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Feasibility of Developing Hybrid Electric General Aviation Aircraft

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Abstract In this work, the feasibility of utilizing the electric energy during three segments of flight of a 6-seater aircraft is investigated. The overall design features of the baseline design configuration are first presented. The required electrical energy is calculated, and the weight of the battery is estimated based on battery specific energy improvement forecast until 2030. These weight variations are then used to calculate the fuel weight reductions compared to conventionally propelled aircraft. The purchasing and operations and maintenance costs of the hybrid electric aircraft are analyzed using modified RAND DAPCA IV model. Numerical results show a saving of about 15 % in fuel consumption for 2030 production. Results also show that operational cost of the designed hybrid electric powered aircraft is 20% less than average cost of current similar aircraft.

Keywords: Hybrid Electric Aircraft · Aircraft Design · Aircraft Cost Analysis · Sustainable Aviation · Green Aviation · Battery Development · General Aviation Technology · General Aviation Hybridization.

List of symbols

H_E	Engineering hours [hr]
R_E	Engineering rate [$]
H_T	Tooling hours [hr]
R_T	Tooling rate [$]
H_M	Manufacturing hours [hr]
R_M	Manufacturing rate [$]
H_Q	Quality control hours [hr]
R_Q	Quality control rate [$]
C_D	Development support cost
C_F	Flight test cost [$]
C_M	Manufacturing materials cost [$]
C_{eng}	Engineering production cost [$]
N_{eng}	Total number of engines [-]
C_{avc}	Avionics cost [$]

Abbreviations

MTOW	Maximum Take-off Weight
EIS	Enterprise Investment Scheme
SAR	Specific Air Rang
DAPCA	Development and Procurement Cost of Aircraft
RAND	Research and Development
O/M	Operation and Maintenance
RDTE	Research, Development, Testing and Evaluation
$flyaway$	Cost of production and production tools essential for building a single unit

1. Introduction

There has been a lot of work, recently, related to developing electric motors, controllers, and batteries for the development of hybrid vehicles. Chevrolet Volt, Toyota Prius, and then the fully electrical Tesla, cars led the way to similar implementation in the aerospace industry [1]. In Boeing 787 Dreamliner, electric power systems are used to power hydraulics, engine starter and wing ice protection [2]. More recently, the idea of E-Taxi or Green Taxiing, in which electric motors are connected to main landing gears to propel the airplane during taxiing, was proposed [2].

With the aviation industry interested in implementing similar new technologies to mid-size transport aircraft, the feasibility of developing a 70 passenger hybrid aircraft with a range of about 1,500 nm was studied [3]. In this work, about one third of the shaft work is provided by batteries with assumed 1000 wh/kg specific energy. Batteries with such high energy storage capacity has not materialized yet. AS for matured firms, a Concept of parallel hybrid electric propulsion is utilized by Boeing in SUGAR project, in which a turbofan 154-seater aircraft design is proposed with 2030 technology [4]. Another Hybrid electric aircraft was designed by Zunum Aero. They are developing a regional aircraft that carries 12 passengers that will eventually transition to fully electrical within twenty years as the technology develops [5]. Also, All-electric commuter aircraft is being developed, such as Alice by Eviation. However, 60% of the MTOW comprises batteries, which reflects the battery low specific energy challenge, compared to conventional fuel [6].

The objective of the current work is to investigate the feasibility of designing a fuel efficient 6-seater general aviation hybrid aircraft in the near future, and to address the design features of such an aircraft. The work focuses on the effect of year of market entry of lithium batteries to store energy on the amount of saved fuel, and the expected flyaway and operating cost of the aircraft.

2. Methodology

To accurately assess the feasibility of using hybrid electric engine technology for general aviation aircraft, the preliminary design of the base configuration is first introduced, followed by the current and expected capabilities of the batteries. Finally, the method of estimating the flyaway and operating cost is summarized. Most of design approaches and fuel consumption calculations were excused in accordance with [7].

2.1 Baseline Aircraft Design

Aircraft requirements are chosen for the present work is according to the industry requirements for general aviation aircraft:

- Design range of 750 nm.
- Targeted Cruise speed of 200 knots.
- Maximum takeoff and landing distance of 1800 ft over a 50 ft obstacle.
- Sea level climb rate of 1300 fpm.
- Must meet all FAA 14 CFR Part 23 applicable certification rules.

To satisfy these requirements, a low wing with an inverted v-tail configuration was selected. This improved internal volume management, facilitated use of shorter landing gear struts, and simplified the control system by reducing the number of control surfaces. A pusher type configuration is selected to allow for a shorter fuselage, reduction in cabin noise, and taking the advantage of the boundary layer ingestion [7].

The remaining parameters were obtained during the design process in such a manner to ensure the stability, controllability and efficiency of the aircraft. A summary of the calculated values of the most critical design parameters and aerodynamic coefficients are presented in Table 1. The baseline configuration is presented in Figure 1.

Table 1 Baseline configuration design values and aerodynamic coefficients.

Parameter		Value
Wing Loading (lb/ft^2)	W/S	23.4
Power loading (hp/lb)	PL	0.08
Aspect Ratio	AR	8.0
Taper Ratio	λ	0.5
Wing Area (ft^2)	S	199.5
Wing Span (ft)	b	40.0
Lift Curve Slope	$C_{L\alpha}$	4.9
Parasite Drag Coefficient	C_{D0}	0.021
Feathered propeller Efficiency	η_p	0.87
Cruise moment coefficient slope	C_{m_α}	-0.57
Static margin (in)	SM	7.2

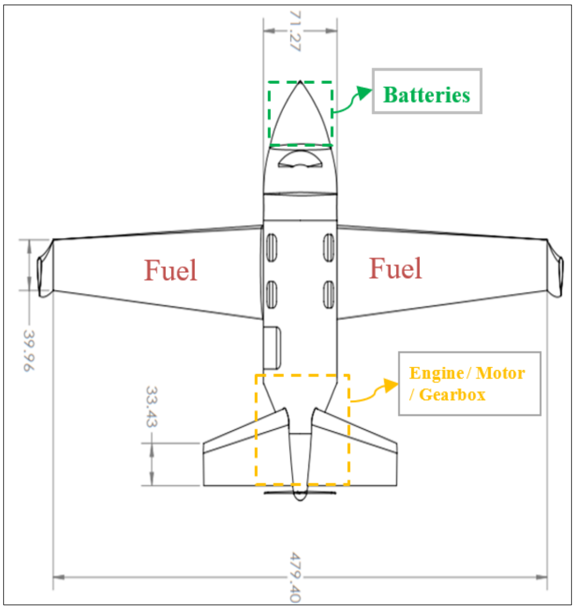

Fig 1 Baseline configuration design and layout: Top view (Dimensions are in inch).

2.2 Propulsion Architecture

The hybrid aircraft is designed to run on electric power during taxi and take-off. In climb segment, the shaft is powered by the electrical motor along with the piston engine at split power percentage of 80% and 20%, respectively. For the remaining mission segments, the aircraft will be propelled conventionally. Thus, parallel hybrid propulsion is found to be the most suitable architecture for the mission described. Such hybridization will reduce gas emissions and noise especially at low altitudes.

Figure 2 illustrate aircraft propulsion architecture. The presence of charger and generator is optional. Their main benefit is to reduce time between missions since batteries will land charged. On the other hand, more fuel is required for charging and aircraft weight will increase as well as flyway cost. However, in this paper calculations are made as if the battery charged in the ground from the electrical grid.

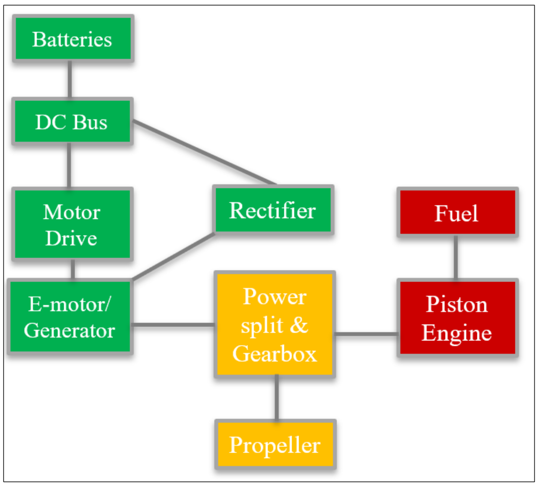

Fig 2 Parallel Propulsion Architecture.

To categorize hybrid aircraft, degree of hybridization is defined [4]. They are known as H_p and H_e. H_p represents the ratio of the electrical power to the total delivered power, whereas H_e indicates the delivered energy from batteries over the total energy needed for the complete mission. Depending on the degree of hybridization, H_p and H_e range between 0 and 1. For all-electric aircraft, $H_p = 1$ and $H_e = 1$, while in conventional aircraft $H_p = 0$ and $H_e = 0$.

The calculated maximum rated engine power is 380 hp. This power can provide the required thrust for the maximum aircraft weight throughout the analysis and will become more than sufficient as the battery and aircraft weight decrease. Table 2 depicts the calculated required energy and power supply during each of the flight segments.

Table 2 Energy requirement for aircraft mission segments.

Power Type	Segment	Duration (hr)	Power (hp)	Energy Required (wh)
Electrically Powered segments	Taxi	0.05	40	1491
	Take-off	0.0072	380	2024
	Climb	0.1667	304	37782
Conventionally Powered Segments		0.1667	76	9446
	Cruise	3.746	340	949710
	Loiter	0.33	160	39771
	Approach & Landing	0.25	30	5593

From Table 2, the delivered electrical energy must be equal to or greater than 41.3 kwh out of the required mission energy, that is 1045.82 kwh. Hence, degree of hybridization, H_e, is 0.04. Also, it can be inferred that H_p equals 1 for taxi and take-off, 0.8 for climb, and 0 for the remaining flight segments. Though, the delivered electrical energy is less than actual batteries storage, depending on the electrical components' efficiencies. According to [8] electrical components efficiencies can be assumed as:

- Power management and controllers: 99%
- Distribution wires: 99%
- Motor deriver: 95%
- Electrical Motor: 95%
- Gearbox: 99%

Hence, the estimated electrical efficiency is 87.6% and stored energy should not be less than 47.16 kwh. To ensure that this amount of energy is contained, 10% energy margin is accounted for battery degradation which make the total energy storage 51.9 kwh. To compensate further battery degradation, fuel can be added, and aircraft will be less electrically dependent during climb.

2.3 Lithium Battery Development

Lithium batteries technology improved considerably since it was introduced by Sony in 1990 [9]. Researchers are investigating variety types of lithium based batteries such as [10]:

- **Lithium cobalt oxide LCO**: This type of battery has high stability and discharge rate. Tough, the low specific energy is the main disadvantage of LCO battery.
- **Lithium air battery Li-air:** Li-air battery replaces cathode with air, and anode consists of lithium. It has relatively high energy density, but it is not certainly realized as rechargeable battery yet.
- **Lithium sulfur battery Li-S:** it consists of lithium as anode and sulfur as cathode, which resulted in high specific energy. However, it is a temperature limited battery.
- **Lithium solid Battery Li-solid:** it has an advantage of high heat stability. Thus, complex cooling mechanism is not required.
- **Lithium nickel manganese cobalt oxide NMC:** this type of battery has the advantages of lithium cobalt oxide high capacity, lithium nickel oxide high current properties and lithium manganese oxide low price. Beside it has high charge and discharge rate.

Figure 3 shows the achievable values of both the volumetric specific energy density (wh/liter) and the gravimetric specific energy density (wh/kg) for various Lithium based battery types. This indicates that operational batteries with specific energy density of 500-700 wh/kg can be expected. Another source reports Li-metal-free prelithiation method to obtain a battery specific energy of 732 wh/kg [11].

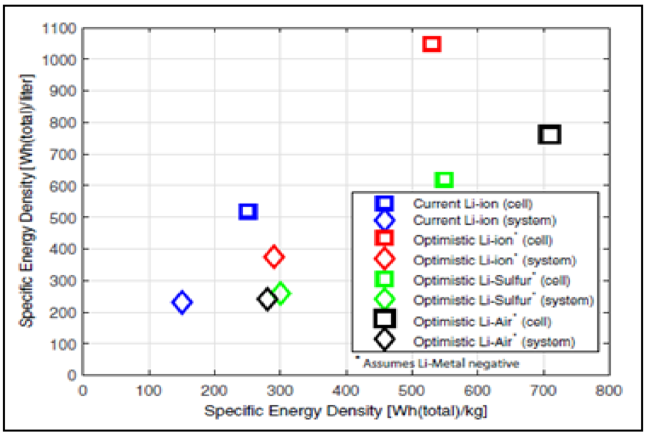

Fig 3 Various types of battery cells and systems volumetric and gravimetric specific energy for current and future prediction [3].

In 2019, Maxwell which is a Tesla owned company, claimed that they patented a battery of over 300 wh/kg. This was made possible using dry-cell technology. On top of that, they aim to reach 500 wh/kg[12]. Recently, Tesla has announced its latest update in battery developments. Cell size is altered to the optimum value with regard to vehicle range and cell cost. For cathode material, Silicon is utilized, while a combination of Lithium, Nickle, and Cobalt is used as anode. By the new cell design and proper vehicle integration, Tesla claims that vehicles range would be increased by 54% and battery cost reduction of 56% can be achieved [13].

Ref. [4] has reviewed a wide range of proposed studies and ongoing projects of hybrid electric and all-electric aircraft. Figure 4 is a representation of each aircraft battery gravimetric specific energy versus

EIS year. It shows that around 650 wh/kg is attainable by 2030. According to the accelerated development, mentioned above, it is expected that battery of not less than 300 wh/kg would be available in 2021.

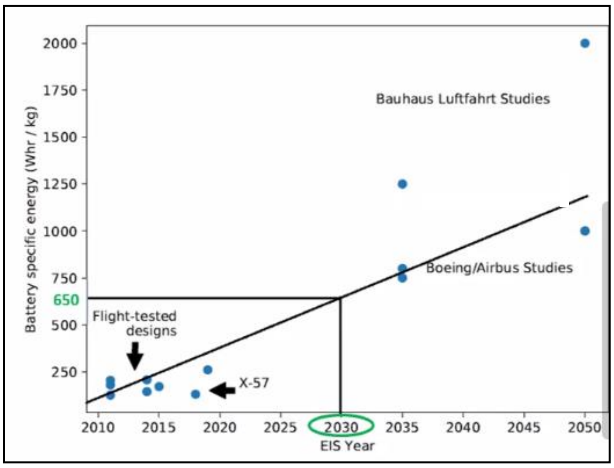

Fig 4 Battery specific energy Vs. EIS Year [4]. Curve fitting by [14].

Regarding battery cost, industry is EEcompeting towards more reduction since it comprises a significant amount of flyway cost. This is achievable by altering battery chemistry, reducing manufacturing cost, and optimizing cell design and assembly. Figure 5 shows battery cost trend and targeted cost of 125 \$/kwh in 2022. Another research by [16], in figure 6, estimates battery cost drop to as little as \$62/kWh in 2030.

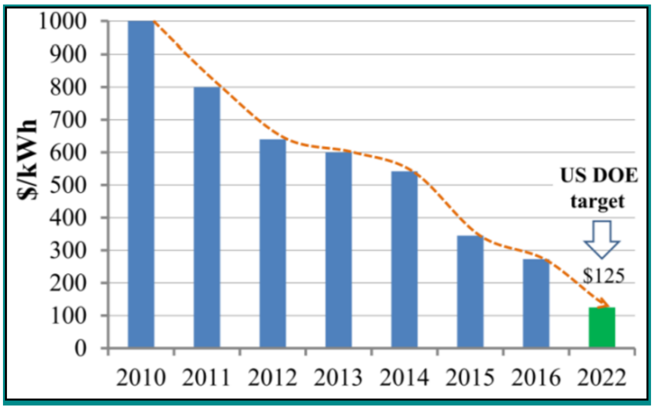

Fig 5 Battery cost trend and expectations [15].

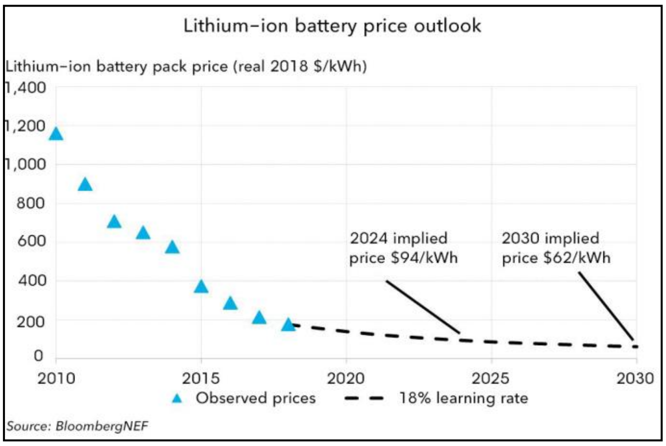

Fig 6 Battery Price Trends 2010-2030 [16].

2.4 Cost Analysis

To obtain a reliable flyaway and operational cost of the designed aircraft, the RAND DAPCA IV model is used [17]. Along the years, the model showed significant applicability, which led civil and general aviation companies to develop their own versions of this model. Here, a general aviation adopted version of this model is used [7].
This cost analysis method determines the development cost as well as the operations and maintenance cost per year. The prices in this model are based on 2012 US dollar, so the model predictions are adjusted to 2030 US dollar value, with a cumulative inflation rate of 30%.

2.4.1 Development Cost

The DAPCA IV model calculates the development cost using the following equation:

$$RDTE + flyaway = H_E R_E + H_T R_T + H_M R_M + H_Q R_Q + C_D + C_F + C_M + C_{eng} N_{eng} + C_{avc}$$

In using this model, some correction factors are used [18]. Since the model was initially used for military aircraft, mostly over-predicts the cost, thus, a 0.9 correction factor is suggested. Also, the initial spares for the aircraft add about 10% to the purchase price. Finally, a fudge factor of 0.8 is used to adjust the engineering, tooling, manufacturing, and quality control costs to account for new technologies in the aviation industry [17]. Finally, a Quantity Discount Factor (QDF) needs to be included [18]. This human factor accounts for the learning and experience curve that engineers, mechanics and technicians acquire along the timespan of producing the aircraft.

$$QDF = (F_{EXP})^{1.4427 \ln N}$$

where F_{EXP} is the experience effectiveness, taken as 0.81 and N is the number of aircraft to be produced. QDF significantly affects market competitiveness of new designs.

2.4.2 Operation and Maintenance Cost

Operations cost for the fossil-fuel powered aircraft are calculated, using the DAPCA model, as the annual cost of fuel, pilot salary, maintenance expenses, depreciation, and insurance. Pilot salary is based on Phoenix East Aviation study [19], whereas fuel cost is based on December 2020 aviation gasoline prices [20]. Depreciation is based on an aircraft lifetime of 20 years and the model uses an insurance cost of 1% of the total operation and maintenance cost.

3. Numerical Results

In this section, the industry trend line will be used to predict battery specific energy until 2030, and the total aircraft weight saving as a function of year of entry of the hybrid design. Finally, the effect of using the hybrid technology on the purchasing and operating cost of the aircraft will be presented for the thin-haul flight operation mode.

Based on the industry trend line and battery chemistry developments presented in Figures 3 and 4 a 7.5% annual increase in battery gravimetric specific energy is expected. Figure 7 presents battery storage capability till 2030. The value of 575 wh/kg in 2030 is reached by the figure below.

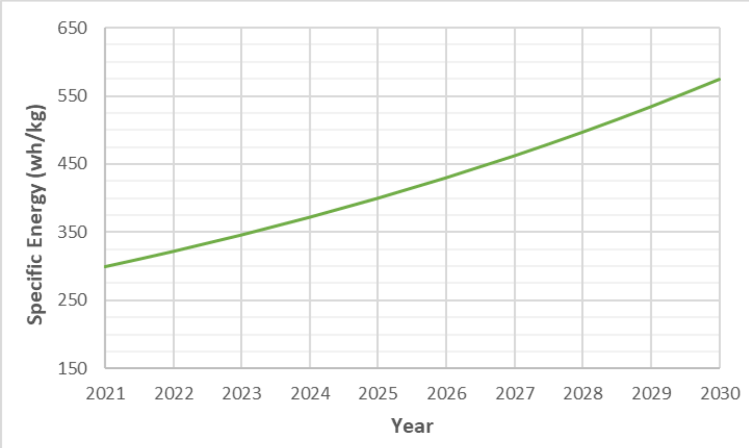

Fig 7 Battery specific energy forecast.

Next, the current and projected amount of fuel saving is calculated. Considering current values of battery specific energy, a battery weight of 374.34 lb is calculated. Fuel savings, however, are calculated to be 9%, or 60 lb. Investigating fuel saving using projected battery specific energy in the future till 2030 is depicted in Table 3. The saving of fuel of about 15% will significantly decrease aircraft total weight. Additionally, Specific Air Range (SAR), which measures the distance flown per unit mass of fuel [4], is calculated initially to be 1.24 and improved by around 7.29% to be 1.35 by 2030.

Table 3 Calculated fuel and battery weights reduction and specific air range projections till 2030.

Year	Battery Weight (lb)	Gross Weight (lb)	Fuel Weight (lb)	Fuel Weight Reduction (lb)	Fuel Weight Reduction (%)	Specific Air Range (nm/lb)	SAR Improvement (%)	Battery Weight to Gross Weight (%)
2021	374.3	5341	596.9	59.23	9.03	1.26		7.01
2022	349.9	5289	591.1	65	9.91	1.27	0.98	6.61
2023	327.0	5241	585.7	70.4	10.73	1.28	1.91	6.24
2024	305.6	5196	580.6	75.47	11.5	1.29	2.80	5.88
2025	285.6	5153	575.9	80.21	12.23	1.3	3.64	5.54
2026	266.9	5114	571.4	84.66	12.9	1.31	4.45	5.22
2027	249.4	5076	567.3	88.82	13.54	1.32	5.22	4.91
2028	233.1	5042	563.4	92.72	14.13	1.33	5.94	4.62
2029	217.9	5009	559.7	96.36	14.69	1.34	6.63	4.35
2030	203.6	4978	556.3	99.78	15.21	1.35	7.29	4.09

From the table above, two relations are highlighted. The first one is shown in figure 8 where battery weight is decreasing, and fuel reduction is increasing as a result of using denser battery.

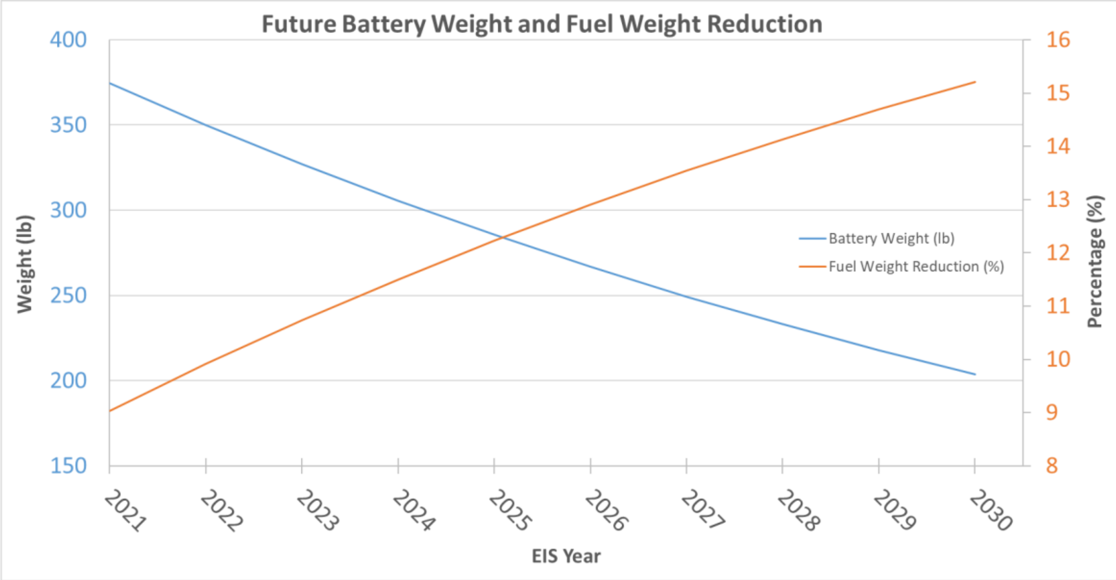

Fig 8 Relationship between battery weight and fuel weight reduction.

Figure 9, shows the relation between battery weight, represented as percentage of MTOW, and SAR increment, translated into improvement percentage.

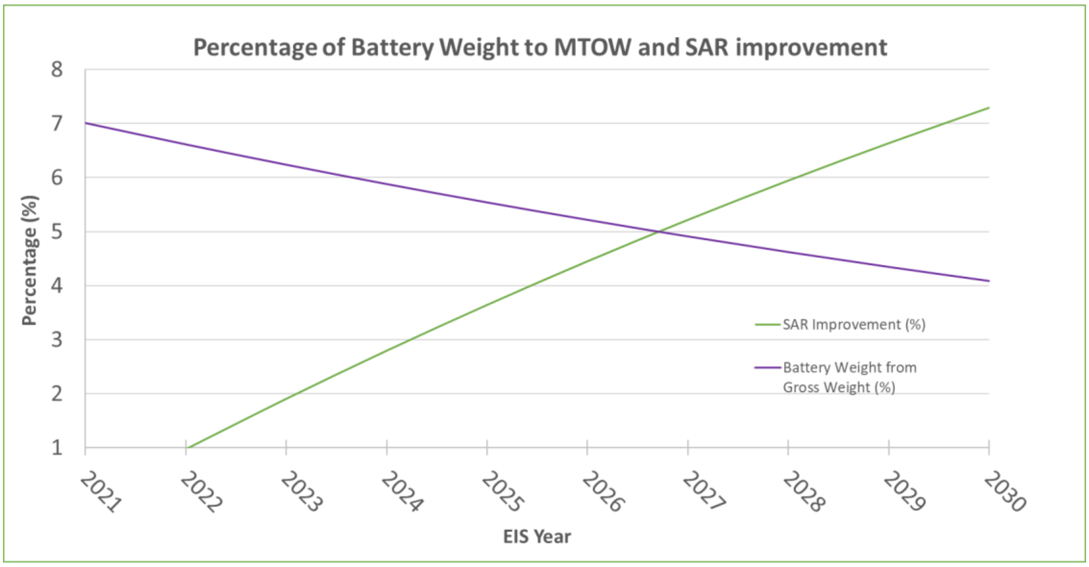

Fig 9 Relation between the percentage of battery weight from the gross weight and the improvement of SAR.

For 2030 production year, RAND DAPCA IV model is used to estimate the development and production cost of the hybrid aircraft. Results of the different calculated cost components are presented in Figure 10. The figure shows that the largest contribution to development cost will be from manufacturing and avionics components. The continuous decrease in electric engine motors and battery cost significantly decreases overall aircraft cost. Based on Figures 5 and 6, battery pack price was calculated to be $3314.

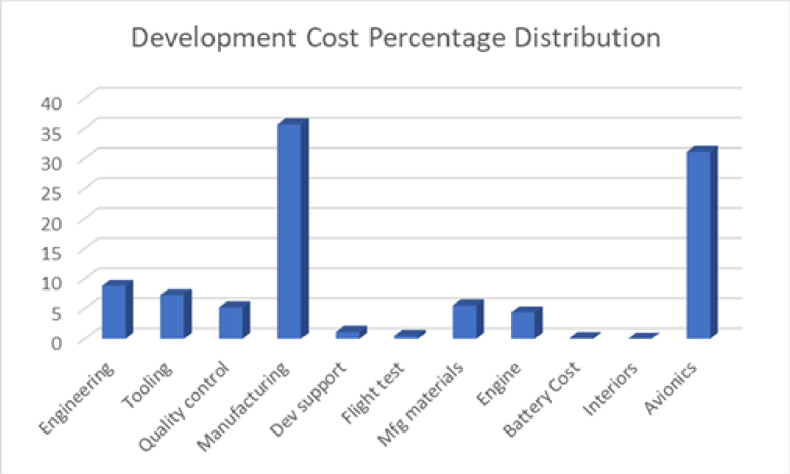

Fig 10 Distribution of development costs.

Figure 11 shows a comparison of the purchase price cost of the newly designed aircraft and existing competitors, corrected to 2030 estimates [21]. The breakeven point of this design is calculated is therefore calculated as 422 units.

Fig 11 Price comparison.

Finally, operations and maintenance costs for the modified hybrid aircraft are calculated using the previously described model. With future trend, values of charging cost $/kwh were calculated from US National Renewable Energy Laboratory (NREL) projection to be $0.04/kwh [22]. The proposed hybrid design O/M cost is found to be $346 per hour. Figure 12 shows that this value is about 20% less than the average value of the current four competitor aircraft of $430 per hour.

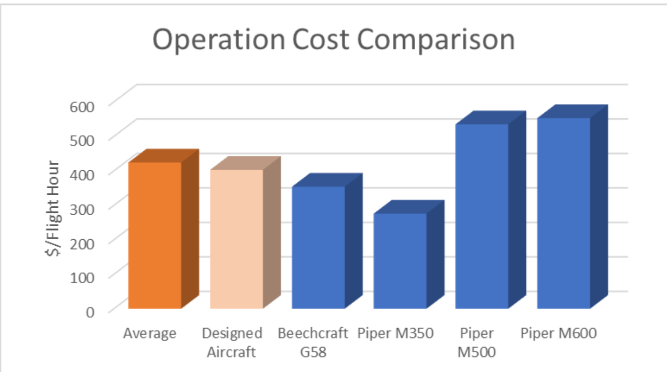

Fig 12 Comparison between Operations and Maintenance costs of proposed design and competitor aircraft.

4. Conclusion

Based on an initial design of 6-seater general aviation aircraft with range of 750 nmi, the feasibility of hybridization was investigated in the aspects of fuel consumption and cost. Lithium batteries were used to power an electric motor during taxi, take-off, and climbing. Depending upon the history of the development of lithium batteries and the prediction of other sources, this paper suggests an improvement of 7.5% in battery specific energy for the next decade reaching 575 Wh/kg in 2030.

In the initial design, the batteries weigh 374.34 lb using recent technologies. Using expected technologies in 2030, however, the weight of the batteries is expected to decrease to 203.62 lb comprising 4.09 % of the gross weight down from 7.01%. This reduction will lead to an increase in fuel saving from 9%, in 2021, to 15%, in 2030. This would imply an improvement of SAR up to 7.29% from 1.26 to 1.35.

A modified RAND DAPCA IV model was used to calculate the costs of production, operation and maintenance for a production of 500 aircraft to start producing as of 2030. The purchase price per aircraft was found to be $2.855 million dollars and was found to be within the current competitors pricing.

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