Hybrid Electric Aircraft Propulsion System Design Analysis and Simulation Tool Development

An Undergraduate Honors Thesis

Presented in partial fulfillment of the requirements for graduation with Honors Research Distinction in the College of Engineering at The Ohio State University

By

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Finally, I want to thank my family and friends that have supported me and encouraged me throughout this research. Your interest in this research kept me going and motivated me to make it as best I could. I hope you all enjoy this work and learn a little about the efforts to electrify aircraft.

Abstract

As climate change becomes an ever-important issue, the aviation industry is looking to eliminate its emissions in the coming generations of aircraft. To make this happen faster, electrified propulsion systems must be designed and analyzed quickly and accurately. Design software and simulation tools tailored to hybrid electric aircraft play an important role in the accuracy and speed of these processes. This paper reviews design methods and software packages for hybrid electric propulsion system design, as well as discusses the modification of modeling and simulation tools for performance analysis. An initial cruise analysis was done using a Matlab script to assess the performance of an aircraft over a wide range of degree of hybridizations (DOH), take off weights, and propulsion component sizes. This analysis narrowed the design range to a DOH of 0-.2, an engine mass fraction of .2-.23, and a maximum takeoff weight of about 4000 lbs. This narrowed design range was then applied to an existing Matlab and Simulink tool on a unique aircraft design to simulate a hybrid turbo-electric aircraft flying a common mission profile. This tool was modified to output important metrics for analysis such as powertrain component power output, fuel and energy consumption, speed and range, and carbon emissions from energy used. Additionally, errors in the flows and assumptions of the tool were corrected to accurately model the weight and power use of the aircraft. With this revised simulation tool, a full mission was simulated for the example aircraft. Battery voltage and capacity, component power output, fuel and electricity use, aircraft mass, and speed and range were all analyzed and used to make design recommendations for the unique 2-passenger general aviation aircraft with a mission range of ~300 nautical miles.

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Terminology and nomenclature

DOH: Degree of hybridization

MTOW: Maximum takeoff weight

e_{bat}: battery specific energy at pack level

e_f: Jet fuel specific energy

η_1: Powertrain efficiency from engine to electric bussing

η_2: Powertrain efficiency from battery to electric bussing

η_3: Powertrain efficiency from electric bussing to fan

$\frac{L}{D}$: Lift to drag ratio

Φ: Power DOH

W_{PL}: Payload mass

W_{empty}: Airframe mass

SOC: State of charge

V_{nom}: Battery pack nominal voltage

Chapter 1: Introduction

1.1 Background Information

Significant effort and technical advancements are being made to positively impact climate change by reducing mass carbon emissions. To accomplish this, the transportation sector must quickly reduce CO_2 emissions from gas powered vehicles. Aviation, in the United States, makes up 11% of total transportation carbon emissions. This is a significant portion of emissions, and if emissions from aviation continues to grow at its current pace – about 34% in the past five years [1] – engineers must continue to work to reduce or eliminate emissions from the aviation industry.

1.1.1 Electrified Propulsion Systems

The aviation industry has long focused on optimizing internal combustion engines to reduce fuel consumption and improve efficiency, but emissions are fundamentally a part of naturally aspirated propulsion systems. Therefore, electric systems are an attractive option for eliminating emissions from the aviation industry. The two main current energy storage systems for creating an emission-free powertrain are batteries and hydrogen.

Hydrogen systems rely on hydrogen gas to power a fuel cell, creating electrical power to drive a motor connected to a fan as seen below in figure 1. Hydrogen powered aircraft have been developed in the past in the form of demonstration aircrafts but have not become commercialized. Now, groups such as NASA, Airbus, and ZeroAvia are making strides in hydrogen aircraft developments with Airbus aiming for a 2035 rollout of their concept design, and with ZeroAvia focused on performing component ground testing for continued development efforts.

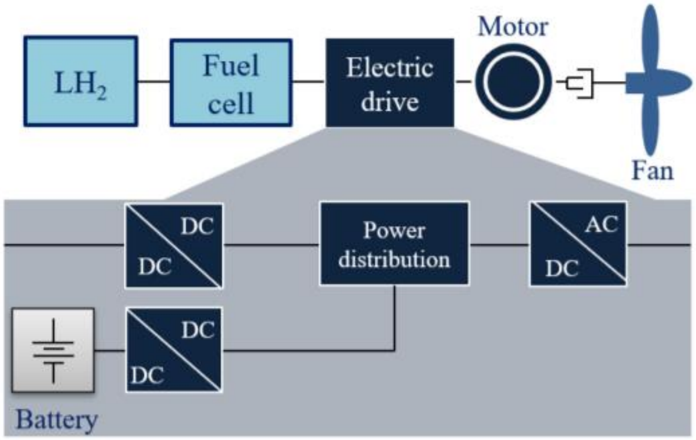


Figure 1: Hydrogen Propulsion System Diagram [3]

The other main form of electrified propulsion systems in development are battery powered systems. Figure 2 below illustrates several configurations of hybrid electric propulsion systems (HEPS) and a pure electric system.

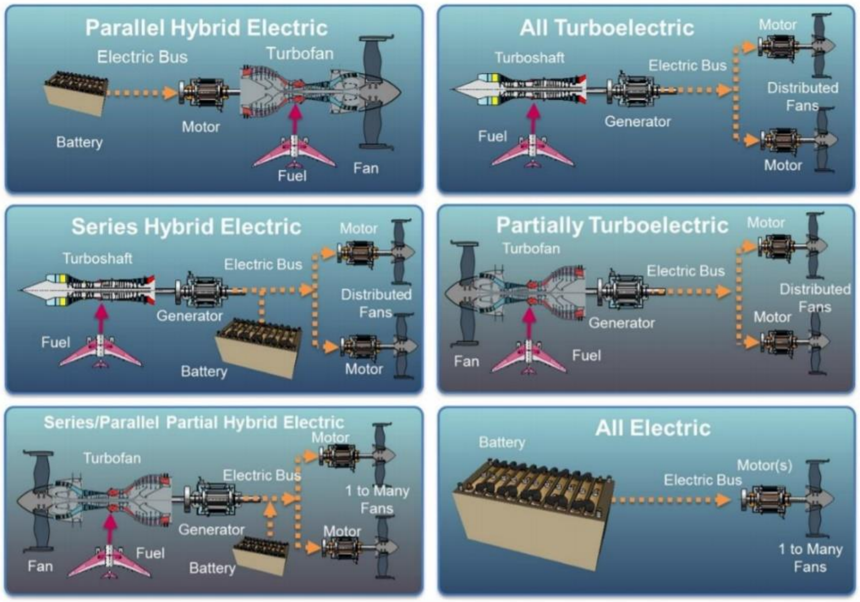
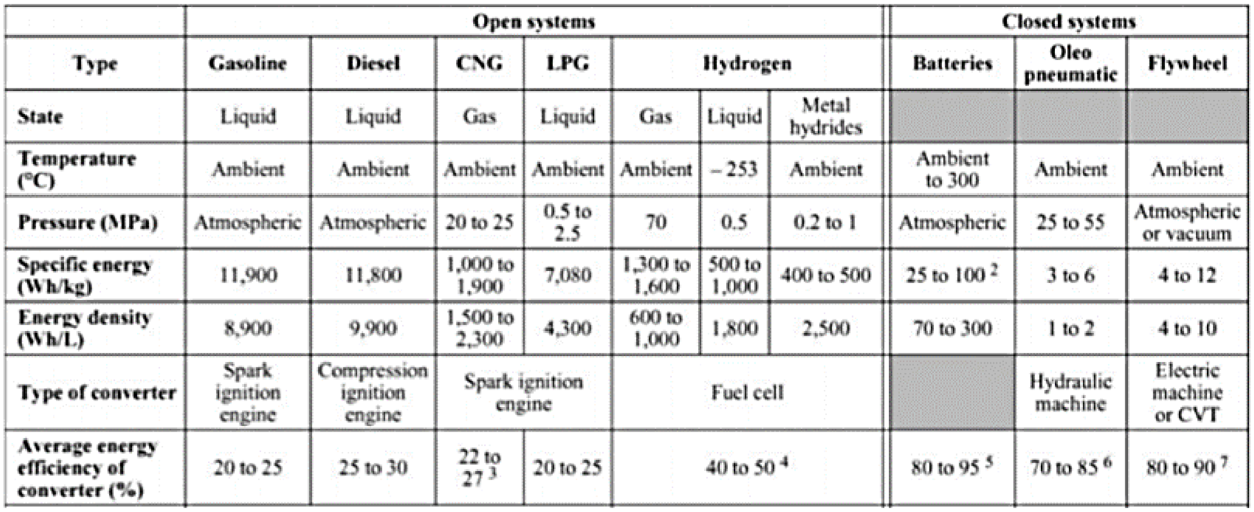


Figure 2: Electrified Propulsion System Diagrams [4]

1.1.2 Strengths and Weaknesses of electrification

The primary benefit of electrifying aircraft propulsion is the potential to reduce or eliminate harmful emissions associated with gas systems. In theory, a fully electric powertrain powered by electricity purely generated from renewable sources would have zero emissions from end to end. However, current limitations on the gravitational specific energy and energy density of batteries and hydrogen heavily restrict their performance despite their higher efficiencies than gas systems.

These limitations can be seen in figure 3 below, where specific energies and energy densities of hydrogen and batteries, compared to gasoline, are ~15/5 times lower and ~100/50 times lower, respectively. This factor is the main limitation in electrifying aircraft, because they would need a much higher energy storage system (ESS) mass to achieve the same range as an internal combustion propulsion system. However, the extra mass drastically reduces aircraft performance and produces marginal benefits for range after a point.



	Open systems							Closed systems		
Type	**Gasoline**	**Diesel**	**CNG**	**LPG**	**Hydrogen**			**Batteries**	**Oleo pneumatic**	**Flywheel**
State	Liquid	Liquid	Gas	Liquid	Gas	Liquid	Metal hydrides			
Temperature (°C)	Ambient	Ambient	Ambient	Ambient	Ambient	– 253	Ambient	Ambient to 300	Ambient	Ambient
Pressure (MPa)	Atmospheric	Atmospheric	20 to 25	0.5 to 2.5	70	0.5	0.2 to 1	Atmospheric	25 to 55	Atmospheric or vacuum
Specific energy (Wh/kg)	11,900	11,800	1,000 to 1,900	7,080	1,300 to 1,600	500 to 1,000	400 to 500	25 to 100[2]	3 to 6	4 to 12
Energy density (Wh/L)	8,900	9,900	1,500 to 2,300	4,300	600 to 1,000	1,800	2,500	70 to 300	1 to 2	4 to 10
Type of converter	Spark ignition engine	Compression ignition engine	Spark ignition engine		Fuel cell				Hydraulic machine	Electric machine or CVT
Average energy efficiency of converter (%)	20 to 25	25 to 30	22 to 27[3]	20 to 25	40 to 50[4]			80 to 95[5]	70 to 85[6]	80 to 90[7]

Figure 3: Energy Storage System Comparison [5]

Liquid hydrogen also requires extremely low temperatures in its system and needs advances in the safety of its storage and distribution before it can be used in an aircraft. Batteries are also limited by concerns of safety in avoiding thermal runaway. Both potential systems face infrastructure issues in terms of speed of refueling and electricity and hydrogen distribution.

However, despite these limitations, due to environmental and potential aerodynamic benefits of electrification and proven technologies, there is promise for future growth. Electrified systems could greatly lower aircraft emissions, allow for more flexible propulsion integration to improve aerodynamics through concepts such as distributed propulsion, and have very high instantaneous power outputs that can enable short or vertical takeoff concepts. To achieve these potentials, batteries must significantly advance to store more energy and output more power.

1.1.3 Electrified Aircraft Design and Simulation

To accelerate the commercialization of electrified propulsion, the design space must be fully explored to find the best design points and accurately simulated to analyze their performance and optimize the systems. Therefore, quick and accurate design and simulation techniques are highly important to quicken the entrance of service for such aircraft.

In the design phase for gas systems, empirical techniques that have been refined for decades are often used. These techniques cannot yet be used for electrified systems as not enough designs exist for empirical techniques to accurately predict performance. Design for electrified systems must also be agile due to the constantly changing field of electrical components used in propulsion. Additionally, hybrid systems introduce several variables such as degrees of hybridization for energy (ratio of energy in one ESS to another) and for power (ratio of rated power in one form of prime mover to another) that make design more complex, as illustrated below in figure 4. To this point, typical design methods must be modified for electrified systems and especially for hybrid systems. Development of software packages to aid these design methods is important, with an emphasis on modularity for quick comparison of different propulsion system configurations.

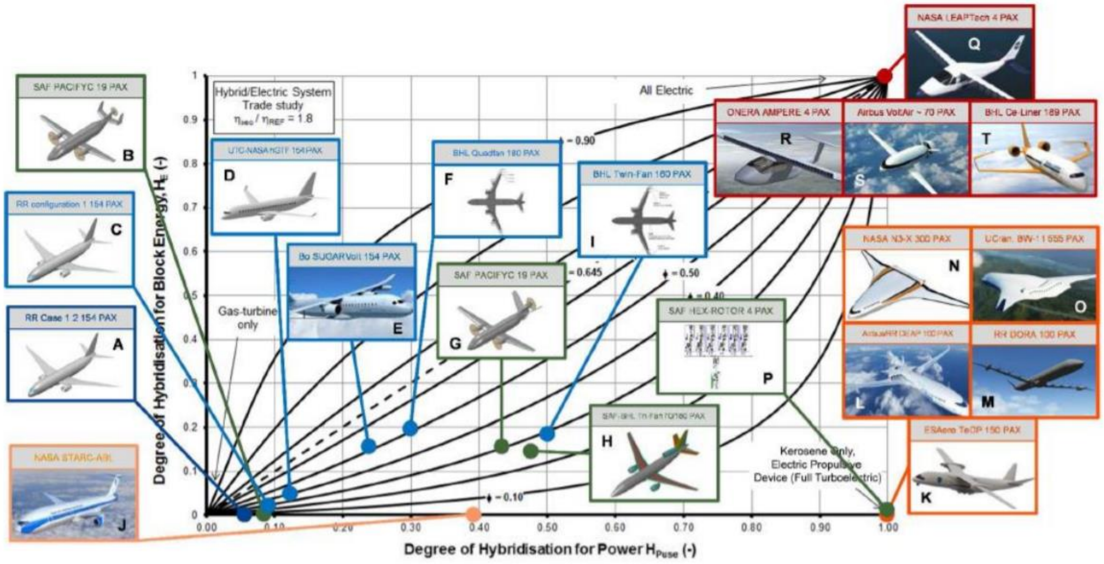


Figure 4: Electrified Aircraft Design Space [6]

For simulation and modeling there is currently a lack of accessible, physics-based simulations of electrified propulsion systems. Similar simulations and models are well covered for gas systems, but accurate models of electrical components and their interaction with gas components in hybrid systems still need development.

1.2 Research motivation and objective

This research aims to make progress in the areas of hybrid electric aircraft propulsion system design and simulation, specifically focused on hybrid electric systems with battery packs as the electric ESS to simplify the design considerations.

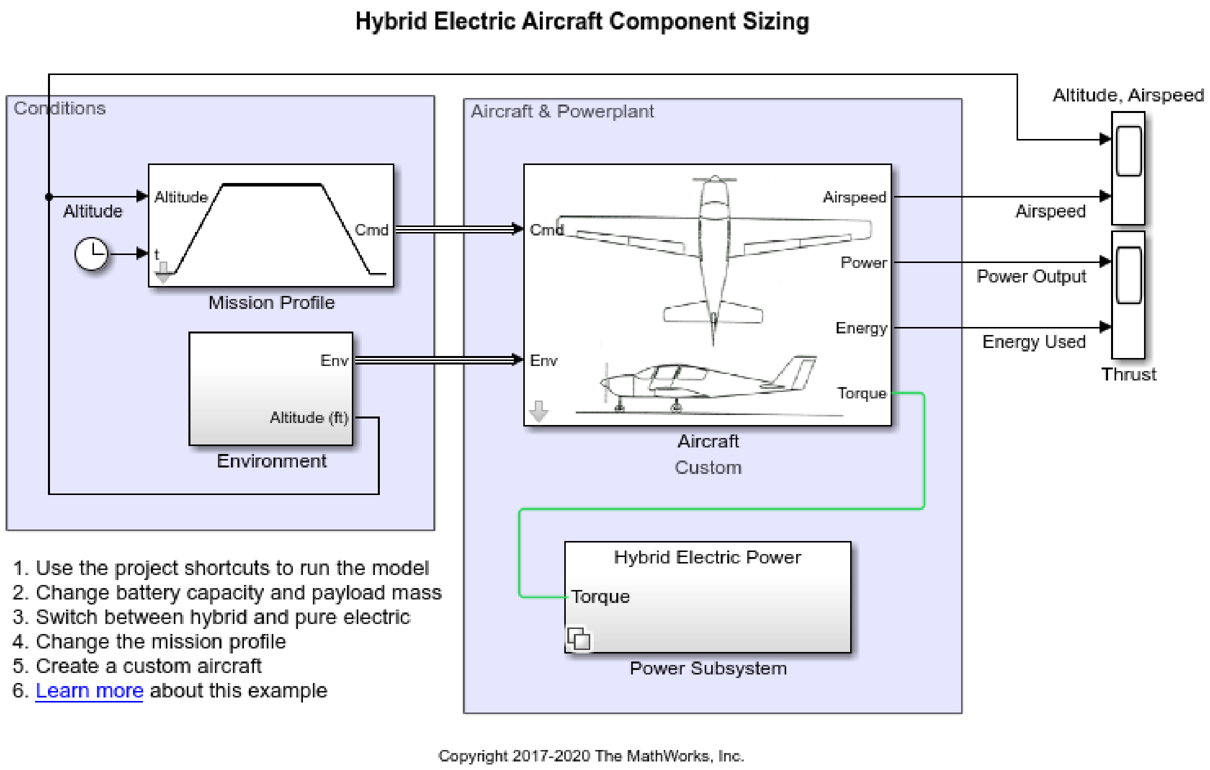
In design, this research surveys different design methods developed specifically for hybrid electric propulsion systems and design software packages that have features specifically for electric systems. Using a selected design method and software package, an example hybrid electric general aviation aircraft was designed to exemplify the strengths and weaknesses of both. An electric propulsion modeling and simulation tool, specific for the example aircraft, was developed and used to analyze the performance of the aircraft against a similar gas-powered aircraft. These results will contribute to industry knowledge on methods and tools to improve the design and simulation processes for electrified aircraft outside of proprietary knowledge.

Chapter 2: Example Aircraft and Design Case

2.1 Design Software Package Selection

To increase the accuracy and speed of the propulsion system design for the aircraft in this paper, a software package was chosen to calculate aircraft performance. The software package requirements were to be preconfigured to deal with a hybrid electric aircraft in the general aviation class, be free of cost and open source, and be implemented in a familiar coding language and environment. This list of requirements was considered in order to efficiently support simulation tool development specific for the aircraft design classification and desired operational flight strategy. These requirements quickly eliminated most software packages and led to the selection of the MATLAB and Simulink project ‘Electrical Component Analysis for Hybrid and Electric Aircraft’ [7].

The selected MATLAB and Simulink project consists of a Simulink model of a hybrid powered, configurable general aviation aircraft that calculate performance over a prescribed mission profile and MATLAB scripts that assess the impact of battery capacity and payload size on range. The Simulink model consists of 4 different subsystems: mission profile, environment, aircraft, and power, all of which can be seen below in figure 5 with their various connected inputs and outputs.



1. Use the project shortcuts to run the model
2. Change battery capacity and payload mass
3. Switch between hybrid and pure electric
4. Change the mission profile
5. Create a custom aircraft
6. Learn more about this example

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Figure 5: Hybrid Aircraft Design Simulink Model

The power subsystem, seen below in figure 6 is a Simscape model of a series hybrid with an engine and generator power system, a battery, a DC-DC convertor and motor, and an offtake load block for the lamp, heater, avionics, and fuel pump. The engine is a generic engine model that uses a 3rd-order polynomial to calculate power at a given torque request. The generator and motor are modeled using permanent magnet synchronous motors tabulated by tabulated torque-speed envelopes. The battery is modeled with a series internal resistance and a voltage source defined by equation 1 below.

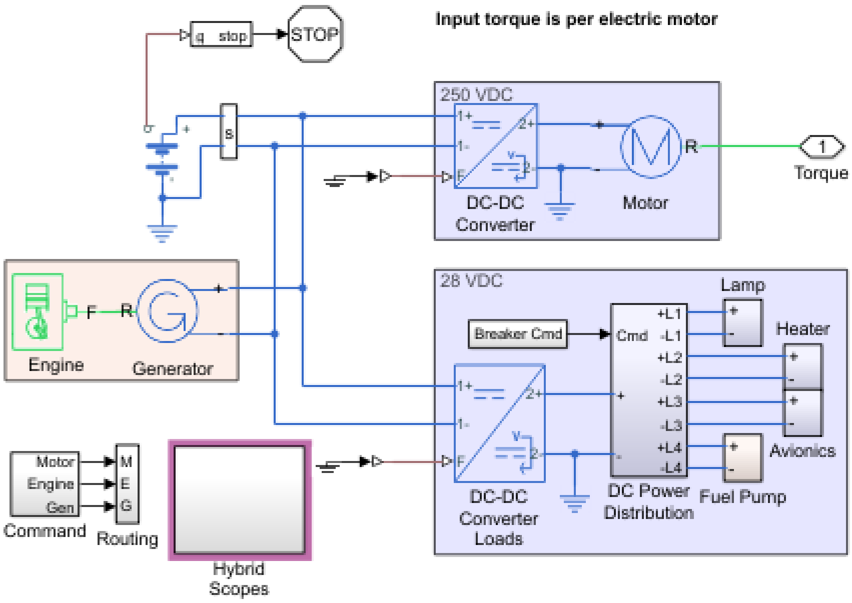


Figure 6: Power Subsystem

$$V = \frac{V_{nom} * SOC}{(1-\beta)*(1-SOC)} \quad \text{(Eq. 1)}$$

The Environment subsystem calculates the aircraft altitude based on vehicle speed and angle and feeds the altitude into a COESA atmosphere model. This model returns the air absolute temperature, density, and pressure for use in the point mass dynamics block of the Aircraft subsystem. The project initially assumes the wind velocity and angular rates as 0 to simplify the calculations.

The aircraft subsystem treats the aircraft as a 4th order point mass with weight, lift, drag, and thrust being the four forces in effect. Roll and bank angles are both assumed to be constants of zero, while flight path angle and angle of attack are inputs from the mission profile subsystem. From these inputs and the environment inputs, the point mass dynamics calculate airspeed, which is used to calculate required power, and the corresponding required torque from each electric motor, while assuming a constant reference motor RPM. The block outputs this torque requirement, as well as power, energy, and airspeed.

Finally, the mission profile subsystem outputs the flight path angle that is calculated dependent on whether the aircraft is taking off, climbing, cruising, or descending. The takeoff segment is a fixed time that the project sets initially as 30 seconds and there is an additional 30 seconds of flight time at the end of the mission where flight is level at the aircraft's descent velocity. The time spent in the climb, cruise, and descent segments are calculated from the entered mission altitudes, distance, speed in each segment, and rates of climb and descent.

The built-in design scripts of the project include sweeps of battery capacity, payload, and a combined sweep, and displays their effects on aircraft range. A combined sweep with the default custom aircraft parameters can be seen below in figure 7.

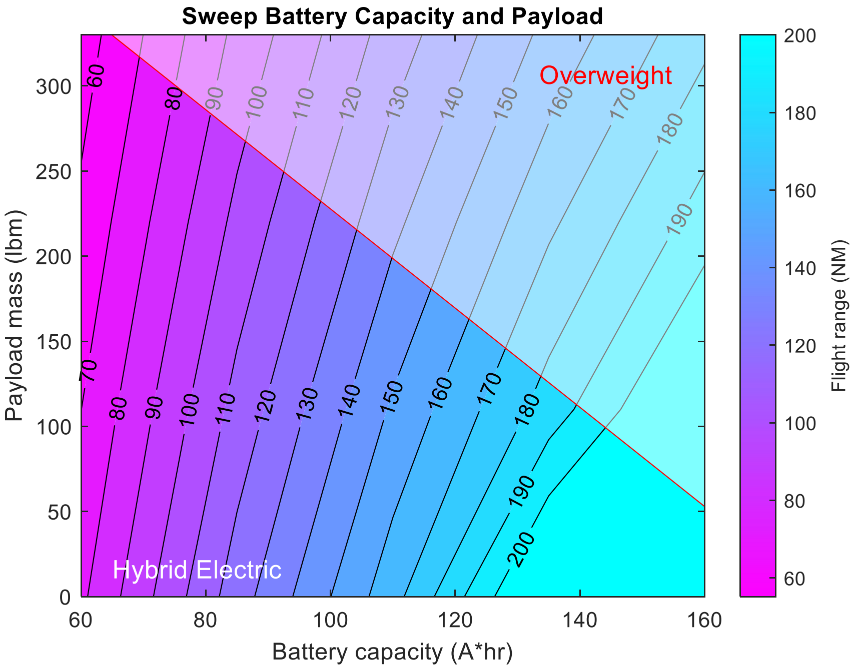


Figure 7: Built-in Payload and Battery Capacity vs Range Sweep

2.2 Design Scope and Method

The scope of this design example will focus primarily on the propulsion system sizing for a 2-PAX, general aviation aircraft. The propulsions system layout has been selected as a turboelectric system with two wing mounted thrust vectoring fans, potentially with a battery as a second ESS to form a series hybrid propulsion system. The aerodynamic and geometric properties of this aircraft were design choices and assumptions to reduce the complexity of the design space and narrow it to the propulsion system. This aircraft will be referred to as the Viaggio in the rest of this paper, and a preliminary sketch can be seen below in figure 8 (Copyright Whitfield Aerospace LLC ©).

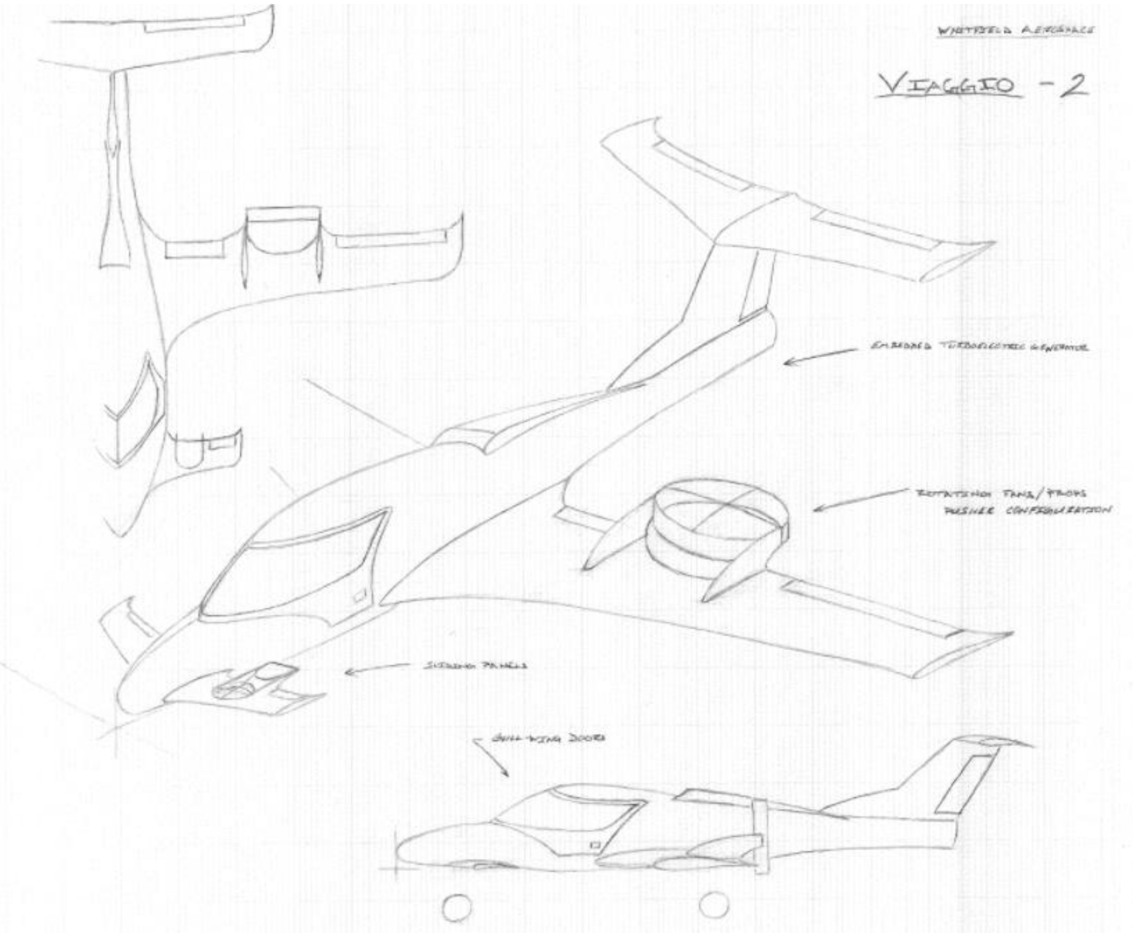


Figure 8: Viaggio Conceptual Drawing

The propulsion system diagram can be seen below in figure 9 using The American Institute of Aeronautics and Astronautics (AIAA) standard component figures for hybrid electric aircraft propulsion systems. The main components of the serial hybrid system make up a combustion branch, electric branch, and the power distribution to the motors and propellors. The combustion branch includes a fuel tank, turboshaft engine, and generator to generate electric power from jet fuel. The electric branch has a battery to store electric energy and an inverter to convert the DC power of the battery to the AC power used by the motors. The electricity from both branches is passed into bussing then through cables to controllers that drive the motors providing power to the two fans.

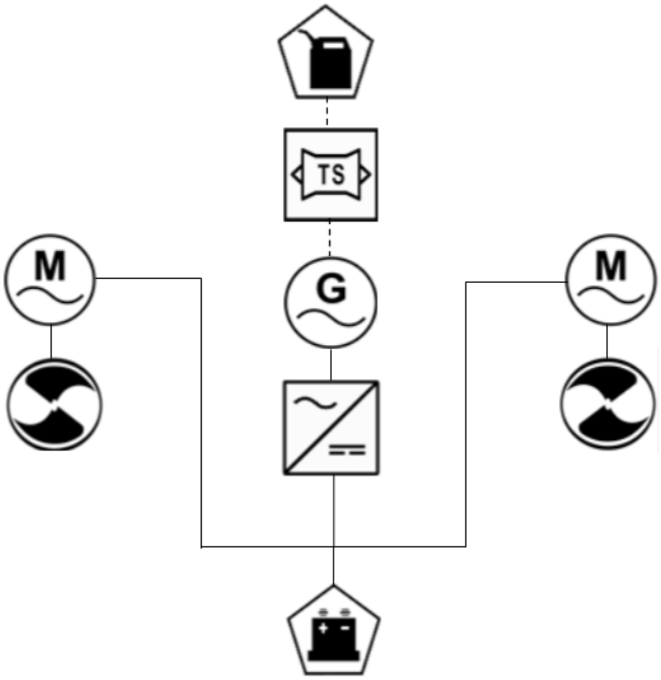


Figure 9: Propulsion System Block Diagram

The design mission profile will be a simple mission profile, with the segments being warm up, takeoff, climb, cruise, descend and loiter, and descend and land.

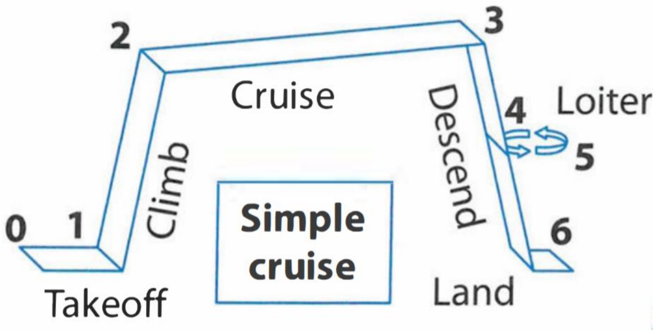


Figure 10: Example Mission Profile [8]

The design analysis will begin with the cruise segment of the mission profile. The power required to meet the design cruise speed will be determined, and an initial analysis of design variable effects on cruise range will be performed.

After cruise analysis, the simulation tool will be used to perform a full analysis of the powertrain during the desired mission. The simulation tool will provide more detailed calculations on the performance of the powertrain, information on the individual components over time, and will be a better representation of the full mission as it will include climb and descent portions of the mission.

2.3 Initial Design Analysis

The first portion of design analysis for this research was to determine the general size of powertrain components that would be required to meet the performance goals for the aircraft. To find these sizes, three design variables were parametrically varied: the size of the aircraft, represented by maximum takeoff weight (MTOW), the amount of energy stored in the battery versus fuel, represented by degree of hybridization (DOH), and the size of the engine as a fraction of the MTOW. With each iteration, the resulting range, speed, endurance, fuel cost, electricity cost, and carbon emissions were calculated and plotted. However, quickly calculating these values for a full mission profile at many different design points would quickly become too complicated and computationally expense. Therefore, a simplified analysis was needed. Since the cruise segment is the longest and most energy consuming portion of the mission, the preliminary sizing analysis was performed only for the cruise segment.

The methodology of the initial cruise analysis began with the assumptions of constant variables used in the sizing equations. All variables with assumed values can be seen in table 1 below.

The specific power ratings of the generator and engine are based off modern examples of similar components for other aircraft. The price of grid electricity is based on the business rate for electricity in Ohio, where this aircraft is to be developed. Component efficiencies are based on current state of the art of for each component, with significant input from an AIAA course on the design of electrified aircraft. A constant payload of 190 kg (418) was chosen to reflect two passengers and their equipment.

The sizing calculations are performed by varying the engine mass fraction, DOH, and MTOW, and calculating the 6 performance variables listed previously for each combination of the design variables. The mass of the airframe is calculated first as half of the MTOW, the payload weight is a constant of 190 kg, the engine mass is calculated as a function of DOH and MTOW as seen in equation 2 below; The generator mass is calculated based on the power of the engine and the specific power of the generator, and the motor weight is calculated as a fraction of MTOW. With all these weights accounted for, the remaining weight (M_{energy}) is allotted to the battery and fuel to power the aircraft, with the mass of the battery being sized by equation 3 below. With the mass of the battery sized based on DOH, the remaining weight is set as the fuel weight.

Table 1: Assumed Variables and Value Ranges Used

Powertrain Variables		Aerodynamic and Geometric Variables	
Variable	**Value**	**Variable**	**Value**
Battery Specific Power	200 w/kg	Payload Mass	190 kg
Engine Specific Power	1180 w/kg	MTOW	2500-4000 lbs (1,136-1,818 kg)
Generator Specific power	3139 w/kg	Empty Weight	1500-2500 lbs
Fuel Energy Density	10,000 wh/L	Wing area	125-150 sq. feet
Fuel Specific Energy	12,0000 wh/kg	Aspect ratio	8-12
Jet Fuel Price	$.642/L	Oswald efficiency	.08-.95
Grid Energy Price	$.1015/kWh	Cruise CL	.1-.25
Jet Fuel Density	.8 kg/L	CDo	.01-.015
Engine Mass Fraction	.15-.23 of MTOW		
DOH	0-1		
C02 Per Gallon of Jet Fuel	2.58 kg/liter		
C02 per watt hour of grid energy	1222/2.2/10^6		
Gas to bus efficiency	.3*.98		
Battery to bus efficiency	.98*.98		
Bus to thrust efficiency	.98*.98*.9		
Battery Specific Energy	250, 500 wh/kg		

$$M_{engine} = EngineMassFraction * (1 - DOH) * MTOW \qquad \text{(Eq. 2)}$$

$$M_{battery} = \frac{e_f * M_{energy} * DOH}{e_{bat} - (DOH * e_{bat}) + (e_f * DOH)} \qquad \text{(Eq. 3)}$$

Using these equations, the engine size has a trend of decreasing as DOH increases and increasing as engine mass fraction and MTOW increase. Battery mass decreases as engine mass fraction increases and increases as DOH and MTOW increase.

With the powertrain sized, the performance variables are then calculated. The cruise range and speed are calculated using equations 4 and 5 below. The range equation's derivation can be seen in the paper by Reynard de Vries [9]. The endurance is then calculated by dividing the range by the speed. The fuel and electricity costs and emissions are the total values reached if the aircraft were to utilize its full range, which were calculated by multiplying the fuel and electricity used by their respective unit costs and unit carbon emissions.

$$Range = \eta_3 \frac{e_f}{g} (\frac{L}{D})(\eta_1 + \eta_2 \frac{\Phi}{1-\Phi}) ln[\frac{W_{empty}+W_{PL}+(\frac{g}{e_{bat}})E_{tot}(\Phi+(\frac{e_{bat}}{e_f})(1-\Phi))}{W_{empty}+W_{PL}+(\frac{g}{e_{bat}})\Phi E_{tot}}] \quad \text{(Eq. 4)}$$

$$Speed = P_{tot} * (\frac{LD}{MTOW*g}) \qquad \text{(Eq. 5)}$$

With the variable ranges listed in table 1 and a battery specific energy of 250 Wh/Kg, a pack level value achievable with today's technology, the results in figure 11 above were calculated. The most important figures in these results are the speed and range of the aircraft, as those define the overall performance and whether the aircraft can be used for any practical applications.

As a benchmark for performance comparison, this paper introduces the Cirrus SR20, a comparable all gas-powered general aviation aircraft. The aircraft can be seen below in figure 12 and summarized with the specifications seen on page 17 in table 2.

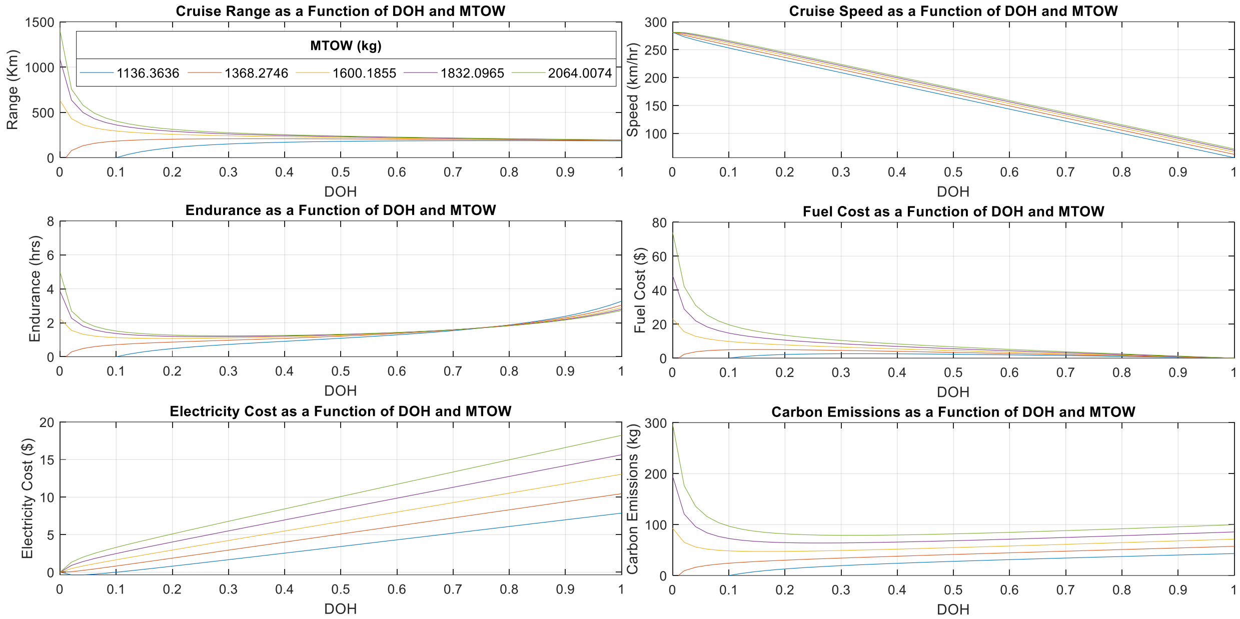


Figure 11: Cruise Analysis, Engine Mass Fraction = .23, Battery Specific Energy = 250 wh/kg

Figure 12: Cirrus SR20 Aircraft [10]

Table 2: Cirrus SR20 Perfomance Statistics

Specification	Value
Power	215 hp
Max Cruise Speed	155 knots (287km/hr)
Max Range (55% power)	709 nautical miles (1,313 km)
Useful Load (Fuel and payload)	1028 lbs (469 kg)

The first comparison made is a common sense check of the range and speed of the Viaggio as a fully gas powered aircraft (DOH = 0). This comparison shows that the top range and speed of the Viaggio at 0 DOH is very similar to that of the SR20. At increasing DOH, the Viaggio shows a large drop in cruise speed and an even higher drop in range, with a fully electric aircraft expecting to have a range of ~250 km (135 nm) and a top speed of ~75 kph (40.5 kts). While the operating cost would be lower with a fully electric aircraft than with a fully gas aircraft, this would be at a greatly reduced performance point and would not justify the lower cost. Additionally, the carbon emissions drop quickly at DOH 0-.2 but sees no benefits beyond this range.

The effects of MTOW are significant on the costs of electricity and fuel at high and low DOH, respectively, emissions, and on range at low DOH. Higher MTOW leads to higher costs and carbon emissions, but significantly more range up to .1 DOH due to the extra weight allocated for energy storage. Elsewhere, changing MTOW has insignificant effects on the performance of the Viaggio.

Another design variable explored was the mass fraction of MTOW allocated for the engine. Increasing the mass fraction of the engine increased the power and the speed of the aircraft but reduced the mass available for energy storage and therefore reduced the range. These

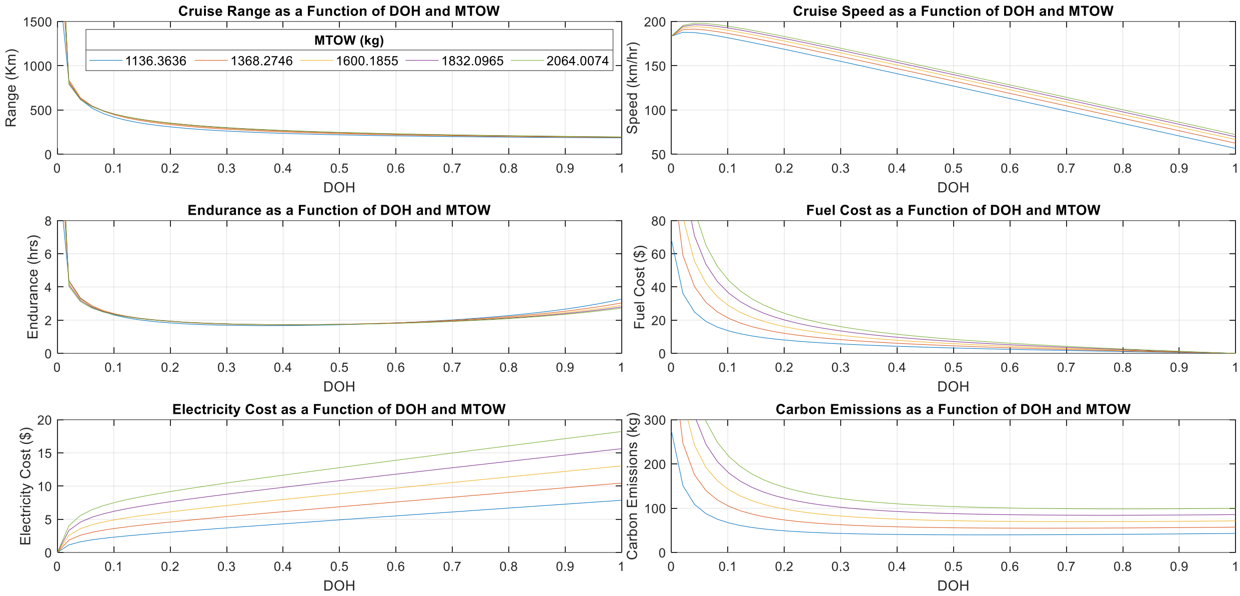


Figure 13: Cruise Analysis, Engine Mass Fraction = .15, Battery Specific Energy = 250 wh/kg

differences can be seen from figure 13 above, which are the same calculations performed previously but with an engine mass fraction of .15 instead of .23. Here the speed does not surpass 200 kph (108 kts) but the range increases significantly, past 3000 km (1620 nm). While this range is attractive, the Viaggio is unlikely to be utilized at missions of that range frequently enough to justify the decrease in speed resulting in the smaller engine.

With such low speed performance at the lower range of engine mass fractions, a mass fraction of >.2 MTOW is suggested to align with the desired performance of the Viaggio. The mass fraction, however, must be limited to avoid having no weight left for energy storage and creating an aircraft with extremely limited range.

The goal of the Viaggio is to be an alternative for frequent commutes that are excessively long to drive on a regular basis and don’t have a public transportation alternative (drive of 1-3 hours). For example, the drive from Cincinnati to Columbus. This drive takes about 2 hours to complete and could be often required of someone with relatives, business, or other interests in one while living in the other.

As figure 14 below shoes, this flight would require a range of 100 miles. To be able to complete the roundtrip and have enough range to turn around before the halfway point on the return trip, a range of 300 miles (482 km) would be required. A similar range is potentially attainable at DOH 0-.2, the same range where increasing DOH reduces range the most but also reduces carbon emissions the most.

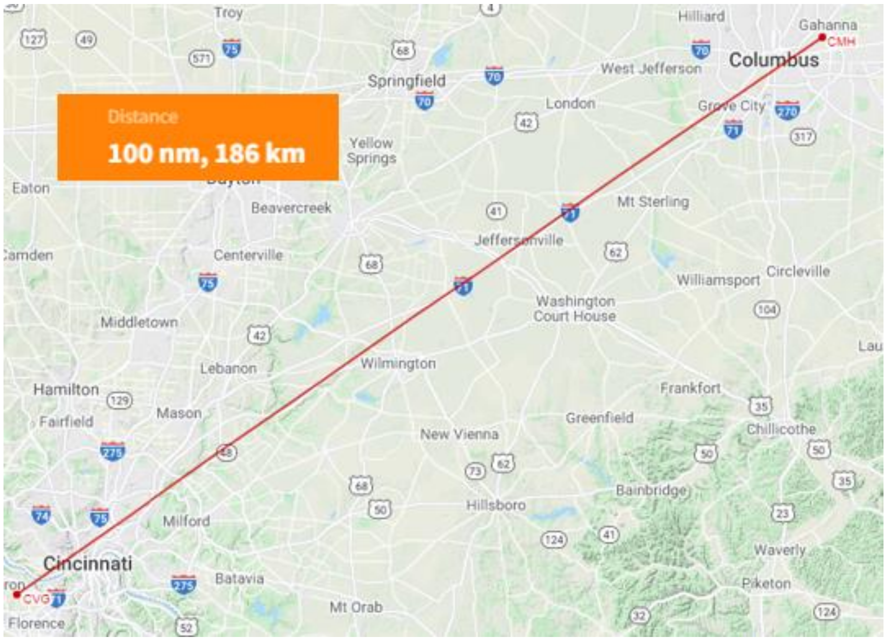


Figure 14: Example Mission Between Cincinnati and Columbus

The final variable considered was the battery specific energy. If the Viaggio's entry to service (ETS) was expected to be past 2030, the pace of battery technology improvement suggests specific energy could improve from ~250 wh/kg to 500 wh/kg. The results in figure 15 below display the effects of this specific energy increase. While the marginal returns on carbon emission reductions and constant reduction of speed with increasing DOH still suggest a max DOH of ~.2, the range at this level of electrification could be as high as 600 km (323 nm), widening the capabilities of the Viaggio.

The results of this initial cruise analysis suggest the Viaggio should have a DOH of 0-.2, an engine mass fraction of .2-.23, and a MTOW as high as possible without significantly altering the aerodynamics. For now, that mass will be assumed to be 4000 lb (1818 kg).

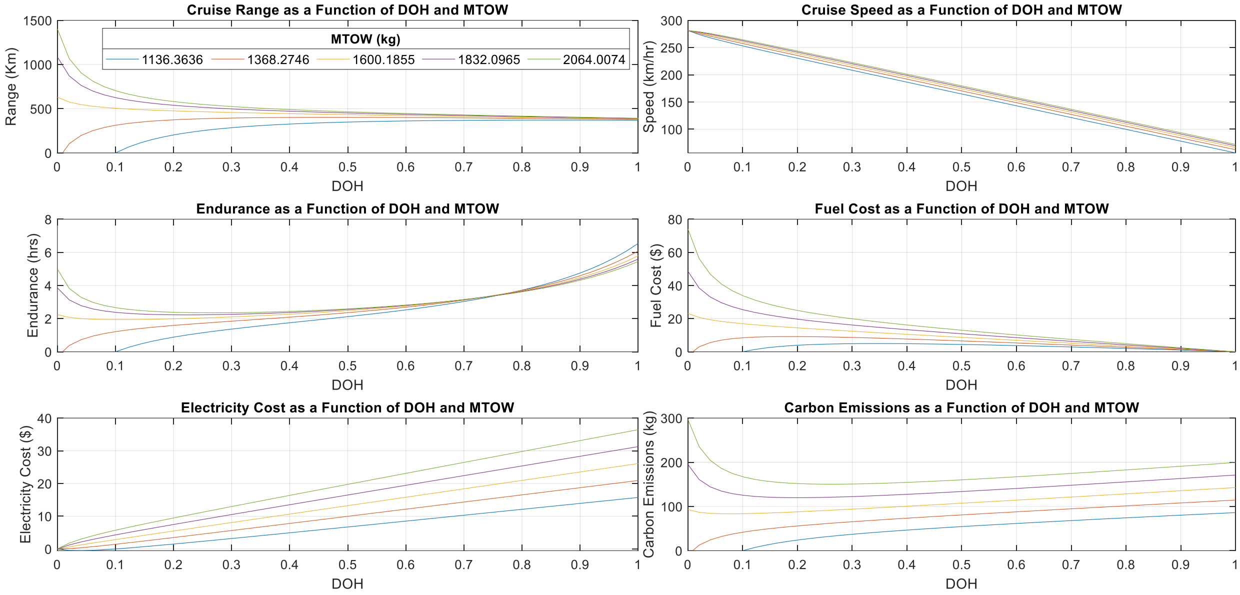


Figure 15: Cruise Analysis, Engine Mass Fraction = .23, Battery Specific Energy = 500 wh/kg

Chapter 3: Modeling and Simulation Development

3.1 Simulation Tool Results Reporting

With the initial cruise analysis completed, the next part of this research was to use a simulation tool to perform more detailed analysis on the performance of the Viaggio. As described in the section ‘Design Software Package Selection’ of this paper, the Matlab and Simulink project that was selected for detailed analysis has several built-in functions that could be useful for various aircraft analyses. However, specific values that were important to the analysis performed in this research were not easily visualized through the standard outputs of the project. The first task in the detailed analysis of this research was to modify the simulation tool to output figures that quickly and easily visualized the desired values.

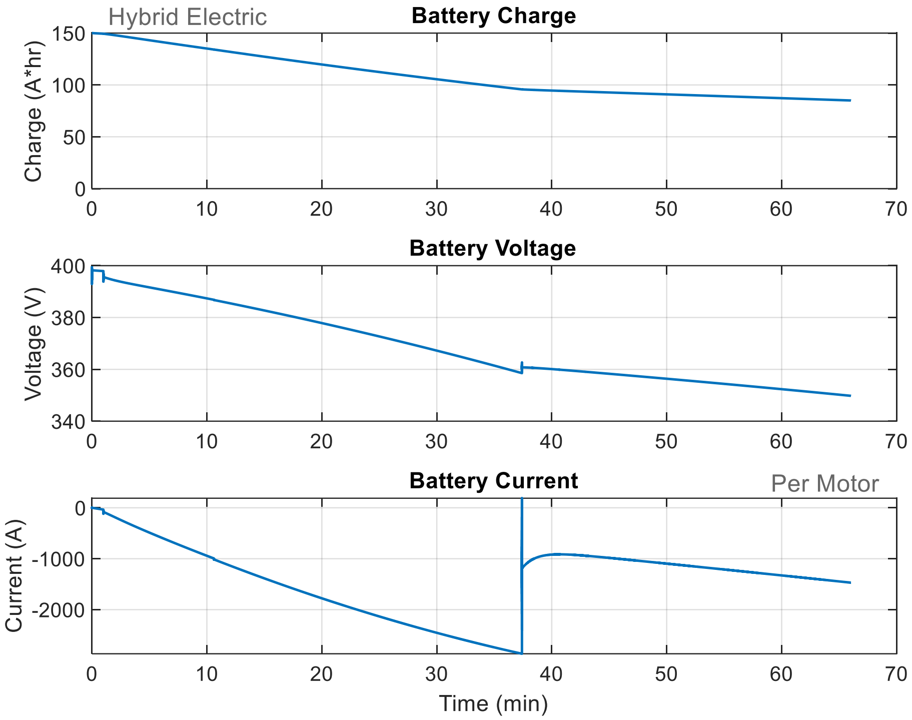


Figure 16: Battery Pack Analysis

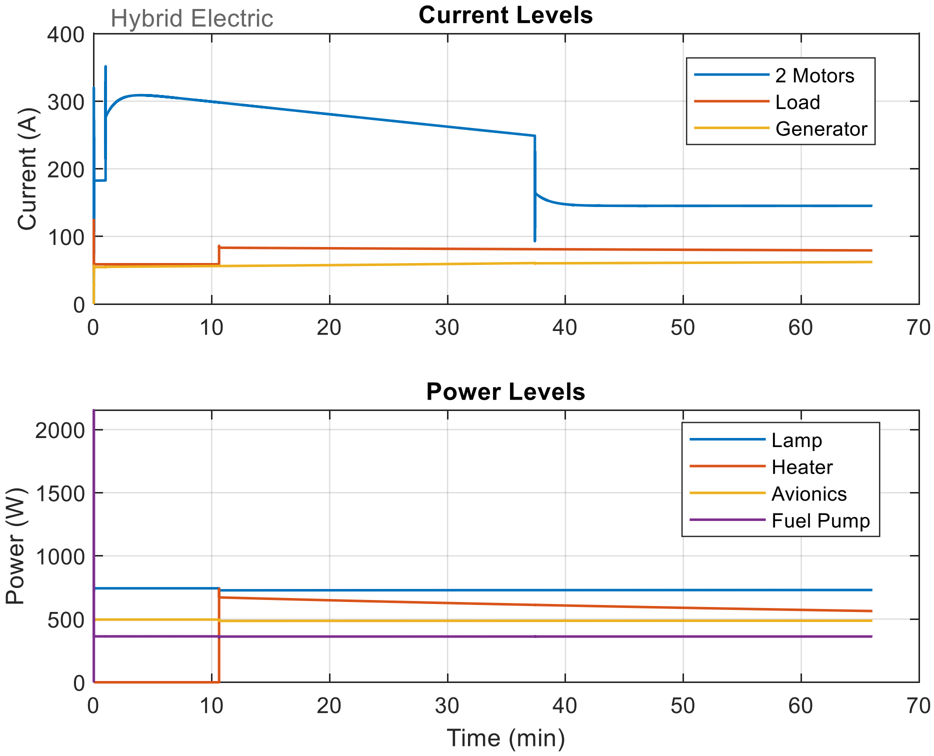


Figure 17: Component Current and Power Analysis

Figures 16 and 17 above show the original figures of the simulation tool, depicting useful information on the electrical components of the aircraft. The first figure added to the output was a plot showing the mission profile as defined by altitude and time of the run, and the airspeed of that profile. This figure was added to see how capable of performing the desired mission the aircraft was and at what speed that range was accomplished and can be seen in figure 18 below. The second figure added was a small dashboard of singular values that describes the performance of the aircraft in 4 metrics and can be seen in figure 19 below.

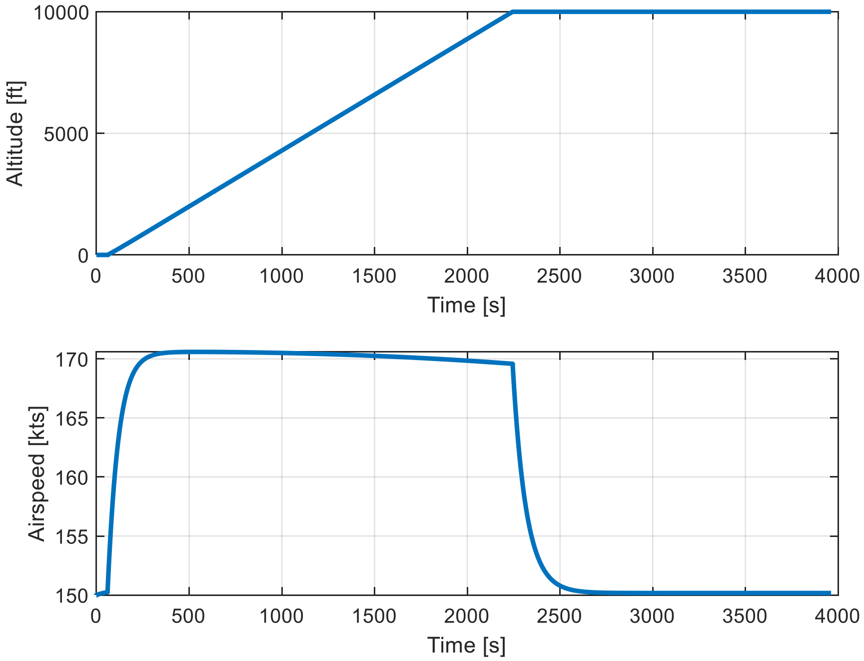
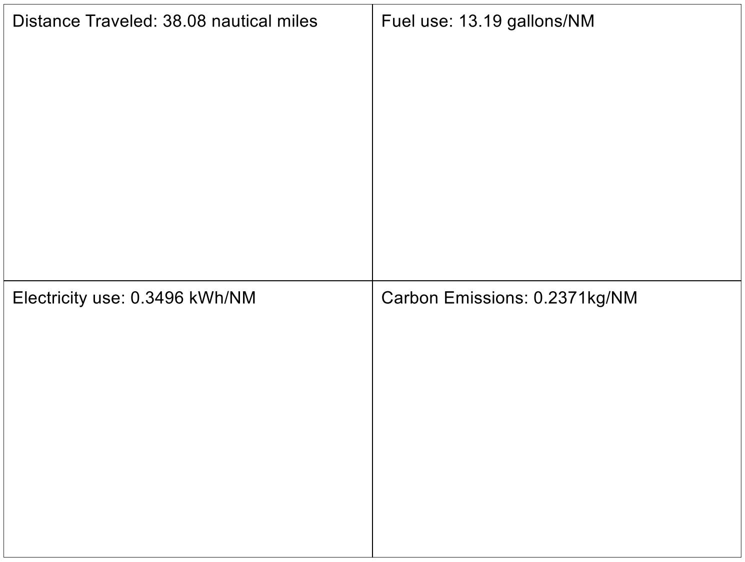


Figure 18: Airspeed and Elevation Figures



Distance Traveled: 38.08 nautical miles

Fuel use: 13.19 gallons/NM

Electricity use: 0.3496 kWh/NM

Carbon Emissions: 0.2371kg/NM

Figure 19: Initial Dashboard Output

3.2 Simulation Tool Development and Improvement

The next step in this research is to take the assumed feasible design range from the cruise analysis earlier in the research and analyze the performance of such an aircraft using the more detailed simulation tool. The goal of this step was to produce a more detailed analysis of the aircraft's performance over a full mission profile with less assumptions and more information about the specific components in the propulsion system.

This analysis included improving the outputs of the simulation further to include details on the operating cost, degree of hybridization, fuel left after the mission, and takeoff mass of the aircraft after sizing of the battery, an example of this updated figure can be seen below in figure 20. Another figure was created to visualize the power output of the overall aircraft as well as the motors, battery, and generator, and an example can be seen below in figure 21.

Distance Traveled: 326.70 nautical miles	Fuel use: 0.1792 gallons/NM
Electricity use: 0.4396 kWh/NM	Carbon Emissions: 1.992kg/NM
Operating Cost: 0.4805 $/NM	DOH Energy: 0.0771
Fuel Remaining: 18.89 kg	Takeoff Mass 4068 lbs

Figure 20: Improved Dashboard Output

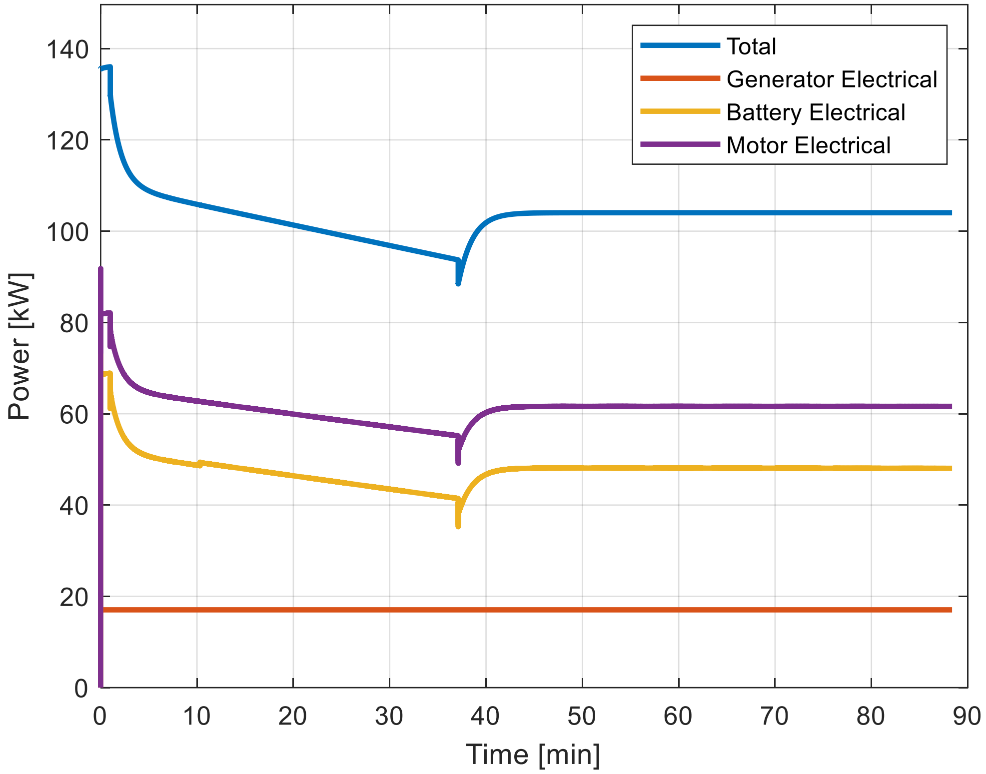


Figure 21: Powertrain Electrical Power Outputs

With these additional outputs added and a design point in the range of the cruise analysis assumptions loaded, the simulation was ran for a powertrain with ~ .2 DOH point to assess its performance. This simulation produced the results seen below in figure 22. While this suggests the aircraft performed quite well, the results are not in line with what was found during the cruise analysis. For a slightly higher DOH and lower MTOW, the simulation expects the aircraft to go a similar range with significant fuel and battery power reserves after completing the mission. These results prompted a further review of the simulation tool's powertrain model. The simulation tool's powertrain model can be seen below in figure 23.

Table 3:Initial Powertrain Model Mission Results

Distance Traveled	347.27 Nautical Miles
Fuel Use	.00808 gallons/NM
Electricity Use	.2204 kWh/NM
Carbon Emissions	.2012 kg/NM
Operating Cost	.04202 $/NM
DOH Energy	.2291
Fuel Remaining	46.13 kg
Takeoff Mass	3387 lbs

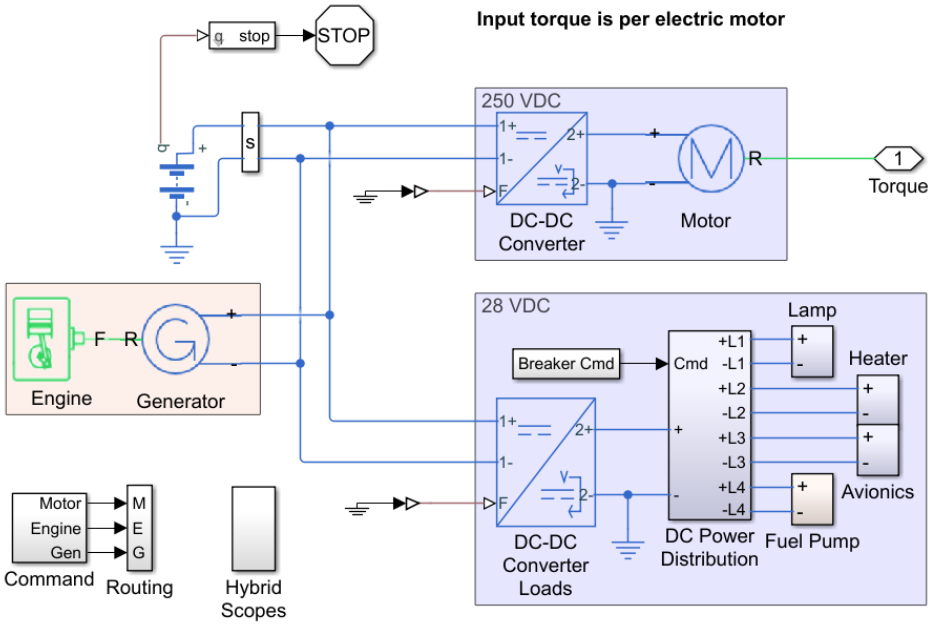


Figure 22: Initial Powertrain Model

The flow of the simulation starts with deriving a torque requirement from applying the desired speed to the set mass and aerodynamic characteristics. This torque requirement is then input to the motor in the powertrain model but divided by the number of motors to determine how much power would need to be provided by each motor in the powertrain. The issue with this approach is the power that is then drawn from the battery and generator are also divided by the number of motors, and this division makes for an inaccurate calculation of the power drawn from the energy sources. So, while the outputs of the motor performance were accurate for this initial model, the battery, generator, and engine were all being calculated to run at much lower operating points than they would in reality.

To resolve this issue, a second motor model was added in parallel to the original motor model, with the torque requirement of one motor being applied to each motor as seen below in figure 24. This change created a much more accurate simulation of the power draw from the battery and generator in the propulsion system, as seen below in figure 25.

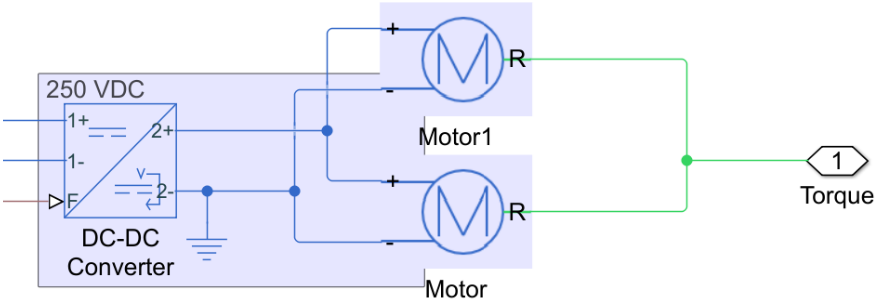


Figure 23: Parallel Motor Model

The electrical power of the generator and battery surpass the total power of the aircraft that is calculated from its velocity and thrust, however this result is expected as some of this electrical power would be lost to electrical losses from transmission and efficiency of the motor, and some would be lost mechanically to the motor and propellor connection and the efficiency of the propellor.

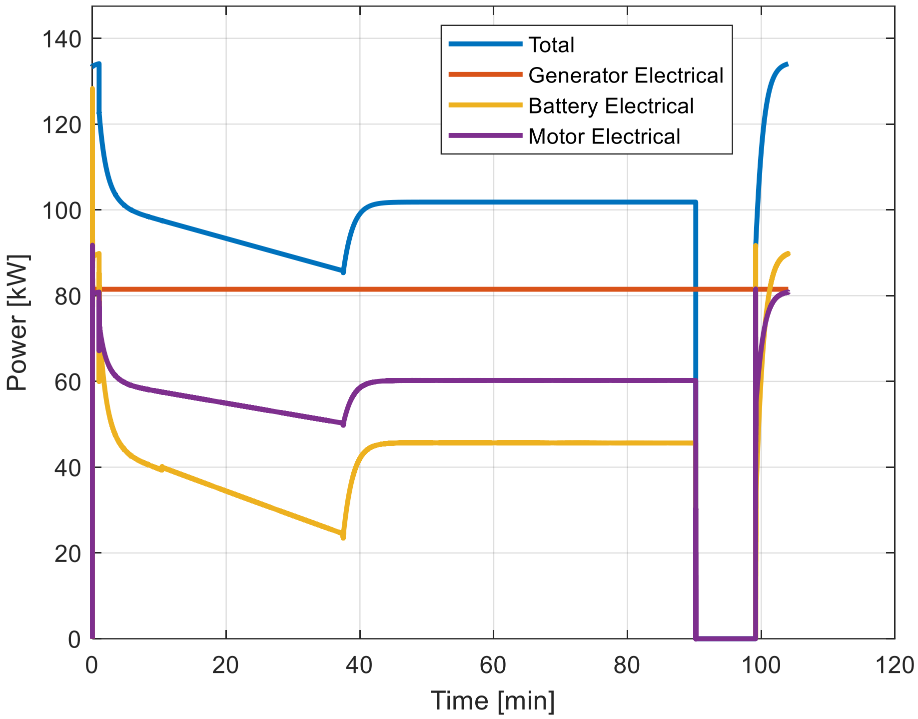


Figure 24: Electrical Power Output With Parallel Motor Model

While the results of this simulation were now more realistic than before, the takeoff weight was still projected to be lower than expected and the performance more optimistic than expected. One further source of this difference was the weights of components in the propulsion system. The simulation tool accounted for the battery and engine system mass, but did not include mass inputs for the generator and motor masses. For the 0-.2 DOH range, the previously done cruise analysis recorded generator masses of ~115 kg and total motor masses of ~130 kg. While these values would change depending on the sizing of the other components in the system, these masses were entered as constants and added to the mass calculation of the aircraft as shown below in figure 26.

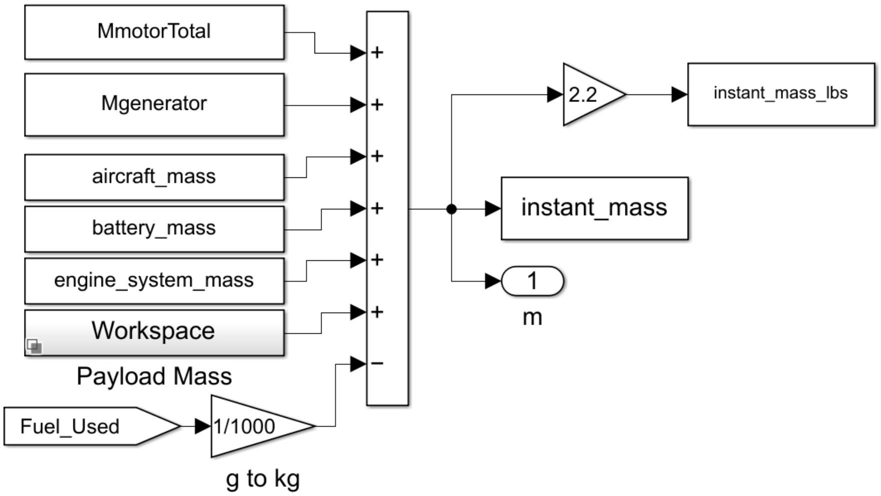


Figure 25: Aicraft Mass Calculation

With these mass assumptions updated the performance of the aircraft hardly changed, although the takeoff mass was more in line with the cruise analysis results, providing a takeoff mass of 3893 lbs.

Another large discrepancy in the simulation tool with the cruise analysis was the amount of fuel used during the mission. With the preliminary engine parameters, the simulation was calculating a fuel burn of ~10 kg for a 350 Nm, while the cruise analysis was calculating a fuel burn of ~200 kg for a similar range mission. This difference was seen likely as caused by not updated fuel burn parameters in the engine model, despite increasing the size and weight of the engine significantly.

To accurately calculate the fuel burn of the Viaggo, the engine model had to be updated with fuel burn data of an engine of similar size to that which it will use. To do so, the Rolls-Royce RR500 turboprop engine’s parameters were used to fill out the simulation tool’s engine model parameters, including engine mass, maximum power, and fuel burn at several power operating points. These values can be seen below in table 3.

Table 4: Rolls Royce RR500 Turboprop engine parameters [11]

Parameter	**Value**
Dry Mass	225 lbs (102 kg)
Maximum Power Output	475 hp (354 kW)
Maximum Continuous Power	400 hp (300 kW)
Cruise Power	350 hp (260 kW)
Max Power Fuel Burn	294.5 lbs (133.6 kg) per hour
Max Continuous Power Fuel Burn	259.6 lbs (117.8 kg) per hour
Cruise Power Fuel Burn	136.95 lbs (107.48 kg) per hour

While the engine in the Viaggio will be a turboshaft engine, it was assumed that the turboprop engine is similar enough to a turboshaft engine that would be used of the same power and size to use these values in the engine model. The RR500 was a good choice for the engine because of its power ratings – 260 to 354 kW aligns with the engine power sizing from the cruise analysis. Additionally, the fuel burn data being available for multiple operating points of the RR500 was useful for updating the engine model of the simulation tool.

After updating the engine model, the simulation produced a fuel remaining value of -126.3 kg, clearly meaning the Viaggio did not have enough fuel for this mission. This is as expected, as the DOH for this mission was .22 and the cruise analysis results had a DOH of .22 likely not being able to reach the mission range of 300+ Nm. Therefore, these results suggest the fuel burn calculations are more accurate and can be assumed to be sufficient for moving forward.

The results of this section show that, while this simulation tool is a useful starting point, it cannot be assumed to be highly accurate in its assumptions or calculations in all parts of the tool.

Any discrepancies with the previous cruise analysis had to be investigated and changed if they significantly deviated from the cruise analysis assumptions or calculations, although some difference was expected. Moving forward, this must be kept in mind when the simulation tool is used for analysis to avoid trusting results from inaccurate calculations.

Chapter 4: Simulation Results and Analysis

The final section of this research focused on using the simulation tool from the previous section to find an aircraft propulsion system design capable of accomplishing the mission that was used to benchmark the cruise analysis. Additionally, this aircraft was compared to the same design without a battery pack to see if the battery pack has any positive impact on the design, as well as to the Cirrus SR20 for comparison to an existing competitor.

4.1 Simulated mission results

The most consistent issue with attempted aircraft designs during this section was the Viaggio would run out of fuel, or the battery would drop too low in capacity, and both would keep the aircraft from running at full power and therefore be unable to finish its mission. This issue was resolved by slightly increasing the battery pack voltage and capacity, as well as significantly increasing the fuel weight on board the aircraft. Table 4 below summarizes the design of the propulsion system, while figures 27-29 summarize the results of the mission.

Table 5: Simulated Viaggio Propulsion System Metrics, Hybrid

Parameter	Value
Battery Capacity	300 Ah
Battery Voltage	600 V
Engine Mass	200 lbm
Fuel Mass	428 lbm
Engine RPM Setting	3200
Generator Torque Demand	100 Nm

Table 6: .077 DOH Design Mission Results

Distance Traveled	326.7 Nautical Miles
Fuel Use	.1792 gallons/NM
Electricity Use	.4396 kWh/NM
Carbon Emissions	1.992 kg/NM
Operating Cost	.4805 $/NM
DOH Energy	.0771
Fuel Remaining	18.89 kg
Takeoff Mass	4068 lbs

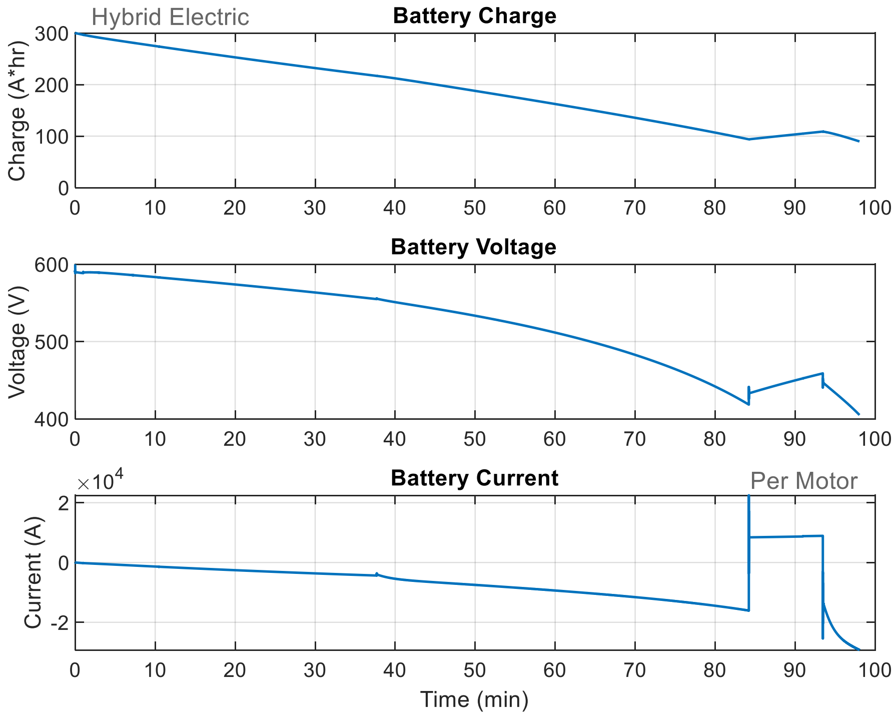


Figure 26: Simulated Viaggio Mission Battery Performance

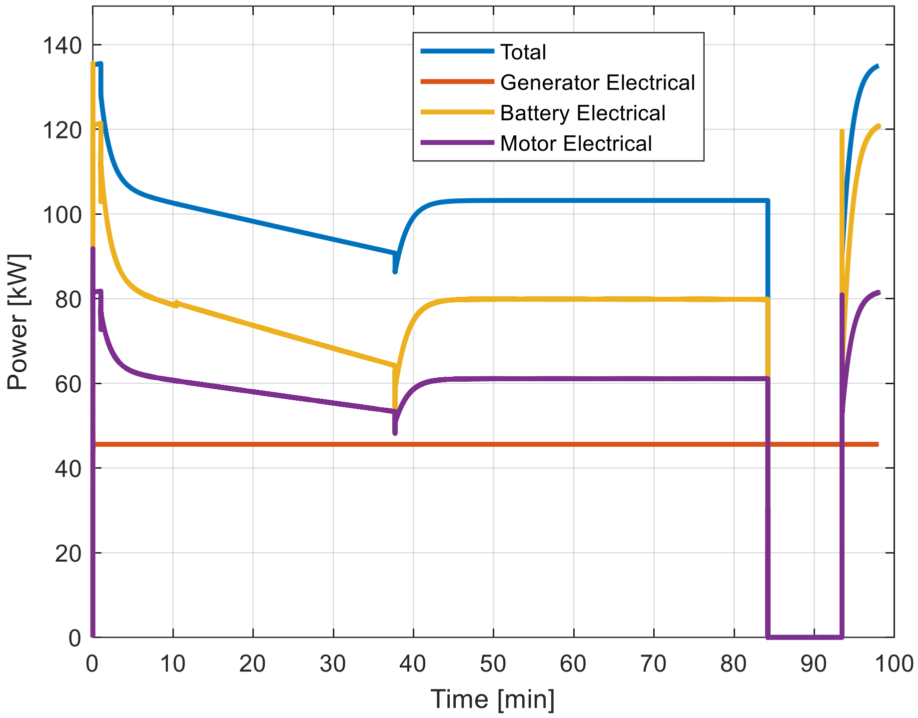


Figure 27: Simulated Viaggio Mission Component Power Output

The results of this simulation had the Viaggio weight 4068 lbs with a DOH of just over .06 to finish the mission with about 40 lbs of fuel left and about 100 amp hours of charge left in the battery, although at a significantly decreased voltage of about 400 V.

Comparing these results to the cruise analysis performed with a battery specific energy of 250 Wh/kg and an engine mass fraction of .23 MTOW showed similarities in the range and speed values, the two most important metrics considered for performance. At a DOH of .077 the cruise analysis gave a range of ~500 km (270 nautical miles) and a cruise speed of ~275 km/hr (150 kts) with a MTOW of 4000 lbs. With the simulation tool calculating a range of just over 300 nautical miles and a cruise speed of 200 kts, the simulation tool was more favorable of this design point than the cruise analysis.

One significant factor in this is likely the difference in engine masses. In the cruise analysis, an engine mass fraction of .23 MTOW was used to size the engine, and at 4000 lbs this brings the engine mass to 920 lbs. In the simulation, the parameters of the Rolls Royce RR500 were used, where the mass was only 225 lbs. This difference of almost 700 lbs left significantly more weight for battery and fuel sizing and suggests the cruise analysis engine sizing should be updated for future use to have a higher engine specific power value to be more realistic.

4.2 Results analysis and comparison

The first alternative powertrain that the previously described powertrain was compared to was a significantly reduced DOH system. The .077 DOH system was compared to a lower DOH system to determine if increasing the DOH improved the performance of the aircraft in terms of operating cost, fuel emissions, mass, and energy remaining at the end of the mission while having the same speed and range.

By reducing the battery capacity from 300 to 200 Ah and the battery voltage from 600 V to 300 V, the DOH of the aircraft was reduced from .077 to .026. The most significant impact of this change was in the mass of the aircraft, reducing it from 4068 lbs to 3442 lbs as seen in figure 30 below. This large weight reduction may be the main reason for the slightly improved performance of the lower DOH, where the operating cost, carbon emissions, and electricity used all slightly decreased. The fuel remaining in the aircraft at the end of the mission was ~10 kg lower than in the .077 DOH powertrain, but this difference could easily be made up for by increasing the fuel weight in the aircraft to begin with. Additionally, the battery remained essentially fully charged after the mission, as seen in figure 31 below.

Table 7: .026 DOH Design Mission Results

Distance Traveled	329.34 Nautical Miles
Fuel Use	.1857 gallons/NM
Electricity Use	.1716 kWh/NM
Carbon Emissions	1.906 kg/NM
Operating Cost	.4689 $/NM
DOH Energy	.0257
Fuel Remaining	11.09 kg
Takeoff Mass	3432 lbs

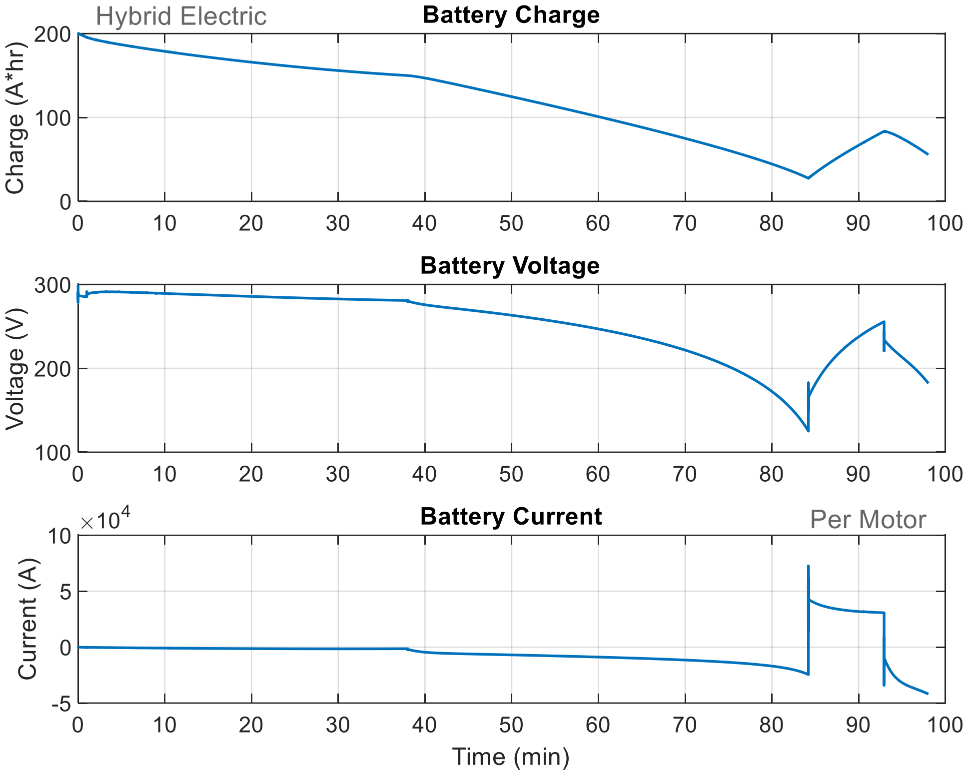


Figure 28: .026 DOH Propulsion System Battery Performance

By running the engine at a higher operating point in the lower DOH mission, more fuel consumed but the battery was very lightly utilized. With a mass of 313 lbs, the battery's mass would likely be better used towards increasing the size of the engine and adding more fuel so the aircraft can go faster and further, given that the even further increased size battery in the .077

DOH system increased carbon emissions or operating cost over the .022 DOH system rather than decreasing them as hoped.

To determine if this trend of higher DOH system reducing the performance of the Viaggio will continue to be true for future generations of batteries, the previous two architectures were simulated again with a higher specific energy value for the battery packs. In the previous simulations, a specific energy of 95.63 Wh/lb (210 Wh/kg) was used. In the following simulation results, a battery specific energy of 225 Wh/lb (495 Wh/kg) was used, similar to the 500 Wh/kg value used in the cruise analysis section for a futuristic battery pack specific energy value.

The results of the Viaggio's simulated mission at a 225 Wh/lb specific energy pack for .077 DOH and .026 DOH can be seen below in figures 32 and 33, respectively. Both design points saw improvements in their performance due to an over 500 lb weight decrease for the .077 DOH design and a 180 lb weight decrease for the .026 DOH design, both purely from a downsizing of the battery. The weight decrease led to a larger improvement in performance for the .077 DOH design in terms of reducing emissions and operating cost, however both of these values would still be outperformed by the .026 DOH design due to its significantly lower electricity consumption.

Table 8: .077 DOH Design Performance, 225 Wh/lb pack

Distance Traveled	328.59 Nautical Miles
Fuel Use	.1782 gallons/NM
Electricity Use	.4101 kWh/NM
Carbon Emissions	1.965 kg/NM
Operating Cost	.475 $/NM
DOH Energy	.0771
Fuel Remaining	18.89 kg
Takeoff Mass	3528 lbs

Table 9: .026 DOH Design Performance, 225 Wh/lb pack

Distance Traveled	329.33 Nautical Miles
Fuel Use	.1857 gallons/NM
Electricity Use	.1749 kWh/NM
Carbon Emissions	1.908 kg/NM
Operating Cost	.4693 $/NM
DOH Energy	.0257
Fuel Remaining	11.09 kg
Takeoff Mass	3262 lbs

From these results, an increased battery size and DOH do not positively impact the design of the Viaggio due to the increased carbon emissions and operating cost at the price points and carbon emission values considered, even with the improved battery technology expected in the near future. This suggests that increasingly electrifying the Viaggio’s propulsion system will not positively impact its performance unless external factors such as the fuel and electricity price and carbon emissions significantly change.

An important consideration for these results is that the operating cost and carbon emissions are derived values that are based on the fuel and electricity consumption of the aircraft, but also on external factors like the price of fuel and electricity and the carbon emissions of grid electricity and jet fuel. For example, if in the future a perfect renewable energy system was set up to have a no cost, no emission electric grid, it would make sense to electrify an aircraft as much as possible without affecting range and speed. However, this is not plausible in the foreseeable future and a detailed analysis of this is outside the scope of this research. The carbon emission and cost values for fuel and electricity are listed below in table 5 for reference.

Table 10: Fuel and Electricity Unit Costs and Carbon Emissions [8],[12]-[14]

	Cost	**Carbon Emissions**
Fuel	2.43 $/Liter	9.75 kg/gallon
Electricity	.1015 $/kWh	.555 kg/kWh

Chapter 5: Conclusion

5.1 Summary and conclusions

The first objective of this research was to conduct a cruise analysis for a 2-passenger, general aviation, hybrid electric aircraft to narrow down the range of feasible design options to be considered in later design phases. The target for performance of the aircraft, named the Viaggio, was to replace intermediately long drives between cities and at least halve the time these journeys would take. An example mission between Cincinnati and Columbus was considered, with a distance of 100 nautical miles. To halve the time it takes, a speed about 150 knots would be required, and a range of 300+ nautical miles would enable the aircraft to complete the mission in both directions with significant reserves to account for any rerouting and regulations required.

With these requirements in mind, the DOH (degree of hybridization), takeoff mass, and engine size of the aircraft were explored at battery pack specific energies of 250 Wh/kg and 500 Wh/kg. The analysis showed that past a DOH of .2, the Viaggio would not be able to meet the requirements, and carbon emissions and operating cost benefits could not justify the reduction in range and speed. The aircraft mass and engine mass fraction were found to be best at the high end of the ranges considered setting the aircraft mass at ~4000 lbs and the engine mass fraction at .23 of the takeoff weight.

The second goal of this research was to develop an existing hybrid aircraft simulation tool to be useful for more detailed design of the Viaggio. The hybrid aircraft simulation tool, developed by Mathworks as a Matlab and Simulink project named ‘Electrical Component Analysis for Hybrid and Electrical Aircraft’, included a full aircraft model and scripts that simulated a desired mission and provided models of components of the aircraft to determine the aircraft and its components performance over the mission. The simulation tool needed several changes to be useful for the analysis required for the design of the Viaggio. First, the simulation needed several more outputs added to the built in figures, the first figure added was a dashboard that reported important statistics on the run including fuel use, carbon emissions, distance covered, fuel remaining and more. Additional figures added include the aircraft elevation and speed as functions of time and power outputs of the individual components of the aircraft and the aircraft as a whole. Next, the simulation did not account for the weight of the generator or motors in the aircraft, both of which add significant weight to the propulsion system. Therefore, the weight calculation of the aircraft was changed to include the weights of the generator and the motors, with both being assigned initial values of 115 lbs to align with results of the cruise analysis. The weight calculation also did not account for the fuel weight, so the fuel weight was accounted for in the airframe weight in the simulation tool and included as a variable in the mission script. Finally, only one motor model was included in the powertrain model, causing the electricity and fuel use values to be highly underreported and the results of the simulation to be overly favorable. A second identical motor model was added in parallel to the first, allowing the simulation to more accurately calculate the fuel and electricity consumption needed to complete the mission.

With this updated simulation tool, a powertrain design with a DOH of .077 was found to be able to complete a mission of 300+ nautical miles with a cruise speed of 200 knots, and a small amount of fuel and battery charge remaining at the end of the mission. This result shows a slightly higher performance than the same DOH in the cruise analysis, likely due to the ~700 lbs lower mass of the engine in the simulation based on the Rolls Royce RR500 engine rather than calculating a theoretical engine mass based on a specific power value and desired power output.

Additionally, a payload weight was not added to the simulation and allowed for more weight to be devoted to fuel and battery size than in the cruise analysis.

While this powertrain was determined to be feasible for the mission, a lower DOH of .026 was used to complete the mission at the same speed but had a lower operating cost and carbon emissions with similar amounts of energy remaining between the battery and fuel. This remained true at a futuristic battery specific energy value of 225 lbs/wh (~495 Wh/kg), although the difference became very small at this value. These results that while the desired mission can be successfully completed with an electrified aircraft, higher levels of electrification do not provide reduced carbon emissions or operating costs in current market conditions. This could change as renewable energy allows energy to become cheaper and less carbon intense but calculating the point at which this becomes true was outside the scope of this research.

5.2 Limitations and future work

Both sections of this research could be improved upon with future work. In the cruise analysis, some assumptions can be changed to be more accurate and consistent with the simulation tool, and the outputs can be altered to be more readable and easier to compare. Specifically, the assumption about the specific power of the engine could be increased in future work to align with the engine used in the simulation tool and the carbon emissions and operating cost values in the cruise analysis could be divided by the range of the design point so they are easier to compare to other design points with different ranges. Other key assumptions, such as component specific powers and energies and efficiencies should be updated to match the components used in the simulation tool to be consistent with each other.

In the simulation tool, the engine fuel consumption and power data would benefit from more data points so fuel consumption calculations would require less interpolation in an effort to improve accuracy. Similarly, the motor and generator torque and efficiency values should be compared to a potential motor and generator to ensure the data for those values is reasonable. Other than the accuracy of the model and its assumptions, the speed at which the simulation tool can be used to explore the design space could be greatly improved by building on its current sweep features. The simulation tool's current sweep features include sweeping the battery size, payload, and range at max payload. These features could be altered to output the same figures as the single mission simulation and new ones to compare the range, speed, operating cost, and carbon emissions over the desired range. Additional sweeps for electricity and fuel prices and emissions could be added to determine their effects on operating cost and total emissions. This would still benefit from a narrow design range to avoid assumptions becoming inaccurate, but it would allow a specific point in the desired range to be singled out more quickly.

After the sizing is done and a design is selected, the simulation tool can serve as a base for creating a more detailed simulation tool for the selected design. This tool could include more accurate models of the engine, models down to the individual cells in the battery pack, systems not considered in this one such as thermal systems, and more. Additionally, a better energy management strategy could be tested and used in future simulations. The simulations in this research brought the batteries down to a capacity of ~.33, leaving room for more utilization of the battery energy that could also allow for the engine to be turned off intermittently during a mission. This simulation tool could continue being built upon throughout the design process to aid with design decisions and help explore the hybrid aircraft design more thoroughly before prototyping begins.

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