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Electric Motor & Power Source Selection for Small Aircraft Propulsion

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ELECTRIC MOTOR & POWER SOURCE SELECTION FOR SMALL AIRCRAFT PROPULSION

In partial fulfillment of the requirements for the
Degree of Master of Science in Technology

A Directed Project

By

Jeremy Fehrenbacher

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Electric Motor & Power Source Selection for Small Aircraft Propulsion

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SECTION 1. INTRODUCTION

The research conducted in this project is on electrical propulsion in aviation. A Cessna 172K aircraft with a Lycoming O-320-E2D piston engine serves as a baseline measurement. Investigation of the components required for electrical flight is performed, and components are selected based on market availability and operational performance criteria.

1.1. Research Question

This research focuses on electrical propulsion in the aviation industry, and is tailored to aircraft within the General Aviation sector leading to the following research question: Can current electric motor and battery technologies conceptually support flight operations for a Cessna 172K in terms of aircraft performance criteria?

1.2. Scope

The area of interest for this research is electrical propulsion in single engine small aircraft. Specifically, this project examines the correlation of currently available electric motor and battery technology to the power requirements of the Cessna 172K, such as the output power required at takeoff and cruise. These are situations in which high amounts of output power are required. After an in-depth survey of currently available equipment for each of these technologies is conducted, the research determines multiple options to each technology. The options are weighed utilizing tools such as a Pugh matrix, and the most viable option for each particular technology is selected. Figure 1 demonstrates the scope of this research. The physical application and testing of this research is limited due to the lack of funding. The expense of the power storage and electric motor is far too great for the researcher to purchase, thus this project is purely a hypothetical application of an electrical propulsion module.

There are factors that limit the adoption of electrical propulsion for flight. A means of powering an aircraft with electric propulsion becomes irrelevant if the fuel or other requirements to operate the motor are unavailable or unreasonable to be utilized by the general public.

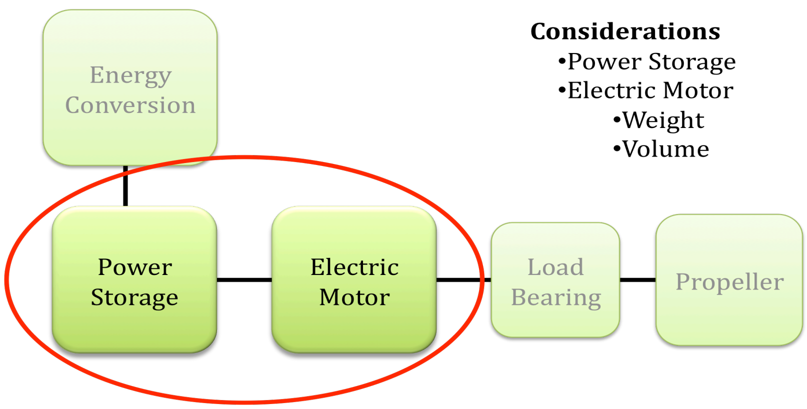

Figure 1. Scope of Considerations

1.3. Significance

Electrical propulsion in aviation has struggled to evolve despite the significant advances in motor and battery technology, as the aviation industry is highly regulated by the Federal Aviation Administration and change within the industry is traditionally slow. Piston engines are some of the most efficient internal combustion engines; however, the electric motor has the potential to reach efficiencies of up to 80-90%. The electric motor power output is relatively unaffected by altitude, temperatures, and humidity factors which significantly impact the power output of an internal combustion engine. The internal combustion engine decreases in efficiency and reduces horsepower output when altitude is increased.

1.4. Statement of Purpose

Research into propulsion within aviation has frequently focused on incrementally improving older technologies. To gain a higher performance out of a propulsion module, engine manufacturing companies have increased piston size, the piston count, and have included turbo and superchargers. While this approach results in technological advances in aviation, repeatedly bandaging a problem will never ultimately solve the greater dilemma of engine inefficiencies. A need for an alternative propulsion module has arisen as manufacturers are nearing a maximum efficiency, at approximately 35-40%, in regards to aviation engines. Limiting the engine market even more is the Environmental Protection Agency (EPA), which has threatened the prohibition of current leaded aviation fuels due to the potential for the heavy metal to pollute ground water. The lead in some piston engine aviation fuels is required to maintain proper engine operation. Removing this additive will cause many aircraft not to be operable. In places, such as Alaska where there are sixteen times more planes per capita than the rest of the county (Friedman, 2010), operating aircraft is a requirement and a means of living.

1.5. Definitions

EDLC: (Electric Double-Layer Capacitor): An ultracapacitor, or "super-capacitor", stores energy electrostatically by polarizing an electrolytic solution. Though it is an electrochemical device (also known as an electrochemical double-layer capacitor) there are no chemical reactions involved in its energy storage mechanism. This mechanism is highly reversible, allowing the ultracapacitor to be charged and discharged hundreds of thousands of times. An ultracapacitor can be viewed as two non-reactive porous plates suspended within an electrolyte, with a voltage applied across the plates. The applied potential on the positive plate attracts the negative ions in the electrolyte, while the potential on the negative plate attracts the positive ions. This effectively creates two layers of capacitive storage, one where the charges are separated at the positive plate, and another at the negative plate (Maxwell Technologies).

EMF: (Electromagnetic Force): The fundamental force that is associated with electric and magnetic fields and is responsible for atomic structure, chemical reactions, the attractive and repulsive forces associated with electrical charge and magnetism, and all other electromagnetic phenomena (www.dictionary.com, *Electromagnetic force*).

E-Rev: (Electric-Range Extended Electric Vehicles): Extending the operational range of current electric vehicles requiring high output and high efficient generators (Raser Technologies, n.d.).

FAA: (Federal Aviation Administration): FAA's continuing mission is to provide the safest, most efficient aerospace system in the world (Federal Aviation Administration, 2010).

Fuel Cell: A device that produces a continuous electric current directly from the oxidation of a fuel (www.dictionary.com, *Fuel cell*).

HTS: (High Temperature Superconductor): a phenomenon observed in certain metals and ceramic materials that, when cooled to very low temperatures, have no electrical resistance (DOE).

MCFC: (Molten Carbonate Fuel Cell): fuel cell that uses high-temperature compounds of salt carbonates (Garrison).

PEMFC: (Proton Exchange Membrane Fuel Cell): a fuel cell that works with a polymer electrolyte in the form of a thing, permeable sheet (Garrison).

Pugh Matrix: The Pugh matrix is a tool used to facilitate a disciplined, team-based process for concept selection. Several concepts are evaluated, comparing their strengths and weaknesses against each other, to arrive at an optimum solution. The Pugh matrix encourages comparison of several different concepts against different criterion and is a useful tool because it does not require a great amount of quantitative data on the concepts(Parial; Parial).

SOFC: (Solid Oxide Fuel Cell): a fuel cell that uses a hard, ceramic compound of metal oxides as electrolyte (Garrison).

Operational Performances: This paper defines operational performances as the aircrafts' airspeed, payload, range, takeoff/landing distances, and climb rate.

VFR: (Visual Flight Rules): Rules that govern the procedures for conducting flight in visual conditions. The term "VFR" is also used to indicate weather conditions that comply with specified VFR requirements(NASA Quest).

1.6. Assumptions

- It is assumed, for the sake of research, that the manufacturers and leading electric motor research teams will provide the researcher with operational and power output information regarding their respective motor technologies.
- The assumption is made that the leading market electrical storage/producing teams will provide sufficient information regarding their technologies and the respective company's potential for supporting this project.
- Controlled variables (CV) in this study include humidity, altitude/air density, temperature, wind directional and velocity, barometric pressure and air viscosity. These controlled variables operate at standard day conditions. NASA defines standard day conditions as follows (NASA, n.d.):
    - Humidity: H = 0%
    - Altitude: a = Sea Level
    - Air Density: r = 0.00237 slug/ft^3
    - Temperature: T = 59^{o}F
    - Barometric Pressure: p = 14.7 lb/in^2
    - Wind Velocity: V_w = 0 mph (constant)

1.7. Limitations

This research considers only technology that is currently available to the market. Until a product is officially on the market, it is not to be assumed as a viable option for electrical propulsion in this research. During the course of this study, it is expected that battery technology and power storage devices are becoming significantly more efficient on a monthly basis.

The second factor that will not be taken into account for the purpose of this research project is the electromagnetic force created by the electric motor. It is assumed that avionic shielding or motor grounding to the aircraft has the potential to prevent disturbances by any electromagnetic force created during the operation of the electric motor.

The selection of the electric motor is dependent upon the operational demands of the propeller. As the conventional constant speed propeller operates through oil supplied from the engine, an alternative actuating method must be utilized. Electrically actuated propellers are readily available to the market through such companies as MT-Propeller. The second motor limitation derived from the propeller is the propeller rotational speed. Typical constant speed propellers can operate up to approximately 2700 to 2800 rpm. If the electric motor makes peak efficiency above this rpm, the motor might need to be gear reduced through a transmission before entering the propeller system. Otherwise, the propeller blade length will need to be reduced. The blade length must be reduced because otherwise tip speeds of the propeller would reach supersonic speeds and would create more drag than forward thrust.

The limitation to the duration of flight is the power storage device. With an increase in power storage, a larger supply of electricity to the electric motor is available and thereby increases the duration of flight. The limitation to large quantities of power storage devices, however, is the physical space and weight available onboard the aircraft. Thus, a significant limitation to a flight's duration is the space and weight available onboard the aircraft.

1.8. Delimitations

A small aircraft in this research paper is defined as aircraft approximately the size and power of the Cessna 172K utilizing a Lycoming O-320-E2D engine.

The area of interest for this research project is primarily focused on the side-by-side comparison of the required horsepower and torque output of the O-320-E2D piston engine versus the market available electric motor technology. This research also takes in to consideration the limitations of altitude and environmental changes that cause power deviations upon the piston engine. The paper also includes a qualitative section detailing the pros and cons of the electric motor technology in regards to aircraft propulsion.

An additional item of research references the electrical storage technology capable of supporting operations for the electric motor. This is important, as the power storage device is assumed as being the limiting factor for electrical propulsion in aviation. Additionally, heat dissipation may prove to be a limiting issue in the physical placement and configuration of the electrical storage device. Proper heat dissipation should be found by testing configurations and measuring the total input and output temperatures. As this project is purely hypothetical, no products are being purchased for this testing.

The research that is performed in this project does not include design issues regarding aircraft thrust production, such as the use or experimental development of a ducted fan technology, or propeller/compressor advanced designs.

1.9. Summary

The push for alternative propulsion modules is due primarily to depletion of unsustainable fuels. Having the potential to meet current horsepower requirements while being commercially available, electrical propulsion is one option to improve the sustainability of aviation. Electric motors provide a “Green” option to flight as power can be generated from sources such as solar and wind. The benefits of electric motors also include instantaneous torque and silent operation. The study in this paper theoretically replaces the Cessna 172K engine with an electrical propulsion module.

SECTION 2. LITERATURE REVIEW

2.1. Introduction

Aircraft electric propulsion is not a new, groundbreaking concept. The idea of an all-electric air vehicle has been researched and implemented since the mid-70's (Newcome, 2004). Electric propulsion offers many positive effects for the aircraft, aircraft owner, and the environment of operation. From the accumulated literature review, it may be found that there is a substantial interest in the field of alternative propulsion within the aviation market. NASA, being the primary sponsor in this research area, has published multiple papers on the electrical propulsion topic. This review covers topics of electric motor integration into aircraft, fuel cell applications, motor technology, the benefits of electrical propulsion, the limitations to electrical propulsion in aviation, and an explanation of the use of Pugh matrices for this project.

2.2. Research

Research, being conducted at multiple prestigious universities and government affiliates, has proven the capabilities of electrical propulsion within aviation. In depth, sophisticated motors have been developed and proved sufficient efficiencies. A study conducted by NASA affiliates has provided a relatively reasonable comparison of a High Temperature Superconducting (HTS) motor in comparison to current Cessna 172 engine capabilities. The Cessna, operating at 2700 RPM and 200HP, weighs 160 kg (~353 lbs), while the developed motor produces 220HP at 2700 RPM and weighs 28kg (Masson & Luongo, 2005).

The Glenn Research Center is in the midst of developing a magnetically levitated ducted fan. This integrates the efficiency of the electric motor, while optimizing the thrust output with the ducted fan. This technology is beneficial, and applicable, to electric motor propulsion as it utilizes the motor for propulsion and reduces bearing friction drag, which can be a substantial system limiter (Emerson, n.d.).

Aircraft design is also a major consideration with the introduction of electric motors. The University of Notre Dame and Nanjing University of Aeronautics and Astronautics collaborated to investigate the needs of such an aircraft for subspace operation. The group designed an intricate framework for electric-powered unmanned aerial vehicle. Though this article primarily relates to aerospace dynamics, several parts are relevant to electric motor system design in which multiple variables were identified and analyzed. The paper contains a significant amount of information that could potentially increase the knowledge base of those who wish to implement an electric motor into an aircraft application (Batill, Stelmack, & Qing Yu, 1999).

Another application of the HTS motor is coupled with a high efficiency ducted fan in another IEEE article. HTS motors are efficient enough to provide power to the aircraft, but the primary question at that point is, how to change that energy into forward propulsion. A logical solution to this inquiry is the utilization of ducted fan technology. As this introduces another variable to the research, the author did not address this topic. However, this conjoined technology has enough potential to operate and support a jumbo-sized aircraft (Masson, et al., 2009). This potentially could prove the theory of electrical propulsion coupled with ducted fan technology within the Very Light Jet (VLJ) sector of aviation.

The negative for these motors, however, is the usage of HTS technology. Though extremely efficient, the motor requires deep, cryogenic cooling. This, in turn increases weight, complicates the system in terms of maintenance, and reduces the total power output, as the motor must also operate the cooling agent.

Since the electric aircraft is a relatively new market outside of ultralight aircraft, few standards exist for the industry. Currently, ASTM International, formerly known as the American Society for Testing and Materials, is developing such standards. ASTM International is a world respected organization which develops standards for every aspect of engineering and manufacturing. ASTM's committee F37 is focused on light sport aircraft, and is examining required standards for the development and production of all-electric aircraft.

In 2011, the FAA will examine the necessary standards and regulations needed for electric flight. The FAA has been quoted saying, "This is all in the beginning stages. Our approach is to have the companies and industry prove the technology first and establish that the technology is viable under ASTM standards. Then the FAA will examine how we will accommodate the aircraft from the regulatory and/or policy side" (Coppinger, 2010).

Other entities such as Flight Design, an aftermarket, light-sport aircraft modifier originating in Europe, and the European Aviation Safety Agency (EASA) have also expressed the urgency of developing standards for an all-electric aircraft stating, "Sometimes people are asking for this [the certification of an electric engine], we have some companies in mind. We are open minded to new technology as long as they are safe enough" (Coppinger, 2010).

Currently, an industry-respected entity has begun developing guidelines for a "green" aircraft by developing a challenge. The CAFÉ Foundation is a non-profit organization focused on advancing personal aircraft technology through means of research and education. Originating from EAA Chapter 124 in Santa Rosa, California, the organization has continually challenged the industry by developing competitions. From these competitions, CAFÉ has developed hardware, charts and software improving the technological industry of General Aviation operators. Some of the developments include new barographs and more efficient flying technique (CAFE Foundation; Story).

CAFÉ has developed flight test equipment and software packages known as CAFÉ 400 that record the following environmental factors:

1. Aircraft speeds
2. Aircraft weight
3. Ambient temperatures
4. Ambient pressures
5. Frequencies, and

6. Sound levels

This software package has been a prominent asset recognized by organizations such as Aircraft Owners and Pilots Association (AOPA), Experimental Aircraft Association (EAA), and National Aeronautics and Space Administration (NASA) (CAFE Foundation; About).

Most recently, they have developed the Green Flight Challenge, which is a $1.65M NASA-funded contest, promoting more efficient fuels and propulsion units within General Aviation. The contest will take place on July 11-17, 2011 in Santa Rosa, California. In this paper, certain standards from the CAFÉ competition are being used as a mission profile, which can be found in the Methodology section(CAFE Foundation; Green).

2.3. Fuel Cell Integration

Multiple analytical assessments of fuel cell integration within the aviation market have proven beneficial to the industry. The main categories of fuel cells with possible applications for aviation include: Proton Exchange Membrane (PEM), Alkaline, Direct Methanol, Phosphoric Acid, Molten Carbonate, and Solid Oxide. While all of these fuel cells offer individualistic characteristics that are beneficial in specific situations, they each are associated with their disadvantages, as well. PEM fuel cells, being the most prevalent in the automotive market, offer a significantly low operating temperature (80^{o}C) in comparison to the other fuel cell configurations, but require the use of platinum and an extravagant water management system. At the other end of the spectrum, Solid Oxide fuel cells operate between 800-1000^{o}C, but utilize nickel instead of platinum, and can provide efficiencies up to 85-90% efficient (aviation's current, most efficient mode of power generation derives from piston engines at approximately 45% efficiency (Revankar, 2009).

In 2003, NASA once again published an article in regards of alternative propulsion within aviation. NASA assessed the potential of a fuel cell-powered, electric aircraft utilizing the Proton Exchange Membrane fuel cell. This research found that flight could be made with this fuel cell in a very light aircraft with restrictions and reductions on rated speed, climb rate, range, and payload-carrying capability. Also, notable in this article, it is stated that heat management, hydrogen production, and airport storage of hydrogen are continuous dilemmas of this operation (Berton, Joshua, & Timothy, 2003). Hydrogen, possessing explosive characteristics, poses an economical threat, as the element is not readily found in nature. The hydrogen must be isolated from compounds, which is a process that involves poor efficiencies and a high-energy loss.

On the other hand, Solid Oxide fuel cells do not require hydrogen to operate. This fuel cell becomes more efficient as the temperature rises, and produces hydrogen naturally as a by-product of the natural gas fuel that it utilizes. Another article from the American Association for the Advancement of Science (AAAS) illustrates the potential of using a commonly used hydrocarbon as the primary catalyst within a solid oxide fuel cell. Utilizing a high-octane fuel (specific octane number not given), the research group was able to produce a ~0.6W/cm^2 output at

770°C. In comparison, operating with the common natural gas with internal reforming, efficiencies can reach peaks of 1.1 to ~1.2W/cm^2. Outputs of this magnitude appear very significant, as with an octane-based catalyst, the system contains few moving parts, fewer endothermic reactions near the fuel inlet, and a more readily available fuel source for operation (Zhan & Barnett, 2005).

2.4. Applicable Motor Technology

Motor technology has been a key factor in the limitation of aircraft operations with an electrical powerplant structure. Recent developments have altered these limitations, however. Though HTS motors are capable of producing a significant power to weight ratio, as demonstrated by Masson and Luongo (Masson & Cesar, 2005), major drawbacks in consideration for cryogenic operations prevent the use of this technology in aircraft, at the present time.

Electric motors have advanced in the last several decades. Electric motors now have the capabilities to reach more than 500 horsepower and can directly compete with the internal combustion engine. There are many options when selecting an electric motor that are all application dependant (i.e. AC vs. DC, single vs. multi phase, brush vs. brushless, etc).

For an electrical propulsion application, this considers the following motor characteristics:

1. Direct Current (DC)
2. Brushless
3. Pancake Configuration

The first choice for optimal electric flight is Direct Current (DC) over Alternating Current (AC). Table 1 compares the positives and negatives of each system.

Table 1. AC/DC Motor Comparison

	AC Motor	DC Motor
Pros	Higher Torque/Horsepower Capabilities	Less Rotor Heat
	No Permanent Magnet	Wide Spectrum of Optimal Power Setting
	Magnetic Field Strength Adjustable	No Efficiency Losses due to DC to AC Conversion
	Cost Advantage	
Cons	Optimal Power Factor: 85 percent	Permanent Magnet Expensive
	Cumbersome to Control	

DC motors require at least two permanent magnets that generate a magnetic field, whereas the AC motor has no magnets but stacks of steel laminations with secondary conductors. These permanent magnets cause the construction of the DC motor to be more expensive than the AC motor. The DC motor, however, can operate uniformly across a wider spectrum of power settings, while the optimal power setting for the AC motor is approximately 85 percent of the motor's total capability. Even though the AC motor has a cost and a maximum torque advantage over the DC motor, the efficiency loss of converting the DC battery power to AC current for an aircraft application is a primary reason that a DC motor is selected for this project (Rippel, 2007).

Single phase vs. multi phase construction are characteristics of an AC induction motor. In this study, a DC motor has been selected, so these phase characteristics are not applicable to the paper. The DC motor has a brushed vs.

brushless construction. Table 2 compares the positives and negatives of each system.

Table 2. Brushed/Brushless Motor Comparison

	Brushed Motor	Brushless Motor
Pros	Simplicity of Control	Less Maintenance
	Simplicity of Maintenance	More Controllable Speed/Torque Settings
	Lower Cost of Construction	No Voltage Drop Across Brushes
	Simpler Control Unit	High Output Power
	Extreme Environmental Operation	Small Frame Size
		High Speed Range
		Low Electromagnetic Forces
Cons	Higher Electromagnetic Force	High Cost of Construction
	Poor Heat Dissipation	Complexity/Expense of Control Unit
	Continuing Maintenance	
	Lower Operating Speed	
	Speed/Torque Less Optimized	

The brushed motor offers a simplicity factor over the brushless motor due to the fact that a brushless motor requires three phases of driving coils, one or more Hall effect sensors to detect rotor position, and an external rotor. An advantage of the brushless motor over the brushed motor is lack of touching parts. The brushed motor contains carbon blocks that transfer power to the commutator on the spinning rotor. These blocks wear out, induce friction heat, reduce the overall operating speed of the motor, reduce the useful torque, require periodic maintenance of these brushes, and cause arcing which leads to electromagnetic interference (Dynetic Systems). For these reasons, a brushless DC motor is the motor chosen for the paper.

The choice of a pancake motor over a conventional motor is due to the nature of the motor's physical dimensions. Size is a factor due to aircraft cowling size. A pancake motor would be an optimal choice; however, this is not a requirement. The requirement is that the motor physically fits within the aircraft engine compartment.

Based on the selection criteria, DC, brushless motor is narrowed down to the following alternative motors:

1. Raser Technologies: G-100 Generator
2. Lange Aviation: EA42 Electric Motor
3. Tesla Motors: Roadster Motor
4. U.S. Hybrid: HPM 450 Motor

Another leader in electric motor technology is the Baldor Electric Company. Baldor is a self-proclaimed, "leader in energy efficient electric motors, linear motors and adjustable speed drives"(Baldor Electric Company; Products). This industry-respected entity provides well over 300 DC motors ranging from 0 horsepower to 500 horsepower. While the supplied horsepower is quite adequate for the Cessna 172K, the motors are not designed for transportation applications. For example, without a controller, the 150 horsepower D50150P-BV motor has a shipping weight of 1519 lbs and a price tag of $40,284 (Baldor Electric Company; Product Overview). These motors prove to be not viable for an aircraft application at the present time.

More recently, however, an innovative, Utah-based company has created an efficient alterative to the current reciprocating/piston engine powerplants. The company, Raser Technologies, has developed a motor that weighs 172 lbs, creates greater than 406 ft-lb of torque, and a 134 continuous horsepower output with a ~161 peak horsepower, all of which is condensed to a 9.5 x 13.5 inch housing (Raser Technologies, n.d.). This motor has been designed for the purpose of integration into Hummer H3 E-Rev applications; however, the motor is not necessarily limited to this application. The company has focused primarily within the automobile industry; however, they have shown an interest in advancing into other markets including, but not limited to, aerospace. After extensive conversations with the company, the evidence is quite clear that the company has interests, but a lack of understanding of aviation market/ requirements. Should Raser Technologies begin research and motor application into several aircraft test beds, the potential for electrical propulsion could be beneficial to both industries.

Lange Aviation GmbH is a German company that has developed the fully-electric self-launching Antares 20E sailplane. While this aircraft is not an equivalent of the Cessna 172K, it is one of the only commercially available fully-electric aircraft in the industry. This paper analyzes the 42kW electric motor employed on the aircraft in the motor selection Pugh matrix.

The next motor analyzed in the motor selection Pugh matrix is the Tesla Motors Roadster motor. The Tesla Roadster is a fully-electric automobile and not an aircraft, but it still commercially available. The motor, controller, and battery system have proven viability as these products have been utilized in over 1,500 Tesla Roadsters that have been manufactured in the last three years(Tesla Motors).

The last motor in consideration is the U.S. Hybrid HPM 450 motor. Founded in 2000, U.S. Hybrid specializes in the design and manufacturing aspects of power components for vehicles requiring high amounts of electrical power. U.S. Hybrid has developed two motors applicable to aviation that include the HPM 450 and the HPM 1000. While both motors share similar characteristics including maximum power, input voltages, and efficiencies, the HPM 450 is more applicable to the Cessna 172 aircraft due to the motor's higher torque and lower rpm. The HPM 1000 motor is approximately 66 lbs heavier than its counterpart, and both of the motor's 2500 rpm matches the propeller used on the Cessna 172. (U.S. Hybrid International). U.S. Hybrids has recently developed an electric motor system for Sikorsky, a subsidiary of United Technologies Corp. In July of 2010, Oshkosh, Wisconsin, a network of Sikorsky employees known as Sikorsky Innovations developed the proof of concept helicopter, Firefly. The team replaced the internal combustion components of a S-300C™ with a U.S. Hybrids motor and Gaia battery system (Sikorsky, 2010).

2.5. Applicable Battery Technology

Whether referencing automobile or aircraft, battery technology is commonly considered the greatest limitation to electrical propulsion. In recent years, battery technology has steadily improved. With the development of the lithium-ion, the battery industry was revolutionized. Since that time period, variations of the Li-ion battery have produced some varied results.

Popular Science provides the following explanation of Li-ion technology and Li-ion advancements:

> Li-ion batteries work by transferring lithium ions between a cathode and an anode through a liquid electrolyte. The capacity of a battery is determined by the number of ions it can contain and how quickly those ions can be exchanged. Silicon is an ideal material for anodes because it allows lithium ions to pass in and out of the electrode very quickly. But the expansion and contraction of silicon particles as the ions enter and leave degrades the silicon in short order, ruining the battery. Instead, nearly all li-ion batteries contain graphite anodes that can withstand repeated charge cycles. *(Dillow, 2010)*

While lithium-ion batteries are not the only selection available for electric flight, they do pose the largest electric capacity to weight ratio than any other electrical storage solution. For a complete analysis of available battery solutions, see Appendix A.

Lithium-ion batteries do pose a problem in aviation. On February 7, 2006, a United Parcel Service (UPS) DC-8 aircraft, Flight 1307 reported a cargo smoke indication. Instead of proceeding on to the Atlanta, Georgia destination, the crew landed at Philadelphia International Airport and evacuated the aircraft. Soon thereafter, the aircraft became engulfed in flames. After referring to similar incidences in 1999, 2004, and 2005, the National Transportation Safety Board (NTSB) reported that the primary factor of the fire were the lithium-ion batteries in the cargo hold (Hilldrup, 2006). As the aircraft climbs, the ambient pressure changes with altitude. Lithium-ion batteries, stored in unpressurized portions of aircraft, much like that of the UPS flight, overheat with these pressure changes and can even cause surrounding materials to ignite. It should be noted that lithium-polymer based batteries do not have similar characteristics, and thus are still in consideration for electrical storage onboard aircraft.

2.6. Aircraft Integration

The most prevalent form of electrical propulsion within aviation occurs within the sailplane sector. Both Pipistrel and Lange Aviation have created aircraft that are capable of flying significant distances on electrical power due to their light weight airframe and the aircrafts' low amount of drag. A major drawback however is the cost to provide power. Whether utilizing a battery, fuel cell, or ultra capacitor, the price of the item is greater in comparison to the current fuel supply. Aviation gasoline is capable of producing approximately 6.0 kW/lb of fuel, whereas lithium-ion batteries are the next most efficient source of energy at a miniscule 0.25kW/lb of fuel (Collum, 2010).

More recently, companies such as Lange Flugzeugbau, have integrated existing electric propulsion modules with sailplanes that can give an accurate estimate of current motor technology in reference to operational performances. With a maximum weight of 1455 lb, the aircraft is capable of a maximum climb rate of 866 ft/min on a 42kW/57 horsepower DC brushless motor with a 1700 RPM (European Aviation Safety Agency, 2006). Relating this horsepower to the previously mentioned Raser Technologies motor, it becomes evident that research needs to be conducted with a larger scale aircraft using current power supplies.

More recently, however, Boeing has entered the market with a world-first fuel cell powered aircraft. The aircraft, Diamond Dimona, is a motorglider that made its maiden voyage in early 2008. The aircraft is capable of reaching 63 mph for at least 20 minutes (Boeing, 2008).

Competing directly alongside of Boeing is the Italian aircraft, SkySpark. The completely battery-powered aircraft is capable of reaching speeds up to 154 mph on a 75 kW brushless motor and lithium polymer batteries (Grady, 2009). The aircraft affiliates, consisting of Digisky and Turin Polytechnic University, now are working together to create a hydrogen fuel cell aircraft and a solar-powered airplane.

One of the more recent developments in electrical propulsion is an experimental electrically powered aircraft coupled with hover capabilities at NASA. NASA's Puffin aircraft would be capable of cruising at 149 mph with a top speed of 298 mph. With a theoretic range of 80 kilometers, the motors have the capability of propelling the aircraft and single pilot with just 60 horsepower (Barnstorff, 2010).

Bye Energy is committed to the commercialization of alternative energy technologies. Creating a Strategic Advisory Council, Bye Energy focuses on alternative aviation biofuels and electrical propulsion. In November of 2010, Bye Energy announced their newest project, an electric Cessna 172. Bye Energy is utilizing a 40 to 45 pound electric motor to gain approximately one hour's worth of flying time in Phase 1. The company will then initiate Phase 2, which is the implementation of a six-bladed propeller, solar panels, and regenerative circuitry increasing the Cessna's flying time to approximately two hours(Trescott, 2010). This project adds evidence supporting the viability of a fully-electric Cessna 172 aircraft.

Most recently, Yuneec International, a Chinese company, has developed the Yuneec e430 twin seat, single engine electric aircraft. Designed for the Light-Sport Aircraft (LSA) class, this fully-electric aircraft has a potential flight time between 1.5 to 3.0 hours, depending on the configuration of the aircraft. Expecting to be commercially available in 2011, the e430 will have a price tag of $89,000 USD. The aircraft specifications can be found in table 3 (Yuneec International, 2010)

Table 3. Yuneec e430 Specifications (Yuneec International, 2010)

Yuneec e430 Specs			
General		**Batteries**	
Seat Quantity	2	Type	Li-Po
Empty Wt w/ Batteries	561 lbs	Weight	184 lbs
Useful Load	385 lbs	Voltage	133.2V
Flight Time (hours)	1.5 to 3.0	Amperage	100 Ah
Motor		**Flight Characteristics**	
Output	40 kW 54 hp	Maximum Speed	95 mph
		Cruise Speed	60 mph
Size (diameter)	9.45 in	Glide Ratio	24:1
Weight	42 lbs		
Controller Weight	15.4 lbs		

2.7. Benefits of Electric Propulsion

The application of electric motors in aviation introduces multiple benefits to the industry. Electric motors have the potential for 95% efficiency. In comparison, the internal combustion engine may operate at approximately 18-23% efficiency (Choi, 2010).

From an audible standpoint, at 150 meters, electric motors typically operate at peaks of 50 decibels, which may roughly be compared to the volume level of a conversation. Currently, flight operations are heavily regulated during hours that may affect surrounding neighborhoods. As some airports are technically a public domain, the citizens surrounding the airport have an input on the operations. Thus, as many aircraft produce noise that may be found undesirable to some, airplanes must sometimes follow a strict fly/no-fly schedule.

Another major factor is that motors produce significantly less heat than do internal combustion engines. This dramatic reduction in thermal heat may reduce an aircraft signature, thus improving pilot and aircraft safety while operating in hostile territories (Choi, 2010).

Electric propulsion systems are beneficial in the sense of maintenance. With currently utilized engines, the systems are a conglomerate of multiple moving parts, heat controls, fuel controls, starters, all of which require maintenance. With electric motors, the only systems required for operation are the throttle, batteries, a controller and a motor. This reduces the required overall moving parts, thus fewer bearing replacements, fewer controls, fewer wear points, and a reduction in the potential for system failure. Also, even though engines may be identical makes and models, each engine operates differently from each other, thus the controls, gauges, and computers must be added to the system to maintain synchronous operation. In contrast, with proper circuitry, a single voltage regulator can control multiple electric motors. Thus, electric motor operation reduces the required amount of controls, gauges, and computers. Motors are simplistic in operation relative to engines. Once again, as the applied voltage is the only variable introduced into a system to regulate the operation of the motor, the only required component is a throttle control. This, once again, reduces the required systems for engine operation, reduces the potential for failure, and reduces the overall cost of the system in terms of both maintenance and initial investment.

Unlike combustion engines, where the efficiency of the system is impacted by fuel input, altitude, humidity, air temperature, aircraft speed, and other atmospheric conditions, the electric motor generates rated power throughout a relatively wide range environmental changes. This can be accomplished due to the fact that the motor operates the same throughout the variety of environmental changes that occur during flight. The motor is a closed system that does not consume air, thus the variables mentioned at the beginning of this paragraph do not have an effect on the motor.

Multiple other factors promoting electric integration in comparison to current internal combustion engine technology include improved reliability, improved safety, and a lower overall cost in terms of initial purchase and operation. Electric propulsion is, in comparison to internal combustion engines, cleaner, economical, and has the wider horizon for innovative technology (Bye, 2009).

Finally, the major push for alternative propulsions is due to the lead emissions issue within the aviation industry. The fuel utilized in some aircraft applications still requires a lead additive to prevent the engine from detonating. The tetra ethyl lead (TEL) is used to increase resistance to detonation, and allows for a higher compression. With this lead additive, however, the FRIENDS OF THE EARTH, an world respected progressive environmental advocate organization, have petitioned the Environmental Protection Agency (EPA) to force an elimination of lead found in the atmosphere is caused by aviation(FRIENDS OF THE EARTH, 2006). This will cause the airline market in extreme conditions where airplanes are the only mode of transportation, such as Alaska and Hawaii, to suffer and even potentially destroy markets.

2.8. Reasons for Delay

A primary issue regarding the market delay in the integration of electric motors within aviation is partially due to the lack of power supply technology. While companies such as EEStor have utilized advanced ultra capacitor technology to supply a great amount of power in comparison to weight, few cutting edge power supply technologies have emerged for public application. EEStor, for example, have supposedly developed an innovative ultra capacitor system capable of supplying power for hours of electric motor use, however all of their work has been very secretive and has been purchased by government affiliated companies such as Lockheed-Martin (Vanbebber, 2008).

Lead-acid batteries continue to be extremely heavy in comparison to other battery technology; however, lithium-ion batteries are relatively expensive and are reportedly harmful for the environment to even manufacture. Ultra capacitor technology, while having a typical three to five minute charge time and light weight, introduce maintenance hazards such as electrocution and consume four to five times as much physical area as lead-acid batteries for the equivalent power output.

In 2009, Popular Mechanics author David Nolan suggested that the Federal Aviation Administration (FAA) was also a primary reason that the electric aviation market has not taken off. As explained in the article, the FAA, which regulates all aviation issues within the United States, has prohibited electric motor implementation within the light sport aircraft sector. Nolan also mentioned that other countries, which have more lenient aviation authorities, are taking advantage of this situation and are producing electric aircraft to be sold within the United States. The FAA obviously opposes this theory stating, “We need to get some more flight experience with electric motors” (Noland, 2009, p. 16).

2.9. Pugh Matrices

The Criteria Based Matrix, also known as a Pugh Matrix, is implemented in Six Sigma and is a method of evaluating options against one another. This method is commonly used with the Quality Function Deployment, also known as a House of Quality. Originally developed by Mr. Stuart Pugh at the University of Stathclyde in Scotland, the matrix identifies user requirements, the importance (or weight) of each requirement, and compares each option against a predetermined baseline. The baseline is typically defined as the system being replaced. The output of this analysis is a prioritization between the options, demonstrating the significance of one over another (Thompson, 2007).

SECTION 3. METHODOLOGY

This section includes the study design, the hypothesis and the means of collecting the relevant data.

3.1. Study Design

The research method chosen for this study is a quantitative comparison approach. Quantitative results support or negate the hypothesis that electrical flight in General Aviation aircraft such as the Cessna 172K is possible using existing technology.

The framework for this study is a descriptive comparison between the O-320-E2D internal combustion engine and a comparable electrical motor. The Cessna 172K with the existing O-320 engine, serving as a baseline case, is compared side-by-side to the electric motor and supporting technology in both a numerical and a qualitative form. Engine to the motor output power capabilities, empirical data for crucial operations, such as landing, take-off, cruise, climb rate, maximum payload, and aircraft range is analyzed in a side-by-side, graphical form.

A selection of the motor and supporting technology is made using a Pugh matrix analysis for each technology. The selection method for each technology is as follows:

1. Analyze commercially available potential motors and power storage devices to gain a thorough knowledge regarding the current technology.
2. Define the feasible range for parameters. Filter out options that do not fall within the feasible range for this research.

3. Design a Pugh Matrix to evaluate the following criteria for each technology
    a. Motors:
        i. Maximum continuous horsepower,
        ii. Maximum torque vs. RPM,
        iii. Physical weight,
        iv. Physical dimensions,
        v. Cooling techniques,
        vi. Required controller,
        vii. Gear reduction
    b. Power Storage:
        i. Physical weight,
        ii. Physical dimensions,
        iii. Continuous voltage capability,
        iv. Maximum voltage capability
        v. Continuous ampere-hour capability,
        vi. Maximum ampere-hour capability
        vii. Capable of high altitudes
4. Decide a motor solution. The reasoning for this is that the motor capabilities are the primary driver of the electrical propulsion solution.
5. Identifiy the battery solution, which ultimately limits the aircraft range. The selection of battery is limited by the amount of physical space and weight

available aboard the aircraft, once all of the internal engine and associated components are removed and the motor is implemented.

3.2. Measurement and Instrumentation

Aircraft manufacturers publish data for each aircraft regarding required flight operations and engine performances for a given situation. These are usually delivered in a graphical form and can be utilized as the primary data for the O-320-E2D engine, relative to the Cessna 172K. Information can also be obtained via the Maintenance Manuals and Parts Catalogs in order to find component weights, center of gravity ranges, and specific component placements.

Electric motors do rely on oxygen for operation, as internal combustion engines do, therefore atmospheric conditions do not impact motor performances. Motor performance factors do not vary in relation to humidity, altitude, air density, barometric pressure, air viscosity, aircraft velocity or temperature, as motors do not operate on the principles of combustion, which require oxygen. Thus, a change in altitude will have little to no effect on the motor. These controlled variables will affect the efficiency of the propulsor, such as a propeller, and is taken into account during flight operations. The primary measurement for the motor is the maximum horsepower and torque outputs.

3.3. Mission Profile

The CAFÉ Foundation's Green Flight Challenge is being used as the primary standard to measure the success of the fully-electric aircraft developed in this paper. This standard is utilized because of several factors including the organization's prestige, the accessibility of the regulations, and the Green Flight Challenge's acceptance in the industry (CAFE Foundation). The performances are as follows:

1. Range: 200 statute miles, with 30 minute reserve, day VFR at ≥ 4000 feet
2. Speed: ≥ 100 mph average on each of two 200 mile flights
3. Takeoff Distance: ≤ 2000 feet from brake release to clear a 50 foot obstacle

The FAA defines the standard weight of a pilot to be 170 lbs in the FAA approved Aircraft Weight and Balance Handbook(Federal Aviation Administration).

Standards for the Cessna 172K with Lycoming O-320-E2D engine are as follows:

1. Climb Rate: 721 feet per minute
2. Cruise: 112.5 Horsepower at 130 mph
3. Landing Distance: 1500 feet over a 50 foot obstacle (500 feet landing roll)

The following CAFÉ Foundation Green Flight Challenge requirements are being disregarded for this paper:

1. Efficiency and Fuel Energy Used: This is being disregarded as this directed project aims to evaluate electrical possibilities given today's available technology for a common General Aviation aircraft, and will not evaluate the efficiency of the system.
2. Minimum Speed, Handling Qualities, Wingspan, Field of View, Control System, Flightworthiness: This is being disregarded because the Cessna 172 aircraft being modified will maintain the manufacturer's center of gravity envelope, thus the aircraft will generally meet the CAFÉ mandated

requirements. The electrical propulsion modification has little to no effect on these factors in compared to the original design of the aircraft.

3. Community Noise: The electrical propulsion modification will have a lower dBA than its internal combustion engine counterpart.
4. Passengers and Seating Configuration: In order to achieve a longer flight, the electric Cessna 172 is designed for a single pilot at the weight described by the FAA.
5. Vehicle Weight: The maximum weight of the Cessna 172 is defined in the aircraft's Type Certificate Data Sheet (TCDS). This weight is the maximum weight allowable for this paper.

3.4. Sampling Approach

Upon acquiring the O-320-E2D performance charts and observing the selected motor's operational chart, a direct comparison is made for each variable. Overlaying the charts upon each other produces numerical data to help support or disprove the hypothesis.

The qualitative analysis also includes the benefits and drawbacks of the electric motor versus the piston engine in terms of the controlled variables. This section also includes the market trend causing the push for alternative propulsion modules. The qualitative analysis also introduces the reader to the advantages and disadvantages of electric motors and piston engines.

The final section demonstrates the potential integration of the fully electric system into the Cessna 172K including weight & balance data and specific component costs.

3.5. Deliverables

The final outcome of this research is to provide a potentially viable option for electrical propulsion in aviation utilizing current market available technologies for the Cessna 172K. The research shall explain the capabilities of selected electric motors and the advancements of power storage devices such as batteries.

In addition, the anticipated effects on the Cessna's center of gravity is analyzed. A viable solution for electrical propulsion must take into account the location of the center of gravity such that it is within the accepted range.

SECTION 4. RESULTS

4.1. Pugh Matrix Results

The electric motor Pugh Matrix can be found in table 4. The total score for each motor can be calculated as:

Total = ($Weight_1$*$Importance_1$) + ($Weight_2$*$Importance_2$) + …

($Weight_n$*$Importance_n$)

As demonstrated in this table, the U.S. Hybrid HPM 450 appears to be the most suitable for an electrical propulsion application. The HPM 450 was selected because of its customizable horsepower to rpm settings, low weight, and maximum horsepower capability. Table 5 demonstrates the weight scaling used in the motor selection Pugh matrix.

Table 4. Electric Motor Pugh Matrix

Scale: (0) to (10)		BASELINE					
		Lycoming O-320-E2D		Raser Tech G100		Lange EA42	
Criteria	Importance	Measured	Weight	Measured	Weight	Measured	Weight
Horsepower	10.0	150.0	.0	160.0	10.0	51.6	3.0
RPM @ Max Horsepower	8.0	2700.0	.0	4000.0	0.0	1800.0	3.0
Power Consumption (Amp-hour)	7.0	N/A	.0	160.0	9.0	133.0 to 202.0	10.0
Weight (lbs)	9.0	268.0	.0	172.0	10.0	64.2	10.0
Volume/ L x OD (in^3)	7.0	29.6 x 32.2 x 23.2	.0	9.5 x 13.5	10.0	10.7 x 9.8	10.0
TOTAL			**.0**		**323.0**		**284.0**

Scale: (0) to (10)		BASELINE					
		Lycoming O-320-E2D		Tesla Motors		U.S. Hyrbid HPM 450	
Criteria	Importance	Measured	Weight	Measured	Weight	Measured	Weight
Horsepower	10.0	150.0	.0	288.0	10.0	161.0	10.0
RPM @ Max Horsepower	8.0	2700.0	.0	5000.0 to 6000.0	0.0	2500.0 to 4000.0	10.0
Power Consumption (Amp-hour)	7.0	N/A	.0	573.0	0.0	171.0 to 267.0	9.0
Weight (lbs)	9.0	268.0	.0	115.0	10.0	143.0	10.0
Volume/ L x OD (in^3)	7.0	29.6 x 32.2 x 23.2	.0	<O-320	10.0	7.0 x 17.0	10.0
TOTAL			**.0**		**260.0**		**403.0**

Table 5. Electric Motor Pugh Matrix Scale

Weight	Horsepower	RPM @ Max Horsepower		Power Consumption (Amp-hour)	Weight (lbs)
		High Scale	Low Scale		
0	0	1500	3900	530	470
1	15	1600	3800	490	450
2	30	1700	3700	450	430
3	45	1800	3600	410	410
4	60	1900	3500	370	390
5	75	2000	3400	330	370
6	90	2100	3300	290	350
7	105	2200	3200	250	330
8	120	2300	3100	210	310
9	135	2400	3000	170	290
10	150	2500	to 2900	130	270

The HPM 450 motor has an input voltage of 450Vdc to 700 Vdc, a weight of 143 lbs, and an efficiency of > 96%. Currently utilized in the Sikorsky Firefly helicopter, the motor has a 120 kW maximum power and a 450 Nm maximum torque at 2500 rpm.

The battery selection Pugh Matrix can be found in table 6. The battery selection was more complicated than the motor selection due to the abundance of innovative battery companies. As demonstrated below, the Tenergy Li-$SOCl_2$ battery was selected primarily because of the massive power-to-weight ratio in comparison to the other battery solutions. The battery technology is the limiting factor to electrical propulsion in aviation, due primarily to the significant weight requirements as the aircraft can lift a limited amount of weight. The primary fuel for the Lycoming O-320 engine is 100LL. The battery acts in a similar fashion as the 100LL, as it supplies the energy to the propulsion module. The 100LL cannot serve as a baseline, however, because the fuel is significantly more energy rich per volume than the batteries. All batteries in comparison to the 100LL fuel would become negative numbers. Therefore, the batteries are compared to each other. Table 7 demonstrates the weight scaling used in the motor selection Pugh matrix.

Table 6. Battery Selection Pugh Matrix

Scale: (0) to (10)							
		Tenergy				A123 Systems	
Criteria	Importance	Li-Polymer		$Li\text{-}SOCl_2$		Prismatic	
		Measured	Weight	Measured	Weight	Measured	Weight
Power Capacity/Weight (Watt-hour/lbs)	10.0	64.500	2.0	230.000	10.0	62.300	2.0
Power Delivery Capability (1 = Yes/0 = No)	7.0	1.000	10.0	1.000	10.0	1.000	10.0
Power Capacity/Volume (Watt-hour/in^3)	7.0	.005	2.0	.024	10.0	.001	0.0
TOTAL			**104.0**		**240.0**		**90.0**

Scale: (0) to (10)							
		Valence		Saft			
Criteria	Importance	LiFe $MaPIO_4$		VL45E Fe		VL52E	
		Measured	Weight	Measured	Weight	Measured	Weight
Power Capacity/Weight (Watt-hour/lbs)	10.0	41.100	1.0	68.700	2.0	84.900	3.0
Power Delivery Capability (1 = Yes/0 = No)	7.0	1.000	10.0	1.000	10.0	1.000	10.0
Power Capacity/Volume (Watt-hour/in^3)	7.0	.004	1.0	.006	2.0	.008	3.0
TOTAL			**87.0**		**104.0**		**121.0**

Table 7. Battery Selection Pugh Matrix Scale

Weight	Power Capacity/Weight (Watt-hour/lbs)	Power Capacity / Volume (Watt-hour/in^3)
0	30	0.001
1	50	0.0033
2	70	0.0056
3	90	0.0079
4	110	0.0102
5	130	0.0125
6	150	0.0148
7	170	0.0171
8	190	0.0194
9	210	0.0217
10	230	0.024

As each of the batteries have different voltage and ampere-hour outputs, this directed project calculates the watt-hour of each battery which is found by the following equation Watt-hour = Voltage x Ampere-hour. After this calculation, all the batteries can be directly compared against one another.

The 3.6V, 19Ah Tenergy Li-$SOCl_2$ battery has an energy density of 925.94 Watt-Hour/lb. In order to meet the HPM 450 power requirement for two hours of operation, a total of 2,637 Li-$SOCl_2$ batteries are needed. The total weight of these batteries is approximately 622 lbs. These batteries have an operating range of -40 ^oC to +85^oC, a shelf life of 10+ years, and are designed specifically for aerospace/aviation applications where impacts are expected (Tenergy) .

The volume of the batteries is 6.99 ft^3. The wing is designed to support approximately 253 lbs of fuel across the Cessna's 36' 2" wingspan. The density of the batteries is large enough to cause damage to the aircraft's wing, should the batteries be spread across the entire wingspan. However, the batteries can be split up and placed in the wings, under the pilot/co-pilot seats and in the cargo hold.

As mentioned in the literature review, altitude changes pose a threat to overheating lithium-ion based batteries. The mission profile states that an altitude of 4,000 feet or greater must be maintained during the durations of the flight. With this low altitude, pressure changes should have little to no effect on the Li-$SOCl_2$ battery.

A benefit of the lithium-based batteries is that the voltage loss over time for the Li-$SOCl_2$ battery is minimal in comparison to lead-acid and NiCd batteries. The discharge rate of the Li-$SOCL_2$ battery provides a constant flow of voltage until the power is completely drained from the battery. The lead-acid and NiCd batteries typically used in the aviation industry continuously loss potential voltage as the battery is drained.

4.2. Mission Profile Results

The HPM 450 motor and the Li-$SOCl_2$ batteries were then hypothetically installed on the Cessna 172K aircraft, while unnecessary equipment such as the Lycoming O-320-E2D were removed. The entire flight profile log can be found in Appendix B. Maintaining a constant voltage; the amperage was varied so as to appropriately approximate the length of a flight. The battery system supply is 600V, 400 amp-hour or 24,000 amp-minute. Table 8 details the flight.

Table 8. Electric Flight Profile Breakdown

	Electric Flight Profile Breakdown		
Flight Operation	**Amps Used**	**Hours**	**Amp-Hour**
Takeoff	200	0.10	20.0
Cruise	150	1.82	273.0
Landing Approach	128	0.10	12.8
Landing Approach	112	0.13	15.6
Taxi	64	0.05	3.2
30 Minute Reserve	150	0.50	75.0
	TOTAL		**399.6**
	Amp-Hour Available		Amps in Range?
	400		Yes

The total amp-hour of 399.6 is below the 400 amp-hour capacity of the electric aircraft. Table 8 defines the speed and distance traveled during this mission profile.

Table 9. Speed/Distance Analysis

	Speed (MPH)	Hours	Distance Traveled
Takeoff	87.50	0.10	8.75
Cruise	140.00	1.82	254.33
Landing Approach	102.00	0.10	10.20
Landing Approach	89.00	0.13	11.87
	TOTAL	**2.15**	**285.15**
	Average Speed		**132.63**

The mission profile details the normal flight of the aircraft. Therefore, the 'Taxi' and '30 Minute Reserve' flight operations are not taken into consideration for this table. Table 10 details the electric Cessna 172K versus the mission profile requirements.

Table 10. Mission Profile/Electric Solution Comparison

	Requirements	Electric Solution
Range (miles)	200.0	**285.0**
Fuel Reserve (min)	30.0	30.0
Altitude	≥ 4000.0	4000.0
Average Speed (mph)	≥ 100.0	**132.6**
Takeoff Distance (ft)	≤ 2000.0	1685.0
Clear 50 ft obstacle?	Yes	Yes
Pilot Weight (lbs)	170.0	170.0
Climb Rate (ft/min)	721.0	721.0
Cruise (hp)	112.5	**120.6**
Cruise (mph)	130.0	**140.0**
Landing Distance (ft)	1500.0	1340.0
Clear 50 ft obstacle?	Yes	Yes

The electric solution above is derived partially from the manufacturer's published data. For example, the maximum structural cruise speed for this aircraft is 140 mph, which is approximately 75% of maximum power. Thus, 75% of the maximum motor horsepower equates to approximately 121 horsepower. While operating within the manufacturer's approved weight and balance, the Cessna 172K has a 1685 foot takeoff distance, a 721 foot per minute climb rate, and a 1340 foot landing distance (Federal Aviation Administration, TCDS, 2010). As the electric solution operates within the manufacturer's allowable weight and balance, these numbers are assumed as the aircraft's capabilities. As noticed in table 10, the electric aircraft meets all of the requirements and exceeds the minimum range, average airspeed, and average cruise characteristics. A graphical representation of the flight can be reviewed in figures 2 and 3. The hypothetical flight-tested the worst case scenario to analyze viability (i.e. maximum continuous cruise speed, maximum climb rate, etc.). The aircraft could potentially be operated in a more efficient manner to improve the range.

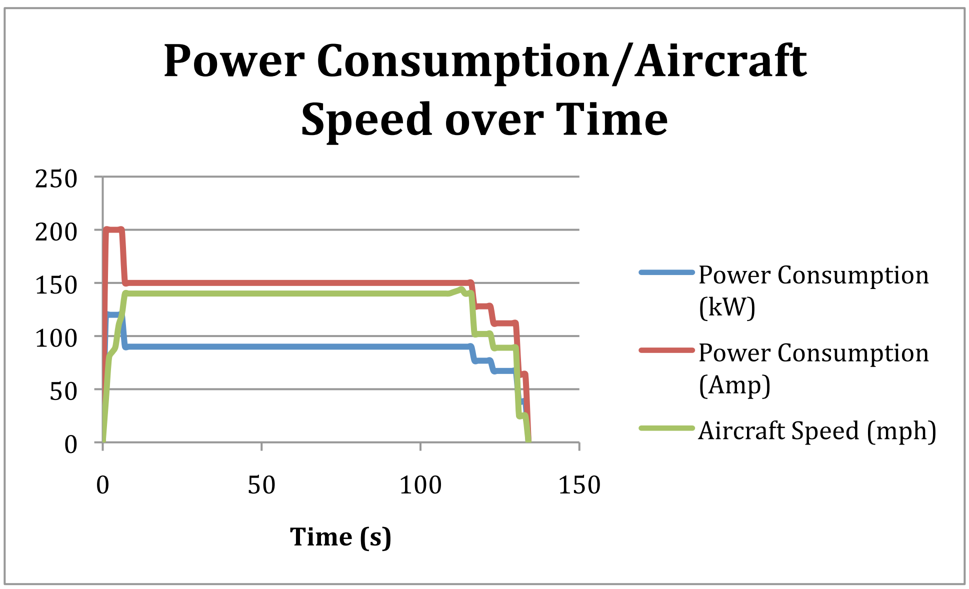

Figure 2. Power Consumption/Speed over Time

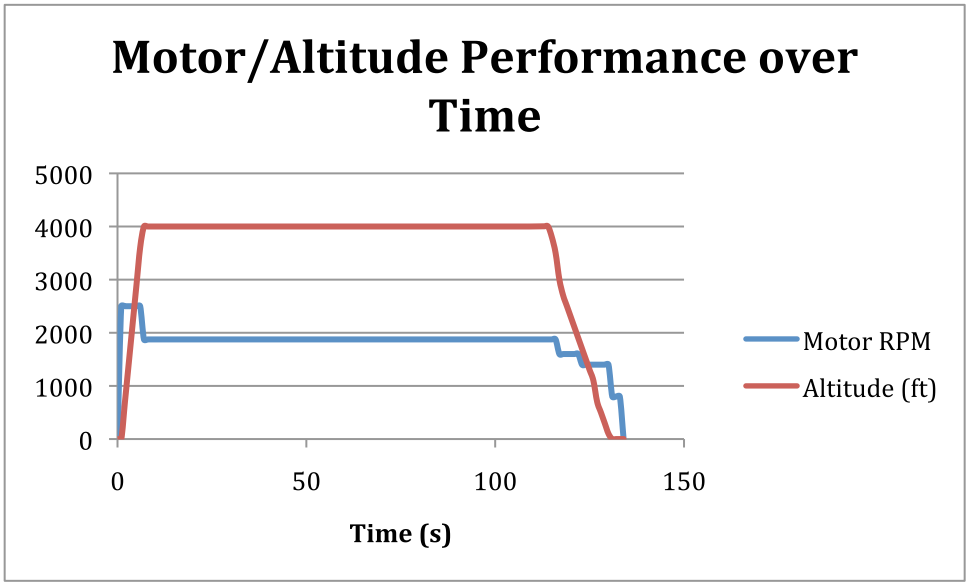

Figure 3. Motor/Altitude Performance over Time

4.3. <u>Center of Gravity Analysis</u>

The center of gravity calculations can be found in Appendix C. Figures 4 and 5 provide a visual representation of the aircraft modifications. The aircraft Datum location and empty weight center of gravity location is 1386.48 lbs at +38.96”. The gross allowable weight of the Cessna aircraft is 2300 lbs.

Figure 4 describes the components being removed from the aircraft and each component’s associated moments. Notice that once these items have been removed, the center of gravity location is moved in the aft direction. The final location of +51.6103” is outside of the center of gravity limits. The total weight at this point is 1057.54 lbs. The items being removed are:

1. Lycoming O-320-E2D: 268 lbs at -16.88”
2. SAE 50 Engine Oil: 16.94 lbs at -16.88”
3. Original Battery: 20 lbs at -3.95”
4. Unusable Fuel: 24 lbs at +48.00”

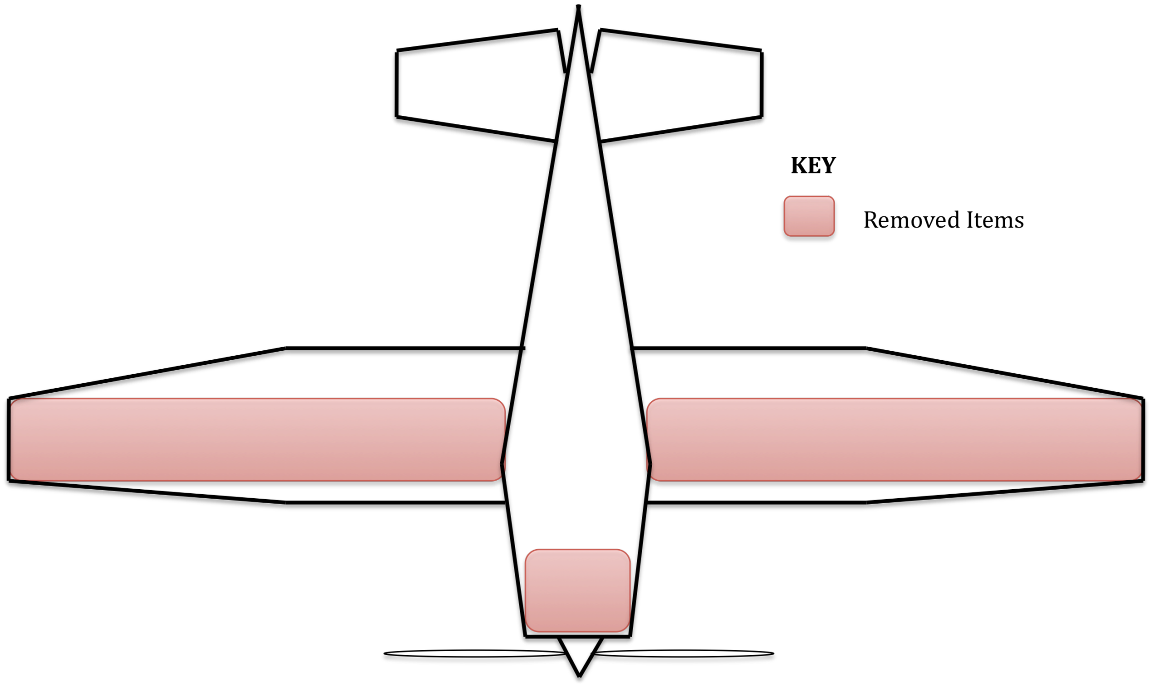

Figure 4. Empty Weight Cessna 172K CG

Figure 5 describes the components being integrated into the aircraft for electrical propulsion. Once these components are installed onto the aircraft, the center of gravity location is +43.99”, which is within the center of gravity envelope. The final weight of the aircraft is 2298.3 lbs. The items being installed are:

1. Electric Motor: 143.01 lbs at -32.0375”
2. Motor Controller: 70 lbs at -3.95”
3. 50mm^2 Battery Power Supply Cable: 20 lbs at +22.025”
4. 30mm^2 Battery Grounding Cable: 10 lbs at +22.025”
5. Batteries: 827.75 lbs at +48.00”
6. Pilot at Full Seat Extension: 170 lbs at +46”

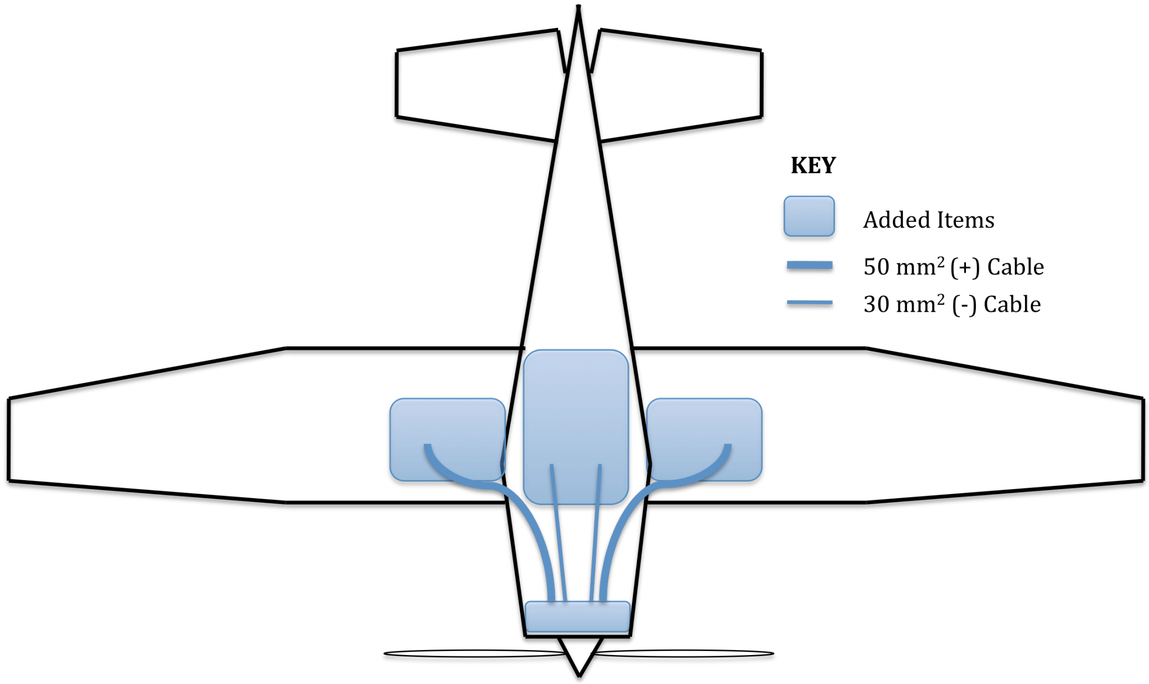

Figure 5. Electrical Solution Cessna 172K CG

According to the Cessna 172K Type Certificate Data Sheet, the gross weight of this aircraft is 2,300 lbs and a Normal Category center of gravity range between +35.0" and +47.3" (Federal Aviation Administration, TCDS, 2010). After the modifications on this aircraft, the current gross weight is 2,298.3 lbs at a moment of 43.99", both that are within the aircraft limits.

4.4. Financial Analysis

The cost of the electrical integration into the Cessna 172K is a deliverable of this project, not a driver. The total cost of the motor, motor controller, battery system, positive and negative electrical conductors, and new motor mount equates to approximately $118,308. The estimated profit from the sale of the Lycoming engine, original battery, engine oil cooler, and the original engine mount equates to approximately $13,097. Thus, the total cost of the electrical propulsion integration minus the profit from the component sales is $105,211. This final number is the estimated cost of the entire electrical propulsion retrofit. An option to reduce this total cost may be purchasing in mass quantity. For example, to achieve the flight described in this paper, over 2,000 batteries must be purchased at $19.00 per battery. Guaranteed, prices can be assumed to decrease for the batteries over time, but this evaluation is current market pricing. Purchasing these batteries in mass quantity can potentially reduce the cost per battery.

4.5. Electric versus Piston Application

A typical piston engine will use 30% of the energy stored in gasoline for forward motion due to its intricate complexity. The additional 70% is then converted into heat and noise, which are ultimately inefficiencies as this energy is usually dissipated and wasted (Tesla Motors). Electric motors, such as the Raser Technologies G-100 motor can reach efficiencies of 94%, well over three times that of the typical piston engine.

The piston engine also does not develop peak torque until many thousand RPM. The electric motor also has the potential to eliminate the need for a transmission, as electric motors produce peak torque at any RPM. The actuation of the power is done by means of a Hall Effect throttle, which eliminates governors, and fuel injectors/carburetors.

Due to the piston engine's complexity, maintenance is a routine task. The engine has springs, moving valves, pistons wear, and additional moving parts in the fuel control. The electric motor, on the other hand, has only one moving part - the rotor. This simplicity reduces the need for continuous maintenance, and reduces the cost of operation over time. This reduction in cost also creates a return on investment, creating an incentive to modify current piston engine aircraft to electrical aircraft.

An additional benefit from electrical propulsion system that relies solely on battery power is the absence of a weight shift. As fuel burns, the aircraft loses weight, which does improve flight efficiencies over time; however this weight reduction changes the center of gravity of the aircraft. With a system relying on battery power alone, no fuel is burnt and the aircraft does not lose weight over the course of the flight. Thus, the aircraft's performances become even more predictable.

If engineered properly, the electric motor with a propeller application can in fact create electricity. While decrease power or losing altitude, the propeller has a potential to turn the motor. The motor, coupled with a proper regenerative circuitry, can then be used as a generator. This eventually supplies power back to the battery. In order to capitalize on this idea, however, some sort of capacitor needs to be utilized, as the capacitors will receive an instant charge from the generator. That stored charge will then transfer its charge to the battery system. The batteries themselves cannot receive a sufficient charge directly from the generator, as the batteries will not fully absorb the instant power delivered.

SECTION 5. CONCLUSION

The electrical solution developed by this project met or exceeded all of the requirements developed in the methodology section while not structurally modifying the Cessna 172K airframe. Additionally, the aircraft maintained the original manufacturer- approved center of gravity. The following were the results:

1. 285 mile range at maximum structural cruise with a 30 minute reserve,
2. Aircraft operated within the center of gravity limits,
3. Aircraft operated within the airframe weight limits,
4. Electric motor met and exceeded the operational performances of the original Lycoming O-320,
5. The aircraft average speed was 132 mph, and
6. The selected batteries are not affected by the altitude changes.

The motor selected was the U.S. Hybrids HPM 450 electric motor currently being tested in the Sikorsky Firefly helicopter. The HPM 450 motor has a weight of 143 lbs and has a 120 kW/160 maximum horsepower and a 450 Nm maximum torque at 2500 rpm.

The batteries selected are 3.6V, 19Ah Tenergy Li-$SOCl_2$ batteries. These batteries have an energy density of 925.94 Watt-Hour/lb, and to meet the requirements of two hours of operation, a total of 2,637 Li-$SOCl_2$ batteries are needed. The total weight of these batteries is approximately 622 lbs. These batteries have an operating range of -40 ^{o}C to +85^{o}C, a shelf life of 10+ years, and are designed specifically for aerospace/aviation applications where impacts are expected

Additionally, the electric motor provides benefits over the internal combustion engine which includes physical dimensions, weight, noise reduction, reduced maintenance, increased operational efficiencies, lack of emissions, and instantaneous torque.

This research project explored the feasibility of electrical propulsion to support flight operations for the Cessna 172K in terms of aircraft performance criteria. The primary limiting factor is the power storage technology. Electric motors are capable of producing the required power for the aviation industry, but the power storage device limits the aircraft's range. Over the course of the last decade, batteries have significantly improved. Should this trend continue and batteries continue to improve, electrical propulsion may become a common configuration within the aviation industry.

SECTION 6. FUTURE RESEARCH

Figure 6 provides a visual explanation of the electrical system as described with the technology above. Future research could possibly include the application and the problems incurred from these technologies.

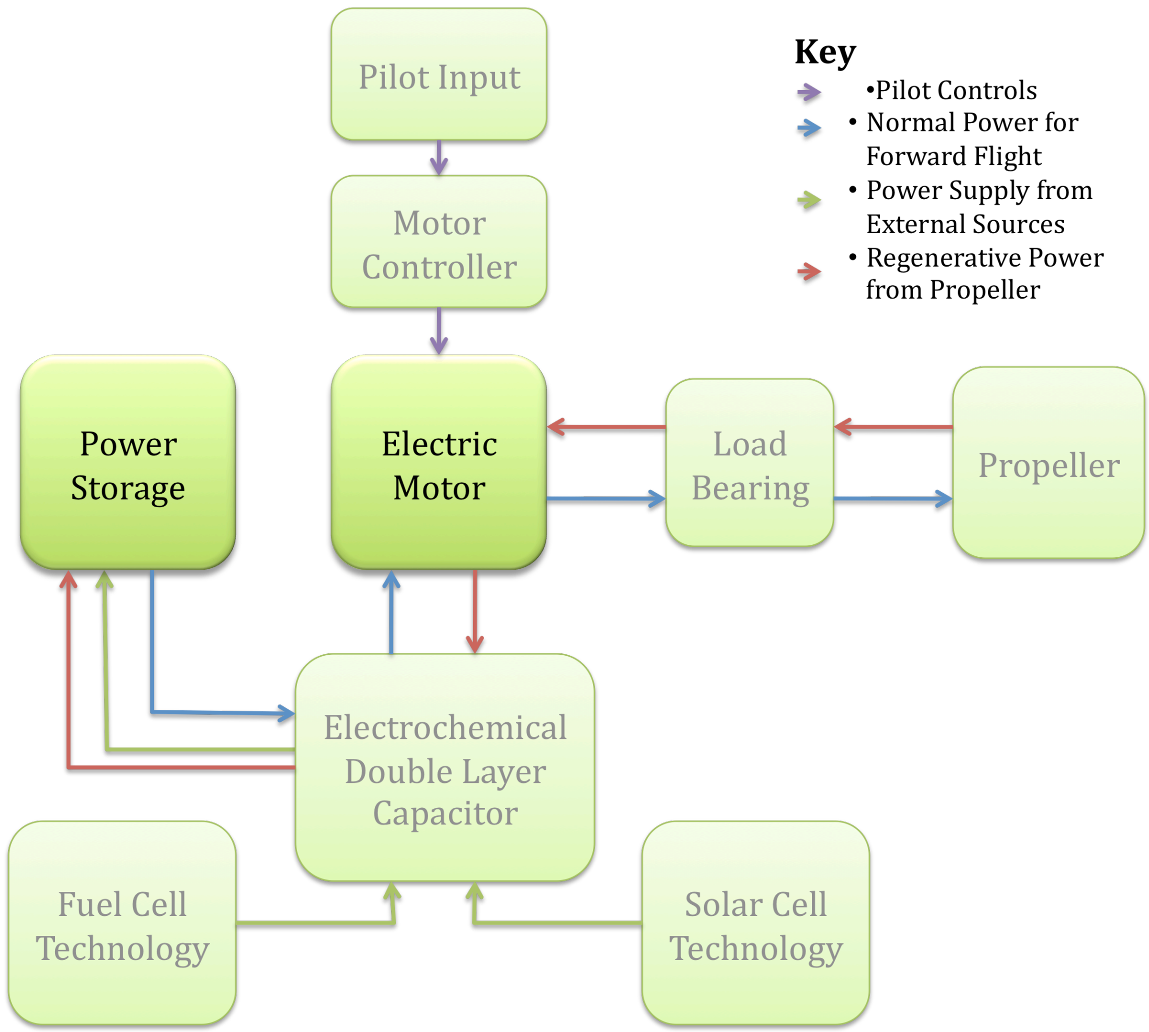

Figure 6. Future Research

Fuel cell technology provides an opportunity to extend the flight duration of a specific aircraft. Delphi has developed a Solid Oxide Fuel Cell (SOFC) for transportation use. Focusing primarily on large commercial vehicles (i.e. semi-truck and trailer), this customizable auxiliary power unit has the potential to supply 12 V_{dc} with near zero emissions. The SOFC has the capability for internal reformation meaning that the fuel cell can operate on a variety of fuels such as “natural gas, diesel, bio-diesel, propane, gasoline, coal-derived fuel and military logistics fuel” (Delphi). The emissions include less than 8 grams of CO and less than 0.2 grams of NMHC per kWh. In comparison, the Lycoming IO-320 produces 2205 g/hr of CO at idle and 49578 g/hr of CO at takeoff. The IO-320 also produces 128 g/hr of NMHC at idle and 475 g/hr of NMHC at takeoff (Pace, 1977). The fuel for this 5 kW output fuel cell can be stored in the wings of the aircraft, as the original fuel is removed, and provide a means of continuous battery charging during the flight. The weight and physical dimensions of the fuel cell are variables, as the SOFC size is determined by the amount of power required (i.e. 3 stack or 50 stack fuel cell).

Solar cells have made significant advancements recently. From companies such as First Solar, Sanyo Electric, Sunpower Corporation, and Suntech, the technology has become more capable and reliable than in previous years. For example, Sharp, a leading name in electronics, has developed a thin film module that has a 25-year limited warranty, and a 142W output system. With a module efficiency of 10.0%, the solar panel extracts light from a wider solar spectrum, thus converting more sunlight into electricity. The system even has a 1,000 volt output (Sharp).

The drawbacks, however, include solar panel price and efficiency. An additional drawback, unique to aviation, is the potential for solar damage. When an aircraft received damage to a wing, the aircraft skin is reformed and rebuilt. With the application of solar panels, if a wing receives damage, the wing still has to be repaired, but now the solar panels need to be replaced and the entire wing may need to be rewired.

Capacitor applications will also increase the effectiveness of a particular flight. Both Maxwell Technologies and The Tecate Group have produced what are known as Electrochemical Double Layer Capacitors (EDLC), also known as ultracpacitors. With the application of this technology, the EDLC can absorb the small amounts of power being created by the solar cells during cloudy or night conditions. The EDLC can also be used in conjunction with the propeller when decreasing altitude. With pilot controls, the propeller can actually turn the electric motor due to windmilling. Windmilling is when the propeller turns by itself by means of oncoming wind. This windmilling effect takes place as the aircraft is descending. The motor then acts like a generator providing power to the EDLC, which absorbs the power instantly. This power then slowly charges the batteries over a longer period of time. If the EDLC technology is not utilized, the large amount of temporary power from the generator will charge the batteries only for a short period of time while the aircraft is descending in altitude.

Also, the EDLC must be used in conjunction with the battery and motor technologies, should the aircraft be used for longer periods of time. If a pilot inputs a significant amount of power in a short time frame (i.e. idle to full throttle on takeoff procedures), the motor will draw a high amount of amperage from the batteries.

This high amount of power burst will destroy a battery over many usages. If the capacitor were to be placed between the battery and the motor, the instant required power would be delivered to the motor from the EDLC while the battery slowly charges the EDLC. In this situation, the EDLC would act as a buffer, thus extending the life of the battery.

Even though EDLC technology is the most efficient type of capacitor, the primary drawback is that in comparison to battery technology, the EDLC is heavy. These capacitors are heavier than batteries in terms of potential power storage to weight ratio. For example, Maxwell Technologies B-series EDLC for heavy transport has a 46.13 Watt-hour/lb (Maxwell Technologies) while Saft Batteries' Lithium Ion VL52E battery has an 84.91 Watt-hour/lb (Saft Batteries). As a reference to weights, utilizing the electric motor from this paper, in order to maintain one full hour of flight at full speed, a total of 1,413 VL52E batteries or 2,601 EDLCs would be required.

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Appendix A

Power Storage Analysis

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Battery Solutions (Metric)	Tenergy						
	Li-Polymer			LiFePO4	Li-MnO2	Li-SOCl2	Li-FeS2
	30102	**30101**	**30100**	**30211**	**CR9V**	**ER34615**	**LFB14505**
Voltage	3.7000	3.7000	3.7000	3.2000	9.0000	3.6000	1.5000
Amp-hours	35.0000	25.0000	50.0000	200.0000	1.2000	19.0000	2.9000
Weight (kg)	1.0000	.6500	1.4000	6.2600	.0340	.1070	.0145
Energy (Watt-hour/kg)	129.5000	142.3077	132.1429	102.2364	317.6471	639.2523	300.0000
Area (mm^3)	354570.0000	453150.0000	643950.0000	4201680.0000	22491.8750	56467.2951	8334.8356
(Watt-hour/kg)/Area	.0004	.0003	.0002	.0000	.0141	.0113	.0360

	A123Systems	Valence				Saft Batteries	
	Prismatic	XP Battery Lithium Iron Magnesium Phosphate (LiFe MaPIO4)				Lithium-Ion	
	AHP 70165227	**U1-12XP**	**U24-12XP**	**U27-12XP**	**UEV-18XP**	Intensium Flex	VL45E Fe
Voltage	3.3000	12.8000	12.8000	12.8000	19.2000	48.0000	3.3000
Amp-hours	20.0000	40.0000	110.0000	138.0000	69.0000	45.0000	44.0000
Weight (kg)	.4800	6.5000	15.8000	19.5000	14.9000	23.0000	.9000
Energy (Watt-hour/kg)	137.5000	78.7692	89.1139	90.5846	88.9128	93.9130	161.3333
Area (mm^3)	2488374.0000	4722681.0000	10062000.0000	11842200.0000	10390932.0000	18581376.0000	476124.4800
(Watt-hour/kg)/Area	.0001	.0001	.0001	.0001	.0001	.0001	.0003

	Saft Batteries						
	Lithium-Ion						
	VL6A	VL5U	VL12V	VL34P	VL 41M	VL52E	VL45E
Voltage	3.6500	3.6500	3.6500	43.2000	3.6000	3.6000	3.6000
Amp-hours	6.0000	5.0000	14.0000	31.5000	41.0000	52.0000	45.0000
Weight (kg)	.3400	.3500	.6400	16.0000	1.0700	1.0000	1.0700
Energy (Watt-hour/kg)	64.4118	52.1429	79.8438	85.0500	137.9439	187.2000	151.4019
Area (mm^3)	166361.1250	158805.5000	299993.2450	8863575.8400	513833.3523	476124.4800	513833.3523
(Watt-hour/kg)/Area	.0004	.0003	.0003	.0001	.0003	.0004	.0003

	Saft Batteries							
	Nickel-Cadmium						Nickel Metal-Hydride	
	MSX	SPH 320	SRM 440	SCH 435 S	STM 5-140	STH 1900	NHP 10-34	NHE 10-100
Voltage	4.8000	1.2000	2.4000	3.6000	6.0000	1.2000	12.0000	12.0
Amp-hours	260.0000	320.0000	440.0000	435.0000	136.0000	190.0000	34.0000	100.0
Weight (kg)	37.0000	16.5000	44.0000	27.7000	17.0000	9.8000	9.0000	18.6
Energy (Watt-hour/kg)	33.7297	23.2727	24.0000	56.5343	48.0000	23.2653	45.3333	64.5
Area (mm^3)	21184995.0000	11142252.0000	37968840.0000	52370784.0000	9706320.0000	6584058.0000	4824105.0000	9126000.0
(Watt-hour/kg)/Area	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0

Battery Solutions (Standard)	Tenergy						
	Li-Polymer			LiFePO4	Li-MnO2	Li-SOCl2	Li-FeS2
	30102	**30101**	**30100**	**30211**	**CR9V**	**ER34615**	**LFB14505**
Voltage	3.7000	3.7000	3.7000	3.2000	9.0000	3.6000	1.5000
Amp-hours	35.0000	25.0000	50.0000	200.0000	1.2000	19.0000	2.9000
Weight (lb)	2.2046	1.4330	3.0865	13.8009	.0750	.2359	.0320
Energy (Watt-hour/lb)	58.7402	64.5497	59.9390	46.3737	144.0823	289.9600	136.0777
Area (in^3)	21.6333	27.6480	39.2892	256.3563	1.3723	3.4452	.5085
(Watt-hour/lb)/Area	2.7153	2.3347	1.5256	.1809	104.9939	84.1628	267.5894

	A123Systems	Valence				Saft Batteries	
	Prismatic	XP Battery Lithium Iron Magnesium Phosphate (LiFe MaPIO4)				Lithium-Ion	
	AHP 70165227	**U1-12XP**	**U24-12XP**	**U27-12XP**	**UEV-18XP**	**Intensium Flex**	**VL45E Fe**
Voltage	3.3000	12.8000	12.8000	12.8000	19.2000	48.0000	3.3000
Amp-hours	20.0000	40.0000	110.0000	138.0000	69.0000	45.0000	44.0000
Weight (lb)	1.0582	14.3300	34.8330	42.9901	32.8489	50.7063	1.9842
Energy (Watt-hour/lb)	62.3690	35.7291	40.4214	41.0885	40.3301	42.5982	73.1796
Area (in^3)	151.8227	288.1441	27.6480	39.2892	256.3563	27.6480	39.2892
(Watt-hour/lb)/Area	.4108	.1240	1.4620	1.0458	.1573	1.5407	1.8626

	Saft Batteries						
	Lithium-Ion						
	VL6A	**VL5U**	**VL12V**	**VL34P**	**VL 41M**	**VL52E**	**VL45E**
Voltage	3.6500	3.6500	3.6500	43.2000	3.6000	3.6000	3.6000
Amp-hours	6.0000	5.0000	14.0000	31.5000	41.0000	52.0000	45.0000
Weight (lb)	.7496	.7716	1.4110	35.2740	2.3589	2.2046	2.3589
Energy (Watt-hour/lb)	29.2167	23.6516	36.2165	38.5780	62.5703	84.9125	68.6747
Area (in^3)	256.3563	9.6892	27.6480	39.2892	256.3563	1.3723	3.4452
(Watt-hour/lb)/Area	.1140	2.4410	1.3099	.9819	.2441	61.8764	19.9333

	Saft Batteries							
	Nickel-Cadmium						Nickel Metal-Hydride	
	MSX	**SPH 320**	**SRM 440**	**SCH 435 S**	**STM 5-140**	**STH 1900**	**NHP 10-34**	**NHE 10-100**
Voltage	4.8000	1.2000	2.4000	3.6000	6.0000	1.2000	12.0000	12.0
Amp-hours	260.0000	320.0000	440.0000	435.0000	136.0000	190.0000	34.0000	100.0
Weight (lb)	81.5710	36.3763	97.0034	61.0680	37.4786	21.6053	19.8416	41.0
Energy (Watt-hour/lb)	15.2995	10.5563	10.8862	25.6435	21.7724	10.5530	20.5629	29.2
Area (in^3)	.5085	151.8227	288.1441	613.9109	722.5259	633.9800	1133.7020	29.0
(Watt-hour/lb)/Area	30.0857	.0695	.0378	.0418	.0301	.0166	.0181	1.0

Appendix B

Electrical Propulsion Flight Profile

Time (minutes)	Power Consumption (kW)	(Amp)	Aircraft Speed (mph)	Motor RPM	Altitude (ft)	Flight Cycle
0	0	0	0	0	0	Startup
1	120	200	40	2500	0	Takeoff @ Max
2	120	200	80	2500	721	Takeoff @ Max
3	120	200	85	2500	1442	Takeoff @ Max
4	120	200	90	2500	2163	Takeoff @ Max
5	120	200	110	2500	2884	Takeoff @ Max
6	120	200	120	2500	3605	Takeoff @ Max
7	90	150	140	1875	4000	Cruise @.75%
8	90	150	140	1875	4000	Cruise @.75%
9	90	150	140	1875	4000	Cruise @.75%
10	90	150	140	1875	4000	Cruise @.75%
11	90	150	140	1875	4000	Cruise @.75%
12	90	150	140	1875	4000	Cruise @.75%
13	90	150	140	1875	4000	Cruise @.75%
14	90	150	140	1875	4000	Cruise @.75%
15	90	150	140	1875	4000	Cruise @.75%
16	90	150	140	1875	4000	Cruise @.75%
17	90	150	140	1875	4000	Cruise @.75%
18	90	150	140	1875	4000	Cruise @.75%
19	90	150	140	1875	4000	Cruise @.75%
20	90	150	140	1875	4000	Cruise @.75%
21	90	150	140	1875	4000	Cruise @.75%
22	90	150	140	1875	4000	Cruise @.75%
23	90	150	140	1875	4000	Cruise @.75%
24	90	150	140	1875	4000	Cruise @.75%
25	90	150	140	1875	4000	Cruise @.75%
26	90	150	140	1875	4000	Cruise @.75%
27	90	150	140	1875	4000	Cruise @.75%
28	90	150	140	1875	4000	Cruise @.75%
29	90	150	140	1875	4000	Cruise @.75%
30	90	150	140	1875	4000	Cruise @.75%
31	90	150	140	1875	4000	Cruise @.75%
32	90	150	140	1875	4000	Cruise @.75%
33	90	150	140	1875	4000	Cruise @.75%
34	90	150	140	1875	4000	Cruise @.75%
35	90	150	140	1875	4000	Cruise @.75%
36	90	150	140	1875	4000	Cruise @.75%
37	90	150	140	1875	4000	Cruise @.75%
38	90	150	140	1875	4000	Cruise @.75%
39	90	150	140	1875	4000	Cruise @.75%
40	90	150	140	1875	4000	Cruise @.75%
41	90	150	140	1875	4000	Cruise @.75%

42	90	150	140	1875	4000	Cruise @.75%
43	90	150	140	1875	4000	Cruise @.75%
44	90	150	140	1875	4000	Cruise @.75%
45	90	150	140	1875	4000	Cruise @.75%
46	90	150	140	1875	4000	Cruise @.75%
47	90	150	140	1875	4000	Cruise @.75%
48	90	150	140	1875	4000	Cruise @.75%
49	90	150	140	1875	4000	Cruise @.75%
50	90	150	140	1875	4000	Cruise @.75%
51	90	150	140	1875	4000	Cruise @.75%
52	90	150	140	1875	4000	Cruise @.75%
53	90	150	140	1875	4000	Cruise @.75%
54	90	150	140	1875	4000	Cruise @.75%
55	90	150	140	1875	4000	Cruise @.75%
56	90	150	140	1875	4000	Cruise @.75%
57	90	150	140	1875	4000	Cruise @.75%
58	90	150	140	1875	4000	Cruise @.75%
59	90	150	140	1875	4000	Cruise @.75%
60	90	150	140	1875	4000	Cruise @.75%
61	90	150	140	1875	4000	Cruise @.75%
62	90	150	140	1875	4000	Cruise @.75%
63	90	150	140	1875	4000	Cruise @.75%
64	90	150	140	1875	4000	Cruise @.75%
65	90	150	140	1875	4000	Cruise @.75%
66	90	150	140	1875	4000	Cruise @.75%
67	90	150	140	1875	4000	Cruise @.75%
68	90	150	140	1875	4000	Cruise @.75%
69	90	150	140	1875	4000	Cruise @.75%
70	90	150	140	1875	4000	Cruise @.75%
71	90	150	140	1875	4000	Cruise @.75%
72	90	150	140	1875	4000	Cruise @.75%
73	90	150	140	1875	4000	Cruise @.75%
74	90	150	140	1875	4000	Cruise @.75%
75	90	150	140	1875	4000	Cruise @.75%
76	90	150	140	1875	4000	Cruise @.75%
77	90	150	140	1875	4000	Cruise @.75%
78	90	150	140	1875	4000	Cruise @.75%
79	90	150	140	1875	4000	Cruise @.75%
80	90	150	140	1875	4000	Cruise @.75%
81	90	150	140	1875	4000	Cruise @.75%
82	90	150	140	1875	4000	Cruise @.75%
83	90	150	140	1875	4000	Cruise @.75%
84	90	150	140	1875	4000	Cruise @.75%
85	90	150	140	1875	4000	Cruise @.75%
86	90	150	140	1875	4000	Cruise @.75%
87	90	150	140	1875	4000	Cruise @.75%
88	90	150	140	1875	4000	Cruise @.75%
89	90	150	140	1875	4000	Cruise @.75%
90	90	150	140	1875	4000	Cruise @.75%

91	90	150	140	1875	4000	Cruise @.75%
92	90	150	140	1875	4000	Cruise @.75%
93	90	150	140	1875	4000	Cruise @.75%
94	90	150	140	1875	4000	Cruise @.75%
95	90	150	140	1875	4000	Cruise @.75%
96	90	150	140	1875	4000	Cruise @.75%
97	90	150	140	1875	4000	Cruise @.75%
98	90	150	140	1875	4000	Cruise @.75%
99	90	150	140	1875	4000	Cruise @.75%
100	90	150	140	1875	4000	Cruise @.75%
101	90	150	140	1875	4000	Cruise @.75%
102	90	150	140	1875	4000	Cruise @.75%
103	90	150	140	1875	4000	Cruise @.75%
104	90	150	140	1875	4000	Cruise @.75%
105	90	150	140	1875	4000	Cruise @.75%
106	90	150	140	1875	4000	Cruise @.75%
107	90	150	140	1875	4000	Cruise @.75%
108	90	150	140	1875	4000	Cruise @.75%
109	90	150	140	1875	4000	Cruise @.75%
110	90	150	141	1875	4001	Cruise @.75%
111	90	150	142	1875	4002	Cruise @.75%
112	90	150	143	1875	4003	Cruise @.75%
113	90	150	144	1875	4004	Cruise @.75%
114	90	150	140	1875	4000	Cruise @.75%
115	90	150	140	1875	3800	Landing
116	90	150	140	1875	3500	Landing
117	76.8	128	102	1600	3000	Landing
118	76.8	128	102	1600	2700	Landing
119	76.8	128	102	1600	2500	Landing
120	76.8	128	102	1600	2300	Landing
121	76.8	128	102	1600	2100	Landing
122	76.8	128	102	1600	1900	Landing
123	67.2	112	89	1400	1700	Landing
124	67.2	112	89	1400	1500	Landing
125	67.2	112	89	1400	1300	Landing
126	67.2	112	89	1400	1100	Landing
127	67.2	112	89	1400	700	Landing
128	67.2	112	89	1400	500	Landing
129	67.2	112	89	1400	300	Landing
130	67.2	112	89	1400	100	Landing
131	38.4	64	25	800	0	Taxi
132	38.4	64	25	800	0	Taxi
133	38.4	64	25	800	0	Taxi
134	0	0	0	0	0	Shutdown

Appendix C

Cessna 172K Electrical Propulsion Center of Gravity

Component	**Weight (lbs)**	**Arm (inches)**	**Total**
Aircraft Empty Weight	1386.48	38.96	54017.26
Subtracted Items			
Engine	-268.00	-16.88	4522.50
Engine Oil	-16.94	-16.88	285.86
Unusable Fuel	-24.00	48.00	-1152.00
Battery	-20.00	-3.95	79.00
TOTAL	-328.94		3735.36
CG Placement	(Empty Total + Subtracted Total)/ (Empty Weight + Subtracted Weight) =		54.61
Added Items for Electric Flight			
Motor	143.00	-32.04	-4581.51
Controller	70.00	-3.95	-276.50
(+) Cable	20.00	22.03	440.50
(-) Cable	10.00	22.03	220.25
Batteries	827.75	48.00	39732.20
Pilot (max extension)	170.00	46.00	7820.00
TOTAL	1240.76		43354.94
FINAL CALCULATION			
Empty Weight	1386.48	38.96	54017.26
Baseline A/C	-328.94	-11.36	3735.36
Electric Integration	1240.76	34.94	43354.94
TOTAL	2298.30		101107.56
CG Placement		43.99	
In CG Range?	(35.0 to 47.3)	43.99	**Yes**
Gross Weight?	(Max 2300 lbs)	2298.30	**In Limits**