki/e054d/attachments/31ca0/performanceanddrag.pdf (accessed on 30 June 2017).
16. Bullis, K. (2013). Once a Joke, Battery-Powered Airplanes Are Nearing Reality. Available online: https://www.technologyreview.com/s/516576/once-a-joke-battery-powered-airplanes-are-nearing-reality/ (accessed on 5 May 2017).
17. Rosenfelt, C. (2014). Skydive Aircraft List. Available online: http://skydiverdriver.blogspot.co.uk/p/skydive-aircraft.html (accessed on 17 November 2016).
18. PIPISTREL d.o.o. Ajdovščina. (2014). Pipistrel Aircraft—UL 3-Axis AIRCRAFT—Alpha Electro—Overview. Available online: http://www.pipistrel.si/plane/alpha-electro/overview (accessed on 12 December 2016).
19. Williams, W.R. *A Simulator Based Approach to DT&E of Small UAVs*; School of Electrical and Sytsem Engineering, University of South Australia: Mwson Lakes, South Australia, 2002.
20. Garcia, R.; Barnes, L. Multi-UAV Simulator Utilizing X-Plane. *J. Intell. Robot. Syst.* **2010**, *57*, 393–406. [CrossRef]
21. Lan, C.E.; Roskam, J. *Airplane Aerodynamics and Performance*; Aviation and Engineering: Ottawa, ON, Canada, 1980.
22. Federal Aviation Administration. *AC 20-128A Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure*; The United States Department of Transportation (USDOT): Washington, DC, USA, 1997.
23. Honeywell. Available online: https://aerocontent.honeywell.com/aero/common/documents/myaerospacecatalog-documents/BA_brochures-documents/TPE331-12JR_for_850_Caravan.pdf (accessed on 25 May 2017).
24. Texas Turbines. (2016). Product Brochures and Spec Sheets Supervan 900. Available online: http://www.texasturbines.com/product-brochures/ (accessed on 25 May 2017).
25. Friedrich, C.; Robertson, P.A. Hybrid-electric propulsion for automotive and aviation applications. *CEAS Aeronaut. J.* **2015**, *6*, 279–290. [CrossRef]
26. Fefermann, Y.; Maury, C.; Level, C.; Isikveren, A.T. Hybrid-Electric motive power systems for commuter transport applications. In Proceedings of the 30th Congress of the International Council of the Aeronautical Sciences, Daejeon, Korea, 25–30 September 2016.
27. Eres, M.H.; Bertoni, M.; Kossman, M.; Scanlon, J. Mapping Customer Needs to Engineering Characteristics: An Aerospace Perspective for Conceptual Design. *J. Eng. Des.* **2014**, *251*, 64–87. [CrossRef]

28. *Part 23—Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes ed: Electronic Code of Federal Regulations*; U.S. Government Publishing Office: Washington, DC, USA, 2016.
29. Ullman, D.G. *The Mechanical Design Process*, 4th ed.; McGraw-Hill: New York, NY, USA, 2010.
30. Gudmundsson, S. *General Aviation Aircraft Design—Applied Methods and Procedures*, 1st ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2014.
31. Markish, J.; Willcox, K. A value-based approach for commercial aircraft conceptual design. In Proceedings of the ICAS2002 Congress, Toronto, ON, Canada, 8–13 September 2002.
32. Ulrich, K.T.; Eppinger, S.D. *Product Design and Development*, 5th ed.; McGraw-Hill: New York, NY, USA, 2012.
33. Eckert, C.; Clarkson, J.; de Weck, O.; Keller, R. Engineering change: Drivers, sources, and approaches in industry. In Proceedings of the 17th International Conference on Engineering Design, Stanford, CA, USA, 21 October 2009.
34. Eckert, C.M.; Keller, R.; Earl, C.; Clarkson, P.J. Supporting change processes in design: Complexity, prediction and reliability. *Reliab. Eng. Syst. Saf.* **2006**, *91*, 1521–1534. [CrossRef]
35. Clarkson, P.J.; Simons, C.; Eckert, C. Predicting Change Propagation in Complex Design of DETC'01. In Proceedings of the Design Engineering Technical Conference, Pittsburgh, PA, USA, 9–12 September 2001.
36. Clarkson, P.J.; Simons, C.; Eckert, C. Change prediction for product redesign. In Proceedings of the International Conference on Engineering Design, Glasgow, UK, 21–23 August 2001.