A Feasibility Research for Sustainable General Aviation

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Abstract. The General Aviation industrial is dedicated to create smaller aircraft, which can be accepted as personal transport vehicle. However, regulations on the noise and pollution limited the active range of the aircraft with conventional fuel power system. General Aviation provides an effective transporting method, which saves traveling time compare to the motor car; it can be design for sustainable and affordable. The research shows using near future technology, GA can be remodelled as a low nuisance, low emission sustainable aircraft. A fuel cell based propulsive system for GA is analysed to improve the system efficiency. The reliability of electrical power system is addressed to create a power converting process that reduce the risk. The feasibility research over sustainable design of GA shows zero emission fully sustainable general aviation is possible in the near future.

1. Introduction
In General Aviation (GA) companies like Cessna and Gulfstream created aircraft to help access to more communities in less time. Unlike the traditional commercial aircrafts, GA usually has a simple and smaller configuration that allows it portable to most airport. In addition, it flexible of flight can freeing people and products from existing transportation system delays. Those advantages allow the European Personal Air Transportation System to predict that the GA would be more attractive as a personal transport [1].

Conventional aircraft use the kerosene engine to produce power, this address the issues in noise and emission. The modern aircraft has improved their propulsion system to reduce it from the source [2]. In this paper a sustainable design concept based on Burt Rutan Long EZ configuration is introduced. A feasibility research over fuel cell based propulsion system and electrical motor in chapter 3 gives the technical evaluation of the GA performance.

The performance of the Long EZ with the electrical motor is analyses for cursing and take off abilities. By design a small, two-person small aircraft with sustainable method, not only reduce the emission and noise production from the aviation transport, but also innovating the general aviation.

2. Concept Definition for Sustainable
The original layout of Long EZ provides a great platform for personal aircraft; therefore overall canard configuration and aerodynamic design is not critical for sustainable design. Therefore the research is focused on the subsystems in the aircraft. The subsystems break down can create the design option tree. Then trade off from the performance, sustainability, reliability perspectives the design choice is made.
2.1. Design Option Tree
In order to reduce the emission, the direct method is to replace the energy resource from fossil fuel to electric. One of the alternations is to use batteries and electrical engine system and this method has been developed and applied on several different types of design [3]. In order to identify the critical design features from the different subsystems, the design option tree (DOT) is generated as figure 1 shows, and different technics from are competed with a trade-off.

![Design Option Tree](image)

2.2. Batteries System
To perform the trade-off a weight is given to each research field to take the importance of the different fields into account. For battery system, the cost and reliability are the two main factors to evaluate it operational abilities. These weights are determined to be 15% for the economic feasibility, 35% for reliability, 35% for sustainability and 15% for performance. The trade-off table concerning batteries is shown in figure 2.

This trade off shows that the Lithium ion batteries has the best specific energy and for the next generation this number can go up to 600 Wh/kg [4]. For reliability consideration, the discharge and charging of Lithium-ion gives a promising result.

2.3. Fuel Cell
Fuel cell uses electrochemical reaction to convert the power, which does not limited by Carnot cycle, the thermal efficiency can reaches 0.5 and beyond. On the market, there are mainly three different types of fuels cells PEM, SOFC and AFC. By apply the same trade-off method we can generate the result in figure 3 that PEM is the suitable option.
Different with the Lithium ion battery, PEM fuel cell use hydrogen and oxygen to produce electric power that does not rely on the internal active material, it has a longer durability and higher power density. The reaction process, which happened in PEM is shown in figure 4. The outcome from the reaction is nothing but water and the charging process is straightforward compare to the Lithium battery.

**Figure 2.** Trade-off for batteries.

| Criteria                  | Specific Energy | Production Cost | Operational Cost | Life Cycle | Material Availability | Battery Availability | Toxicity          | Complexity          | Discharge Rate | Charge Rate |
|----------------------------|-----------------|-----------------|------------------|------------|------------------------|-----------------------|-------------------|-------------------|----------------|-------------|
| Lithium-ion                | Low; 125 [Wh/kg]| Low; Widely     | Low              | Medium; 400-1200 cycles | Low/lithium production tested due to increasing demand | Widely available; contains some toxic materials | Medium | Good             | Good           |
| Next Generation Lithium    | High/medium; 500-600 [Wh/kg] | Slightly Old | Medium; overheating | High; Around 10,000 charges | Low/lithium production tested | Probably available by 2020; contains some toxic materials | Unknown yet | Simple | At least as good as Lithium | At least as good as Lithium |
| Lithium-Sulfur             | Medium; 300 [Wh/kg] | Medium | Low; disputed | Medium; lithium production tested but sulfur highly avail. | Still in development; contains some toxic materials | Slightly more complex | Unknown yet | Unknown yet |

**Figure 3.** Fuel cell trade off table.

| Fuel Cell Type | Specific Energy | Availability | Complexity | Operating Temp | Efficiency | Life Cycle [hr] |
|---------------|-----------------|--------------|-------------|----------------|------------|-----------------|
| PEM           | 0.97 W/cm²      | Available    | Average     | 50-100°C       | 60%        | >5000           |
| SOFC          | 0.15-0.7 W/cm²  | Stationary applications | Complex | 700-1000°C | 60% | 2000 |
| AFC           | 0.1-0.3 W/cm²   | Available, used in space | Average | 90-100°C | 50-60% | >2000 |

**Figure 4.** Fuel cell reaction.
2.4. Electrical Engine
The propeller of the GA aircraft can be driven by electric motors for safety reasons. The different options of these motors are shown in the design option tree. Here it is seen that four different electrical engines will be considered. The brush-less DC motor, the superconductivity engine, the brushed DC and the permanent magnet motor. Their trade off result shows in figure 5, from the result the brushless DC motor is consider the best option.

| Criterion Options          | Efficiency [%] | Power density | Production Cost | Moving Parts | Time to Market | Maintenance | Operational Cost | Complexity |
|----------------------------|----------------|---------------|-----------------|--------------|----------------|-------------|------------------|------------|
| Brushless DC               | 85-90          | Average       | Low; (due to Simplicity) | 1            | Existing       | Almost None | Low;             | Simple     |
| Superconductivity Motor    | >99            | Highest       | High (Low operating T required) | 1            | Not proven in flight | Normal     | High; (Cooling system is needed) | Very Complex |
| Permanent-Magnet            | 96             | High          | Low; (due to Simplicity) | 1            | Existing       | Almost None | Medium;          | Normal     |
| Brushed DC                 | 75-80          | Low           | Low; (due to Simplicity) | 1            | Existing       | Frequent    | High             | Simple     |

**Figure 5.** Electric motor trade-off table.

As the result of the concept definition of the sustainable remodel of the general aviation, the fuel cell base electrical propulsion system is reliable solution to counter the emission problem. The electrical motor with innovative propeller leaves a great challenge and opportunities for the designer, general aviation can beneficial from the technology trending in the near future [5].

3. Feasibility Research
The electrical propulsion system should provide equivalent amount of energy to support the performance of long EZ. Therefore power estimation relay on the original aerodynamic design is 108.9 kW [6]. To achieve this goal fuel cell stack is required to increase the power output. The method is to link multiple fuel cells in series as shown in figure 6. The bipolar plate in between the fuel cell will separate each fuel cell and a gas diffusion layer is used to spread the reactants over the membrane, allow the reactions are evenly distributed over the layers.

**Figure 6.** Fuel cell stacking.
3.1. Balance of Plant
To have the fuel cell stack operating properly on an aircraft, a Balance of Plant is required to determining and control the operating condition. Every subsystem with in the propulsion system requires a BOP. For a typical small aircraft, the subsystem contents BOP are:

- Air Management
- Hydrogen Management
- Water Management
- Thermal Management
- Enclosure
- Auxiliary Power Unit (APU)
- Electrical Subsystems
- Electrical Control Unit (ECU)

BOP act as key for the energy control on the aircraft, like other subsystems it requires energy to operate. By using Cycle-Tempo, energy consumption for the level of Long EZ aircraft is generated as 17.5kW. Recall the energy density of PEM, the current density for a maximum voltage of 0.7 volts is 0.6 A/m$^2$ [7]. A fuel cell stack with 192cell can generate 70kW energy, two stacks is capable producing enough energy of the aircraft.

3.2. Hydrogen Storage
Hydrogen storage tank adds a significant part of weight to the aircraft and in order to fit into the general aviation the volume need to be further limited. Taking Long EZ as an example, the pressure needs for the pressure tank is 700bar. The material for the storage tank can be a non-load-bearing composite structure to satisfy the structure weight, the typical weight for such cylinder is shown in table 1.

| Volume (L) | Pressure (bar) | Weight (kg) |
|------------|----------------|-------------|
| 1          | 55             | 700         | 40          |
| 2          | 108            | 700         | 66.2        |
| 3          | 129            | 700         | 92          |

3.3. Electric Motor
Unlike the reciprocating engine, fuel cell based electric motor has an extra step when convert energy to a rotational motion, and the longer power convert process is the less effective system is. The reliability of reciprocating engine can be calculate as the figure 7 shows.

![Figure 7: Reciprocating engine system.](image)

In the fuel cell based system, this process of generating DC current introduce an unreliable factor. Therefore, by arranging the fuel cell to two parallel parts would reduce the chance of total failure, which makes the system equivalently reliable as the reciprocating engine system. The existing electrical motor like UQM PowerPhase 220 can cope the continuous output power 120kW, the typical efficiency of this level motor is 0.95. The A two parallel fuel cell system reliability shows in figure 8 that the total system reliability is equivalent to the reciprocating engine system, and the efficiency is 10% higher.
3.4. Performance
A typical fly envelop for fix wing general aircraft, like Long EZ, contains eight different phase. In figure 9 shows the sequence of the different phases and the most important stages are the cruise and take-off which have a duration approximately 150 and 16 minutes.

\[ V_{opt} = \left( \frac{W}{S \rho C_L} \right)^{1/2} \]  

The propeller and fuel cell system can generate equivalent amount of power as the reciprocating engine and the fuel tank weight can be reduce with the composite structure, the take-off distance could be maintained with in 253m as before [8].

3.5. Layout
Combining the required subsystem into an aircraft with the size of Long EZ, the basic layout for a two seats fuselage is shown in figure 10.

Figure 8. Electrical motor system.

Figure 9. Fly envelop.

During the 16-minite take-off and landing, the power required equals 109.8 kW and 33.4 kW for both phases respectively. Since the cruising power is a function of the velocity and with the maximum cruising velocity consumes more power due to the induce drag force. The speed can be optimized with equation (1). With the fuel cell Long EZ can reaches 1200 km with speed of 60 m/s.
4. Conclusion

General aviation provides the promising small aircraft like Long EZ, which can carry people travel at maximum cruise velocity of 370 km/h through air. It saves the traveling time and require less needing for infrastructure. The study of fuel cell and electrical motor gives a sustainable design options for the small aircraft. Fly with the fuel cell can remove the emission from the engine and electrical motor system has a higher efficiency that reduces the operational energy cost. In the near future a sustainable aircraft, capable of flying more than 1000 km complying with safety standards is a feasible product for people.

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Figure 10. Layout for two seats.