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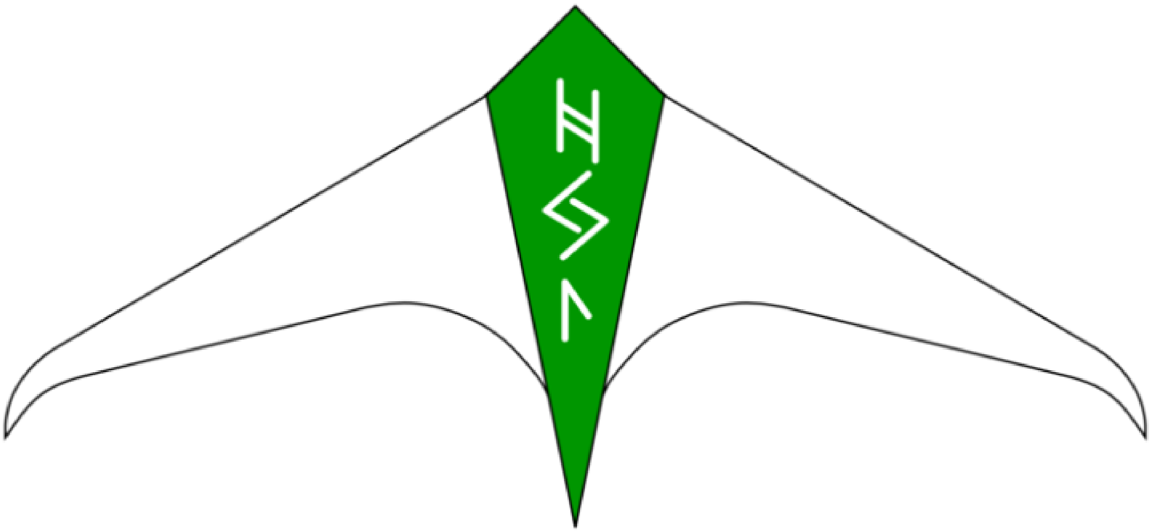
Hybridisation of fuel cells and batteries for aerial vehicles



Bachelor's thesis report
Emil Botling
Katrin Sheibeh
Martin Wood

Examiner:
Prof. Göran Lindbergh

Supervisors:
Martina Butori
Dr. Björn Eriksson

Abstract

There is an ever growing need for environmentally sustainable alternatives in today's society due to the looming threat of greenhouse gasses. One field where the need for new environmentally friendly solutions is needed is the aviation industry. The problem the industry is facing is due to the weight and space constraints that exist in aerial vehicles. In this bachelor project a solution for unmanned drones is proposed where it is powered by a hybrid solution consisting of batteries working together with fuel cells. The batteries compliment each other where the fuel cell is a lightweight energy source while the battery is used to combat the changing power demand. This project was done in collaboration with the Green Raven project to evaluate the optimal setup to power the energy system for an hour. The work was done theoretically in Matlab and Simulink to find the optimal system. From these simulations, data was collected to calculate the optimal configuration between batteries and amount of hydrogen stored in the Hydrogen tank. It was concluded that the best option to store the hydrogen was in a 2 liter tank at 300 bar together with 2 additional batteries with the capacity of 4000 mAh. This setup was concluded as the best option as it used up all hydrogen and landed with less charge in the battery than at the start point.

Sammanfattning

I takt med den globala uppvärmningen så växer behovet av klimatmedvetna hållbara lösningar. Ett område i stort behov av innovation är flygindustrin som länge varit en av de största klimatbovarna. Flygindustrin stora problem är att dess fordon både har begränsad volym och vikt. I detta kandidatexamensarbete kommer vi diskutera en hybridlösning där obemannade drönare drivs av en hybridlösning där batterier tillsammans med bränsleceller driver drönaren. Batterierna och bränslecellerna komplimenterar varandra då bränslecellerna är är lättviktiga och tillför en stabil produktion av ström till drönaren medan batterierna agerar komplement och hjälper till när det behövs extra kraft. Projektet som i samarbete med The Green Raven project utfördes för att utvärdera det optimala systemet för att förse drönaren nog med kraft i en timme. Projektet har utförts teoretiskt i Matlab och Simulink för att hitta den optimala balansen mellan batterier och bränsleceller. Från dessa simuleringar samlades data in för att optimera konfigurationen mellan bränslecellerna och batterierna. Från resultaten drogs slutsatsen att 2 batterier med en kapacitet på 4000 mAh som tillsammans med vätgas som förvarades i en 2 liter tank med ett tryck på 300 bar var den bästa konfigurationen. Denna lösning ansågs som den bästa då all vätgas förbrukades under simulation och att batteriet vid stopp hade en lägre laddning än vid flygstart.

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1. Introduction

The dependency on fossil based fuels is an ever looming threat to the existence of life on earth due to the greenhouse gasses which are released when it is combusted. The largest contributor to the emissions of greenhouse gasses is the transportation industry with 27% of the share [1]. The aviation industry is a major contributor to this and is in need of innovation to be in line with the UN:s goal for sustainability[2].

In most cases the propellant of choice to replace fossil fuel in aerial drones are batteries. The problem with this is weight and size of the batteries which would take up a large capacity of both carrying weight and space if they would replace the fuels used today. Therefore, batteries are not a viable solution when it comes to aviation as both weight and space are limited. To combat this problem fuel cells are a solution which is both lightweight while it uses a renewable fuel source in hydrogen gas.

While hydrogen has quite low energy density in regards to its volume, it is also the most gravimetric energy dense substance[3]. So to harness the potential the hydrogen is kept in high pressure tanks. Due to hydrogen's atomic size this is possible as it will still be light weight as well as being compact. However this is not as easy as it seems as it is very hard to contain at these pressures due to its high diffusivity [3]. With this in regard it is faster to refuel hydrogen tanks than recharging batteries however it is not as easy and requires more infrastructure to do. It also poses a higher safety risk as the hydrogen gas is highly explosive.

Another major issue with using hydrogen as an energy source is the fuel cell itself. Fuel cells want to produce power at a steady state and are not suited for a variable workload. Having a non-stable workload will damage the fuel cell in the long run and will greatly reduce its lifespan. [4, Sec. 3.7 Energy efficiency, Power and Lifetime]

To solve this problem there is a quite easy solution which is to use the fuel cell together with batteries in a hybrid system. In this setup the fuel cell produces a steady stream of electricity while the battery works as a buffer in case there is a higher or lower need for power. This system is both light in weight while still being an effective power source.

In practice this is an environmentally friendly alternative to other common energy sources, however this heavily depends on the source of the hydrogen. As it is today the majority of hydrogen is produced as a product of fossil fuel which makes it neither renewable or environmentally friendly [5]. However it is also possible to produce it through electrolysis of water. The latter is on the rise which would make hydrogen both renewable and a carbon neutral energy source [6]. But as it is today electrolysis is often considered too expensive to be of commercial use.

1.2 Previous Projects

A number of studies has previously been done on alternatives to fossil fuel as a propellant to unmanned aerial vehicles or UAVs for short. The first documented flight of a drone propelled by a fuel cell took place in 2003 and was a concept plane whose purpose was to prove the viability of fixed wing aircraft propelled by fuel cells. The drone had a wingspan of 38 cm and was built by AeroVironment. The same year Nasa proved with their Helios aircraft that electrically driven drones also were possible on a larger scale as it had a wingspan of 75 m. However the main purpose of the Helios was to prove that you could build a drone which was powered by solar energy and only used its fuel cells as a way to store excess energy produced by solar cells mounted on the wings [7]. Fuel cells together with electrolysers were used instead of batteries as the number of batteries that would have been required was deemed too heavy [8].

Since then a large number of fuel cell power UAVs have been produced such as the LH_2 Ion Tiger which had a flight duriantion of 48h. The main focus has also shifted to find more efficient ways of storing the hydrogen and optimizing hybrid solutions including fuel cells [7].

1.3 Purpose

The purpose of this report is in collaboration with the Green Raven project is to optimize the setup of the hybridisation system which is meant to power the drone they have built [9]. The Green Raven project is a research program which develops a drone primarily powered by hydrogen. This Report will discuss the optimal configuration of batteries and fuel cell to be as fuel efficient as possible while still remaining lightweight.

2. Theory

In the following section, basic theory and principles of the components and different maneuvers of the drones will be presented.

2.1 Basic Principles of the Theory

The main principle of a fuel cell is that it converts chemical energy stored in the fuel into a direct electrical current. Therefore a fuel cell can be seen as a battery that can run continuously as long as the fuel is supplied to the cell. This project focused on a hydrogen fuel cell, more specifically a proton exchange membrane fuel cell (or PEMFC for short).
The fuel cell was set up in a hybrid energy management system with a number of batteries to enhance the performance of the fuel cell.

2.2 Components of the System

The information regarding the components of the system is presented below under this section. The components were a tank of compressed hydrogen gas, a PEMFC and a series of battery packs.

2.2.1 Fuel Cell

The hydrogen fuel cell set-up is split up into two compartments separated by a membrane and two electrodes. The PEM fuel cell has a membrane as an electrolyte that is impermeable to gasses and does not conduct electricity but conducts protons (see Figure 1 below). The membrane is located between the two porous electrodes that conduct electricity. The electrochemical reactions occur at the electrodes. At the interface, where the electrochemical reactions take place there is a catalyst. The catalyst is most often Platinum (Pt) which facilitates the electrochemical reactions in the fuel cell. The catalyst is supported on carbon particles that makes the electrode porous, which in turn makes it possible for the gasses to diffuse into the electrode and to remove the water. Another component of the electrodes is the ionomer, which usually consists of the same polymer as the membrane and facilitates ionic transportation to and from the catalyst particles. When the hydrogen gas is sent through the inlet to the anode side of the compartments it diffuses into the pores of the electrode.[10, Ch. 1]

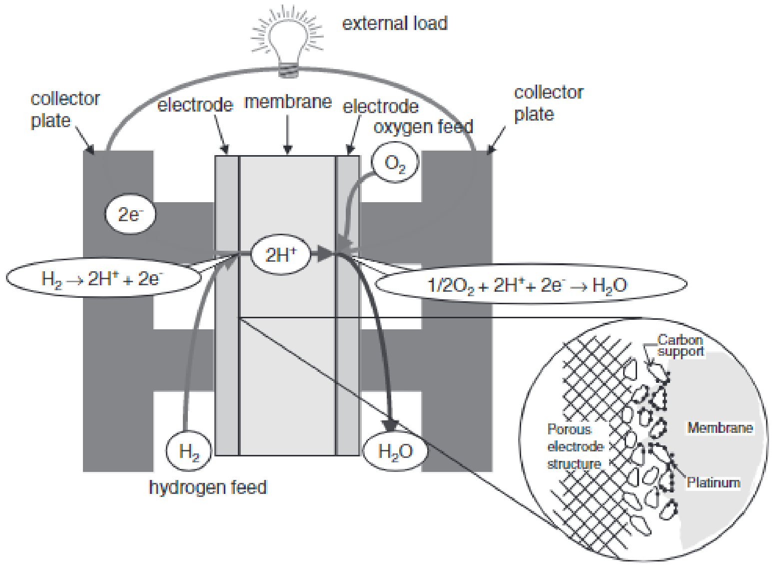

Figure 1: *The picture above shows the basic schematic view of operation of a PEM fuel cell. The Figure is taken from Figure 1-10 in PEM Fuel Cells: Theory and Practice, written by Barbir, Frano.[10, Figs. 1–10]*

The hydrogen gas splits into protons and electrons through a catalyzed oxidation reaction (see reaction I). The protons diffuse through the membrane while the electrons travel from one electrode to the other and produce a current through an external circuit. At the cathode the diffused protons and the electrons that have gone through the external current react with oxygen gas in a reduction reaction resulting in water (see reaction II). The total reaction seen in reaction III produces some energy, or more precisely, a part of the chemically stored energy is converted into electrical work and some waste heat.[10, Ch. 2]

$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{(I)}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad \text{(II)}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + energy \quad \text{(III)}$$

The maximum theoretical amount of energy that can be converted to electrical work is the Gibbs free energy of the total reaction. As equation 1 shows, some of the energy that is released in the reaction will be lost as heat and due to that being entropy for the reaction it will not be converted to work. Therefore an increase in operating temperature of the cell would mean a decrease in the Gibbs free energy. However this is only applicable in the temperatures below 100 ℃ as changes in ΔH and ΔS are small. In cases where the cell temperature is higher the changes in enthalpy and entropy can not be neglected. [10, ch 2]

$$\Delta G = \Delta H - T\Delta S \quad (1)$$

The electrical work produced in a cell is the product of charge and potential (see equation 2). Which can be simplified by combining equation 2-4 and the modified formula for electrical work is obtained (see equation 5).

$$W_{el} = qE \quad (2)$$

$$q = n \cdot N_{Avg} q_{el} \quad (3)$$

$$F = N_{Avg} q_{el} \quad (4)$$

n is the number of electrons transferred per molecule of H, q_{el} is the charge of one electron, N_{Avg} is Avogadro's number which is the number of molecules per mole and F is Faraday's constant.

$$W_{el} = n \cdot F \cdot E \quad (5)$$

$$W_{el} = -\Delta G \quad (6)$$

The maximum electrical work produced is the same as the Gibbs free energy of the reaction, therefore the maximum theoretical potential in a cell is[10, Ch. 2]:

$$E = \frac{-\Delta G}{n \cdot F} \quad (7)$$

Polarization Curve

The theoretical cell potential is calculated when no current is drawn i.e. at equilibrium. However in reality when drawing current from the cell the maximum theoretical cell potential will not result in electrical work. There will always be voltage losses, *polarization*, caused by different factors such as: kinetics of the electrochemical reactions, Internal electric and ionic resistance, diffusion difficulties to the reaction sites, internal currents or reactants that pass through the membrane. The factors mentioned are very important to take into consideration when dimensioning a fuel cell or fuel cell stack. Another form of polarization is *activation polarization* which is the voltage difference from equilibrium to initialize the electrochemical reaction, these losses are present at both anode and cathode. A useful tool to visualize and utilize this is a polarization curve, which depicts the cell potential, or voltage, on the y-axis and current or current density on the x-axis (see Figure 2 below).[10, Ch. 3]

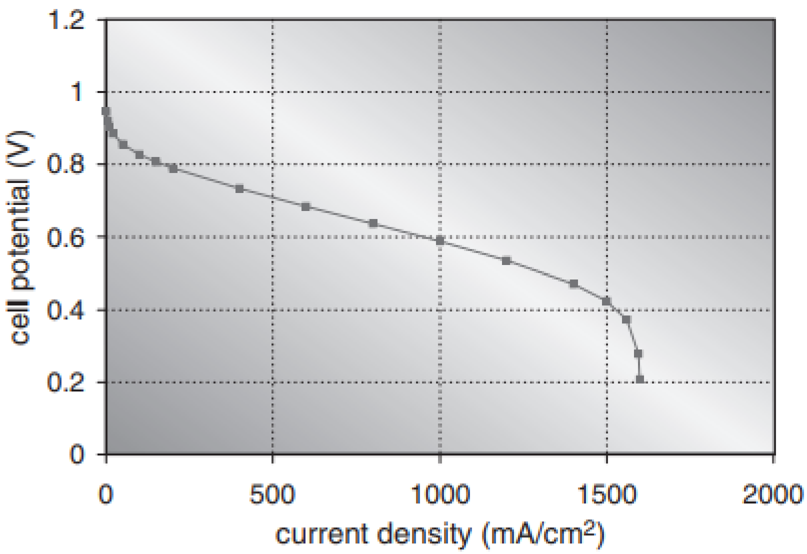

Figure 2: *The diagram above represents a typical fuel cell polarization curve. The diagram is taken from Figure 3-10 in PEM Fuel Cells: Theory and Practice, written by Barbir, Frano.[10, Figs. 3–10]*

Power Curve

Another useful tool that can be constructed from the polarization curve i s a power density curve. This can be obtained by multiplying the potential by the current density according to equation 8 below (where w is power density [mW/cm^2], V is voltage [V] and i is current density [mA/cm^2]).

$$w = V \cdot i \tag{8}$$

This results in a new graph with the power density on the y-axis and current density on the x-axis (see Figure 3 below).[10, Ch. 3]

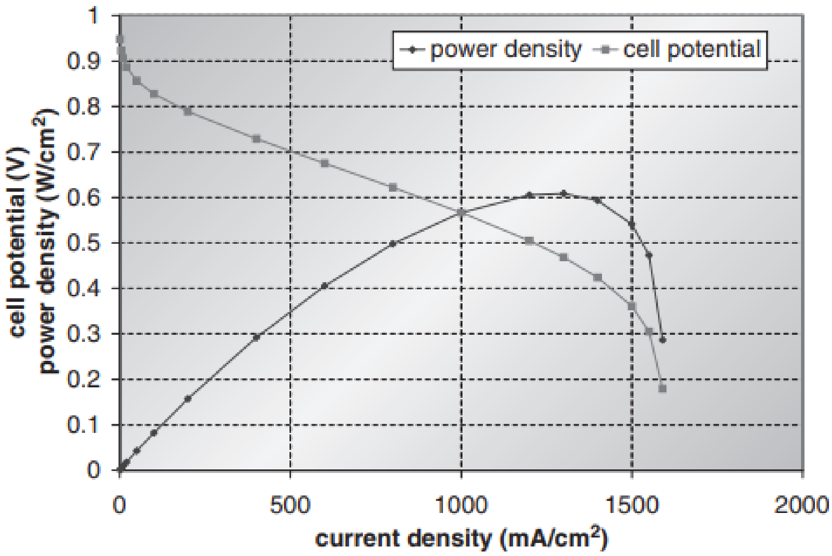

Figure 3: *The diagram above represents a typical fuel cell polarization curve and a power curve resulting from the polarization curve. The diagram is taken from Figure 3-20 in PEM Fuel Cells: Theory and Practice, written by Barbir, Frano.[10, Figs. 3–20]*

Importance of Altitude

The height of which the drone will fly is of great importance as the total pressure and partial pressure of oxygen as well as temperature will drop considerably with the increase of height. The total pressure decreases from roughly 1 bar (at sea level) to around 0.1 bar at the top of the troposphere layer of the atmosphere. The average troposphere thickness is 13 km around the globe. The temperature decreases with a factor of 6.5 ℃ per km in height.[11]

In theory, the voltage losses caused by the pressure difference in the fuel cell is related to the Nernst equation in equation 9 below. An increase in cell operating pressure causes an increase in cell potential, i.e an increase in voltage.[10, Ch. 3] Therefore, If the pressure is decreased it will cause a voltage loss. When the drone climbs in height it will cause a pressure drop of the oxygen due to the atmosphere getting thinner and thinner. Thus, from Nernst equation in equation 9 can be used to define a new relation for the voltage losses depending on height

$$E = E_0 + \frac{RT}{nF} ln\left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}}\right) \tag{9}$$

$$E_{ground} = E_0 + \frac{RT}{nF} ln\left(\frac{P_{H_2} P_{O_2}^{0.5}(ground)}{P_{H_2O}}\right) \tag{10}$$

$$E_{height} = E_0 + \frac{RT}{nF} ln\left(\frac{P_{H_2} P_{O_2}^{0.5}(dep.\ on\ height)}{P_{H_2O}}\right) \tag{11}$$

Equation 11 can be subtracted by equation 10 in order to obtain the difference in potential depending on the height, in relation to ground level.

$$\Delta E_{height} = E_0 - E_0 + \frac{RT}{nF} ln\left(\frac{P_{H_2} P_{O_2}^{0.5}(dep.\ on\ height)}{P_{H_2O}}\right) - \frac{RT}{nF} ln\left(\frac{P_{H_2} P_{O_2}^{0.5}(ground)}{P_{H_2O}}\right)$$

Which can be simplified to the following expression,

$$\Delta E_{height} = \frac{RT}{nF} ln\left(\frac{\frac{P_{H_2} P_{O_2}^{0.5}(dep.\ on\ height)}{P_{H_2O}}}{\frac{P_{H_2} P_{O_2}^{0.5}(ground)}{P_{H_2O}}}\right) = \frac{RT}{nF} ln\left(\frac{P_{O_2}^{0.5}(dep.\ on\ height)}{P_{O_2}^{0.5}(ground)}\right)$$

And as a consequence results in the following relation for voltage losses in equation 12 below.

$$\Delta E_{height} = \frac{RT}{nF} \cdot \frac{1}{2} ln\left(\frac{P_{O_2}(height)}{P_{O_2,ground}}\right) \tag{12}$$

Where R is the ideal gas constant T is the operating temperature, n is the number of electrons released in the electrochemical reaction and F is Faraday's constant.The relation in equation 13 was used in the Simulink model to simulate the extra hydrogen that will be consumed to obtain the desired power output from the fuel cell. This will be explained further in the methodology in section 3.3.2 below.

From Faraday's law of electrolysis, stated in equation 13 below, the amount of moles H_2 that are consumed can be calculated. [12, p. 20]

$$m = \frac{\beta QM}{n\ F} \tag{13}$$

Where Q is charge, β is the stoichiometric factor (it is 1 for hydrogen in this reaction, se reaction I above), M is the molar molecular mass, n is the number if electrons in the electrochemical reaction (2 in this case, see reaction I above) and F is Faraday's constant. The expression in equation 13 can be rewritten so that the amount of H_2 consumed can be expressed in terms of moles depending on current and time, see equation 14 below.

$$n_{H_2,\ consumed}^{tot} = \frac{I \cdot t}{n\ \cdot F} \tag{14}$$

Therefore, the amount of H_2 that is consumed per timeunit can be described by the expression in equation 15.

$$n_{H_2, consumed} = \frac{I}{n \cdot F} \tag{15}$$

In terms of operating temperature, there will be some effects on the performance. When the temperature decreases as the drone increases altitude, the water that is formed as a product can freeze inside the fuel cell and cause the electrochemical reaction to be inhibited. [13] Another aspect of water build-up is that the water evaporates at a slower rate at lower temperatures and therefore also can cause a buildup, resulting in lower reaction rate of the electrochemical reaction.

2.2.2 Batteries

Batteries are supplementary to the fuel cell during high power demand. Understanding of terms such as C-rate and state of charge are crucial when selecting the right battery option and analyzing the system.

The energy density of a battery is defined as the energy a battery is able to provide in relation to its weight and is obtained using equation 16:

$$E_d = \frac{C_b \cdot V}{m} \left[\frac{Wh}{Kg}\right] \tag{16}$$

Where C_b is the total capacity of the battery, V is the voltage and m is the mass of the battery. Higher energy density indicates that a battery can provide either more energy or energy for a longer time in relation to its weight. Therefore, batteries with high energy densities are more suitable for applications where the weight and dimensions are of a great importance, that is to say batteries with higher densities are relatively lighter. However, a battery with higher energy can not always produce a higher power. The batteries used in this project are power optimized which focuses on the power output in relation to the batteries weight and volume. To clarify, the energy density indicates how much energy can be delivered while power density relates to how fast energy can be delivered.[14]

The state of charge of a battery, SOC, is defined as the ratio between the available charge and the maximum possible charge that can be stored in the battery, often expressed in percentage. To clarify, a fully charged battery has a state of charge of 100 % while a fully discharged battery has 0 % as its state of charge. Current integration is usually used for determining the capacity changes in the battery. The state of charge of the battery is generally calculated using that data.[15]

The C-rate indicates the battery's charge and discharge rate relative to its maximum capacity and is calculated by equation 17:

$$C_{rate} = \frac{I}{C_b} \left[1/h\right] \tag{17}$$

Where I is the current and C_b the total capacity of the battery. For example, a battery with 1Ah capacity and a C-rate of 1 C should be able to provide a current of 1 A for one hour. The same battery should provide a current of 2 A for 30 minutes with discharge C-rate of 2 C and a current of 0.5 A for 2 hours with a C-rate of 0.5 C.[15]

In different applications, batteries with different C-rates are required. In applications where very high power is required in a relatively short time, batteries with a higher C-rate are more suitable. It should be taken into consideration that although the same calculations are made when discharging a battery at different C-rates, in reality, there will be some internal energy losses. The capacity can be decreased by 5 % due to transformation of energy losses to heat at higher C-rates.[16] However, these losses have been neglected in this project.

2.2.3 Hydrogen Tank

Hydrogen is present in many chemical compounds. However it can not be naturally found in its molecular form and therefore it has to be generated. One alternative is to produce hydrogen elsewhere and then incorporate it in the fuel cell system. In the past 15 years many efforts have been made for optimizing the hydrogen storage methods including usage of compressed hydrogen gas and cryogenic and liquid hydrogen. Each method has its advantages and disadvantages. When evaluating a hydrogen storage system all the related components such as tank, valve, reactants etc. are included.[17, Para. 1]

Currently, high-pressure hydrogen tanks are the most common way of storing hydrogen. To meet the safety and application requirements, the composition of the tank must be made of material with characteristics such as being light-weighted and sufficiently strong among other things. Additionally, a high thermal conductivity for the material composition of the tank is required to be able to manage the exothermic heat produced while filling the tank. Both the cost of the tanks due to its expensive carbon fiber composite and the volumetric capacity of the tank are the challenges with using this approach.[17, Sec. Compressed gas]

In the cryogenic approach, the temperature for liquid hydrogen at 1 atm pressure should be maintained below 20 K (-253 ℃) which is the hydrogen boiling temperature. Effective thermal insulation is therefore essential for maximum efficiency. When liquefying hydrogen, its volumetric density will increase meaning a relatively larger quantity of hydrogen can be stored. However, there are also some difficulties with this approach. Despite the thermal insulation, the hydrogen can still evaporate causing hydrogen losses. A disadvantage to this approach is that the energy required to liquefy the hydrogen gas is equivalent to 30-35 % of the hydrogen energy value.[17, Sec. Cryogenic storage]

3. Methodology

In the following section, the methods and simulations will be presented. The simulations were done in Matlab® and Simulink based on experimental data and data from data sheets. The assumptions that were made in the construction of this model were the following: that the gasses behave ideally, that the fuel used in the fuel cell was utilized for effective work (i.e. fuel utilization = 1) and that there was no change in operating temperature of the fuel cell. Additionally, the assumption that the weight of the energy system was constant and does not affect the power demand of the UAV was made as well.

3.1 Energy Management Plan/System

The energy management strategy for the simulations were based on the flow-chart seen in Figure 4 below. The central function code was constructed and developed during the course of project in Matlab® and implemented in the Simulink model using the block *Matlab® function* for the different scenarios during the mission, see code in the attachments section.

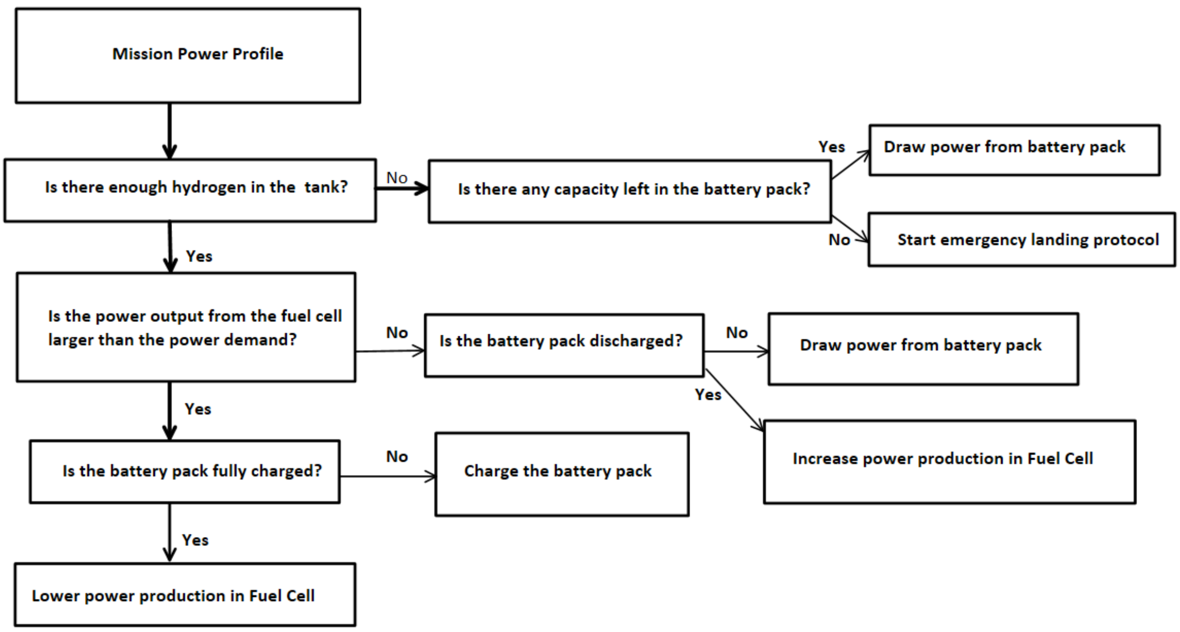

Figure 4: *The picture above is the flow-chart over the energy management system, which was used for the central function code of the Simulink model.*

If the drone has hydrogen our system has six different states as shown in Table 1. The states are divided in two groups based on if the power output from the fuel cell is sufficient to run the system or not. Then it is divided into three sub groups depending on the state of charge in the battery. In the first mode the fuel cell produces more power than is needed while the battery has more than 60% charge, in this case the system will throttle down the fuel cell to not damage any components. In the second state the fuel cell does not produce enough to power the system so the battery is drained to cover the difference in power required. In the third state the fuel cell produces more than needed and the battery has less than 60% charge so the surplus energy produced is sent to the battery to charge it. In the fourth state the output from the fuel cell is too low to power the system while the battery has more than 20% charge, so the battery is drained to cover the difference in power required. The fifth statement is almost the same as the third, the only difference being that the charge of the battery is lower than 20%. The surplus produced by the fuel cell is used to charge the battery. In the sixth state neither the fuel cell or the battery are sufficient to power the system in their current state. So the power produced by the fuel cell is raised to meet the demand.

Table 1: *The table below shows what happens in the system depending on if the fuel cell produces more or less than needed and that state of charge in the battery. The abbreviation used are: SoC stands for State of Charge, Lp is the power required to fly the drone and Fc Pow is the power produced by the fuel cell.*

	Lp < Fc Pow	Lp > Fc Pow
SoC > 0,6	Lower Fc Pow produced	Drain battery
0,2 < SoC < 0,6	Charge battery	Drain battery
SoC < 0,2	Charge battery	Raise Fc Pow produced

3.2 Choice of Batteries

Three different battery choices were provided to us to supplement the fuel cell system. The batteries differ in energy density, total capacity, voltage and C-rate. All batteries are Lithium polymer batteries,Li-Po, and were purchased from *Gens Ace*.[18]

Table 2 shows the specifications of the different batteries available for this project. The data for voltage, capacity and charge respective discharge C-rate has been collected from the specification sheets in the *Gens Ace* website.[18] The mass and size of the batteries was measured. The energy densities of batteries were later calculated using equation 16.

Table 2: *Properties of different battery types*

Battery	Capacity $[mAh]$	Voltage $[V]$	Mass $[g]$	Energy density $[Wh/Kg]$	Volume $[cm^3]$	C-rate discharge $[1/h]$	C-rate charge $[1/h]$
Gens Ace 3.7	3700	22.2	526.16	156.16	254.86	60 C	-
Gens Ace 4	4000	18.5	477.6	154.94	233.43	25 C	1-3 C
Soar	1000	11.1	85.7	129.52	41.68	30 C	1-3 C

Numerous simulations were run using the developed model in Simulink to be able to do a thorough comparison between different battery options and select the most efficient battery solution. The two batteries with higher energy densities were to be preferred i.e. *Gens Ace 4* respective *Gens Ace 3.7*. The Simulations were at first, run with various different fuel cell power profiles. Ultimately, the comparison was concluded using two different fuel cell power profiles. In the first profile, the fuel cell power was maintained at the constant value of 370 W throughout the whole mission. In the second profile, the baseline power of the fuel cell was kept at the value of 370 W during the UAV flight time and increased to 400 W during both take-off and landing, since more energy is needed for these maneuvers during the mission.

3.3 Simulink Model

In the following subsection, the methods and practice for the simulations in Simulink will be presented and discussed.

3.3.1 Maneuvers of the Drone

The main maneuvers of the drone that were simulated in this project were a climbing maneuver to the desired cruise height, a cruise maneuver when cruise height was reached and then a descending maneuver from the cruise height to ground level. The climbing maneuver lasted for 600 seconds [19] and required a power input of 800 W, the cruise maneuver lasted for 2700 seconds and required a power input of 350W and the descend maneuver lasted for 300 seconds and also required a power input of 800 W. Accordingly the flight was simulated for one hour. The power required for each maneuver was calculated from power curves (see Figure 5 below). The expected speed that the drone will fly at was 25 m/s. Therefore, the power required for the climb and descend were calculated by adding the power at 25 m/s from the climb and cruise curve of the diagram. The vertical speed of the climb was 50 ft per minute which is equal to 0,254 m/s. The power required for the cruise maneuver was taken from the cruise curve in the diagram. Additionally, the power required for climb and descent was assumed to be the same, which was recommended by the Green Raven project. Data for the runtime and maneuvers were provided by the Green Raven project.[20]

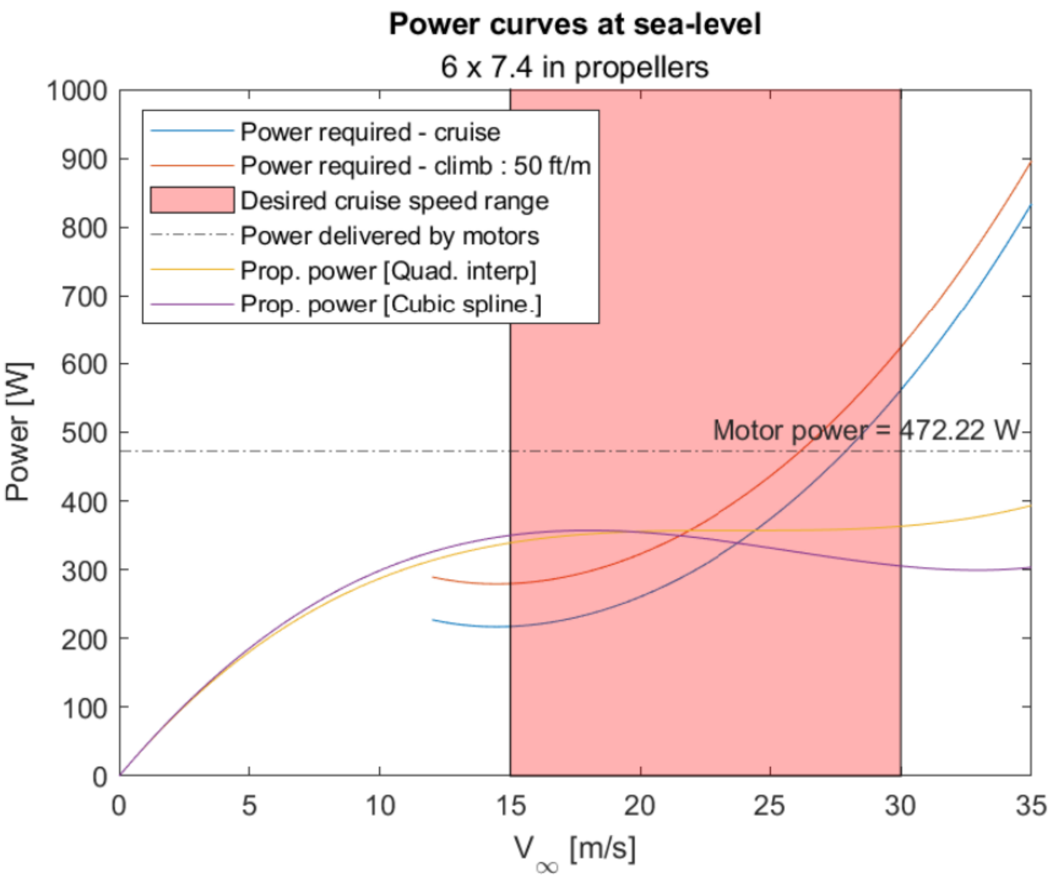

Figure 5: *The diagram above shows power curves at sea-level provided by the Green Raven project.[21, Fig. 4 b)]*

3.3.2 Power and Height Profile of the System

The power profile of the mission was constructed from the data provided by the Green Raven project using excel (see Figure 7 below). As presented in the section above (section 3.3.1), the power required for the maneuvers were calculated from power curves (see Figure 5 above) provided by the Green Raven project. Simulations for three different cruise heights (150, 300 and 450 meters) were performed, and subsequently three mission power profiles and three height profiles were constructed.

From the provided data regarding the vertical climb speed (0,254 m/s) the time span of the climb and descent sections of the profiles had to be adjusted. For the simulation of the cruise height of 150 meters the time required for the climb and descent was as specified from the Green Raven project. However, for the simulations at 300 and 450 meters, the time span of the climb and descend section had to be increased at the expense of the cruise section in order to complete a full one hour mission.

Consequently, the power and height profiles differ depending on the cruise heights. Higher cruise height results in a higher power demand for a longer time span during the climb and descend. This can be seen in Figure 6 and 7 below.

The mission power profiles and height profiles was used as an input to the central Matlab® function of the Simulink model using the block *From Spreadsheet*.

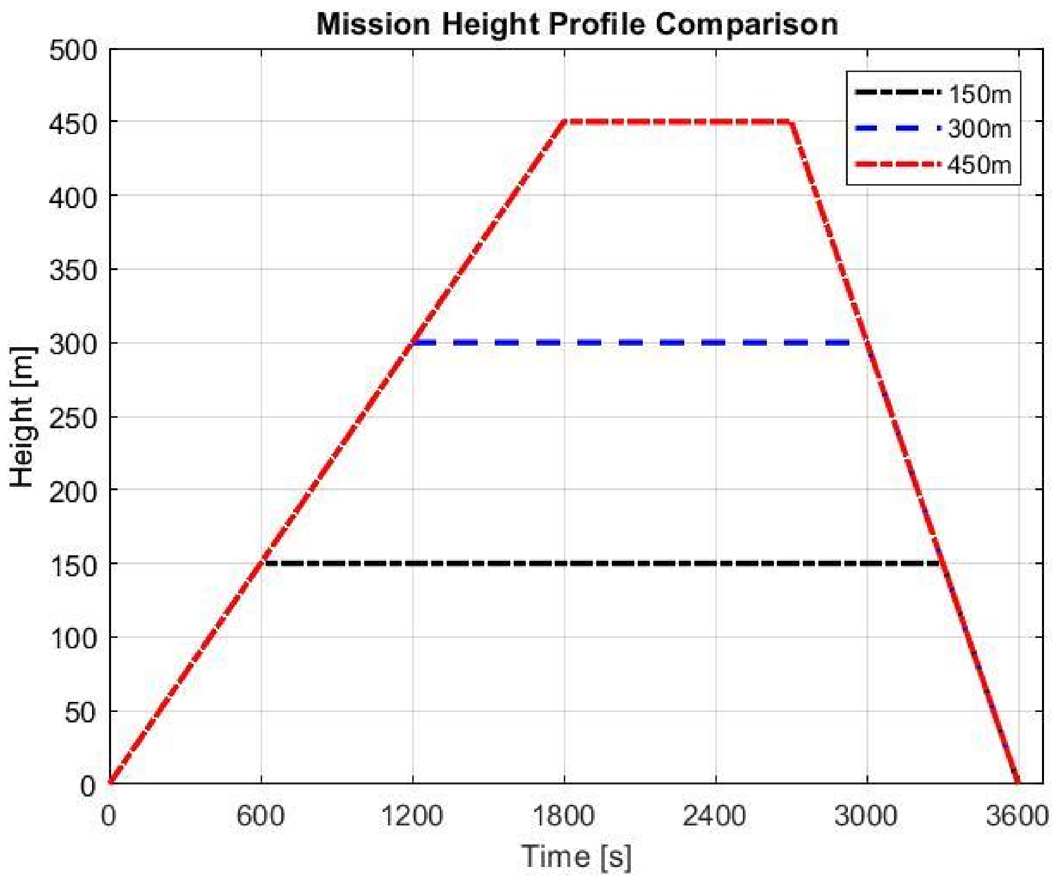

Figure 6: *The diagram above shows the height profiles of the mission simulations at 150, 300 and 450 meters. Due to the fact that the vertical speed for the climb and descend is constant, the time for the climb and descend has to be longer at the expense of the cruise section.*

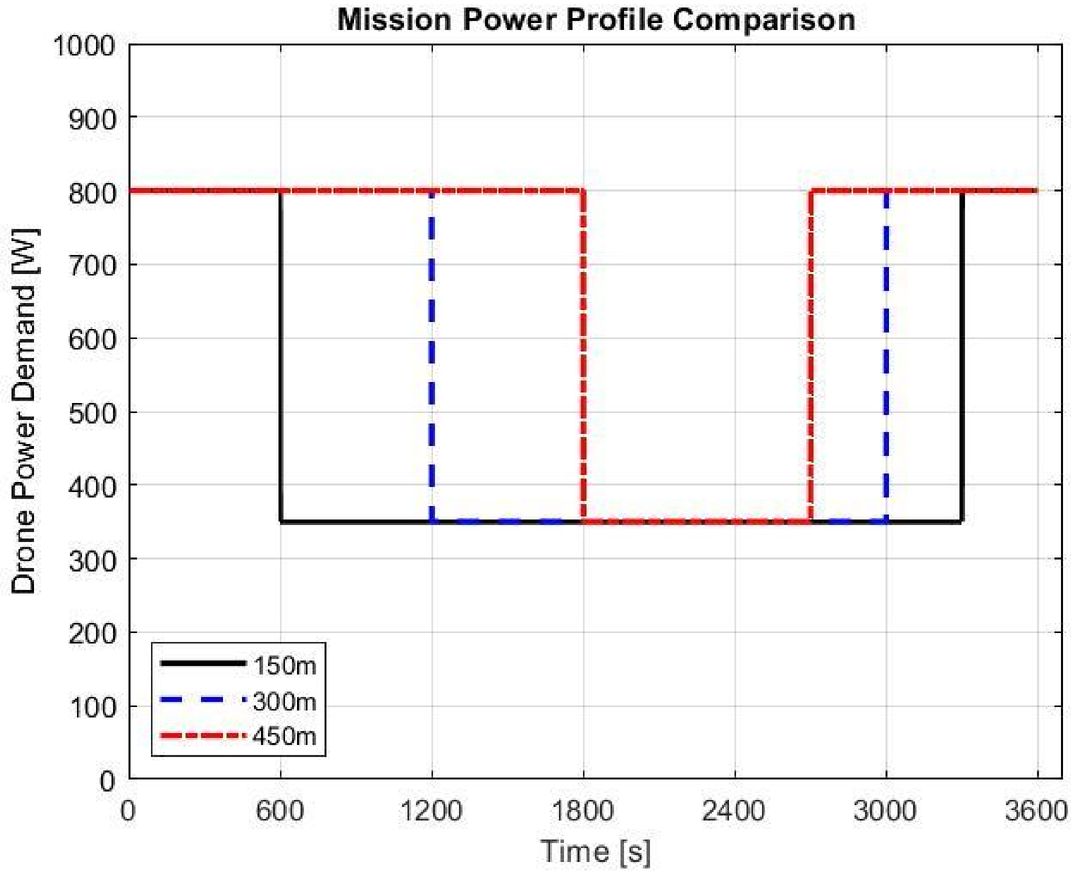

Figure 7: *The diagram above shows the different mission power profiles constructed from the provided data. For the cruise height at 150 m (black full line) the first 600 seconds is the climb maneuver, the section in the middle between 600 and 3300 seconds is the cruise maneuver and the last 300 seconds is the descend maneuver. For the cruise height at 300 m (blue dashed line) the first 1200 seconds is the climb maneuver, the section in the middle between 1200 and 3000 seconds is the cruise maneuver and the last 600 seconds is the descend maneuver. For the cruise height at 450 m (red dashed and dotted line) the first 1800 seconds is the climb maneuver, the section in the middle between 1800 and 2700 seconds is the cruise maneuver and the last 900 seconds is the descend maneuver.*

3.3.3 Basic Model

The Simulink model was constructed from a central Matlab® function block and a series of inputs and outputs was used for calculations regarding the fuel cell and battery packs. Simulink is an iterative simulation program and performs the simulations based on looped variables, specified timesteps and timespans. In the simulations performed in this project, a total time of one hour (3600s) consisting of timesteps of one second each were used. Some of the inputs were "looped" back to the central Matlab® function due to the fact that those variables were specific for each timestep, theses inputs was *H2_LT*, *SoC_N* and *SoC_N_Em* which stands for "H_2 left in tank", "state of charge new" and "state of charge new emergency" respectively. The inputs for *Load_power*, *Load_height* and *Em_Power* in the Simulink model were taken from a tabulated data in excel (see Figure 8 below). The emergency battery system is explained further in section 3.3.4.

The variables *Load_power* and *Load_height* differ at different time steps and are the inputs for the mission power profile and the mission height profile respectively. Additionally, a number of initial values were required for the simulations to function, such as the initial amount of hydrogen in the tank, initial state of charge of the battery pack and the initial charge of the emergency battery pack (see Figure 8 below).

The outputs from the central function were directed to the two subsystems. *FC_P*, *l_p*, and *Height* were directed to the fuel cell subsystem and are the variables for the fuel cell power output, the power demand from the drone (the mission prower profile) and the height of the drone respectively. The remaining three outputs, *Power_Diff*, *Black_Box* and *Power_Diff_Em*, were directed to the battery subsystem. The first of the three latest mentioned outputs was the variable for the power difference i.e the excess or the deficit of power compared to the power produced by from the fuel cell. The two remaining outputs were a part of the emergency battery system, and were the variables for failure in case the battery pack and the fuel cell runs out of charge or energy and the power difference in that scenario would be negative. This is explained further in section 3.3.4.

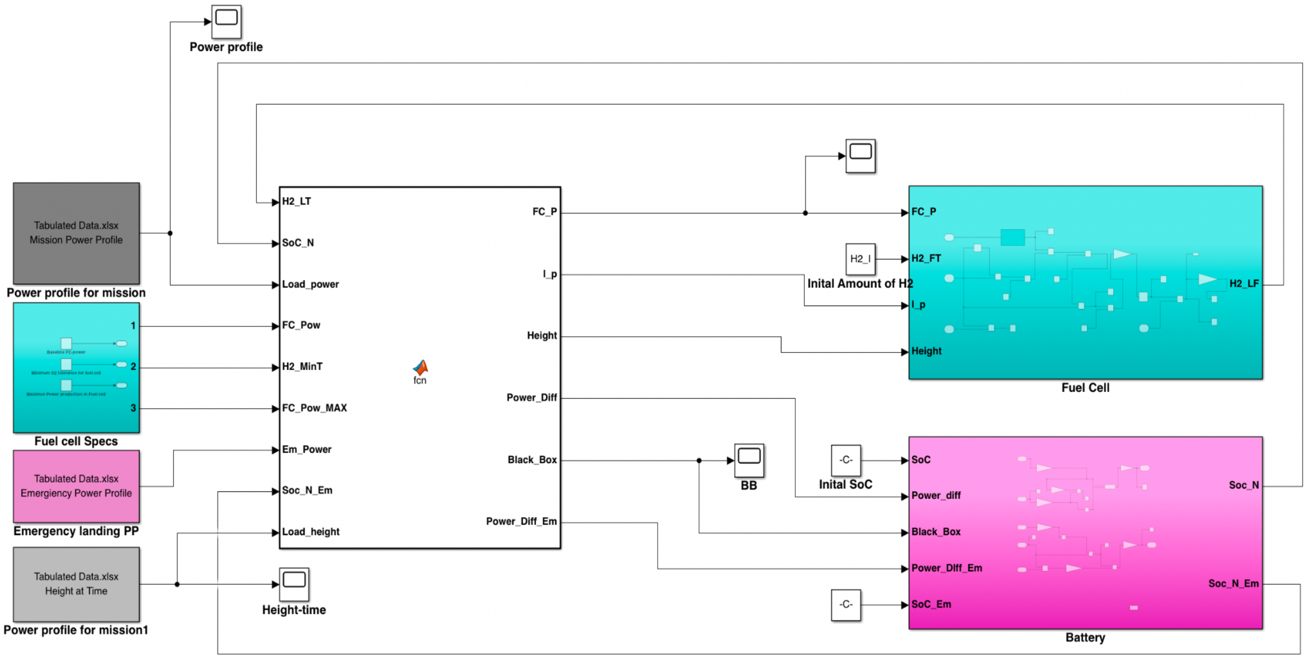

Figure 8: *The schematic above depicts an overview of the Simulink model. The two large subsystems on the right contain calculation blocks for the H_2 consumption, change in state of charge of the battery and emergency battery system.*

The inputs from the light cyan coloured subsystem to the left on the Simulink model displayed in Figure 8 above were specifications that the fuel cell was simulated to run on. Such as a baseline power output in watt, a minimum tolerance of H_2 that the fuel cell requires in order to function and a maximum threshold of power output from the fuel cell. The minimum tolerance of H_2 is derived from the minimum pressure of hydrogen that is required for the fuel cell to function. The value was calculated in the quantity of hydrogen moles in the tank by using the ideal gas law, and then incorporated as a limiting factor in the central function block. The mentioned variables are illustrated in Figure 9.

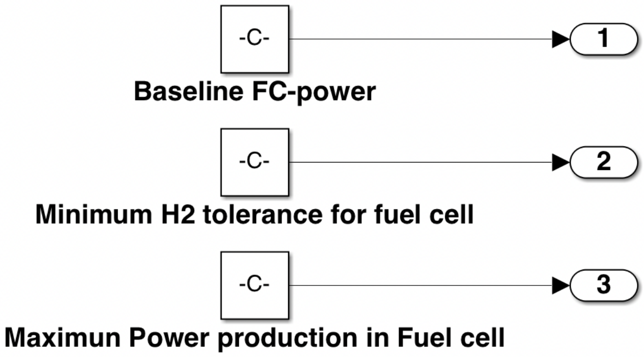

Figure 9: *The schematic above depicts the inputs for the fuel cell specs in the subsystem "Fuel Cell Specs".*

Fuel Cell Subsystem

As mentioned in the theory section, a polarization curve and a resulting power curve is a very useful tool when doing calculations in electrochemistry. The polarization curve for the fuel cell was produced experimentally unlike other specifications regarding the fuel cell and hydrogen tank. This meant that the calculations done in the simulations were more precise and realistic.

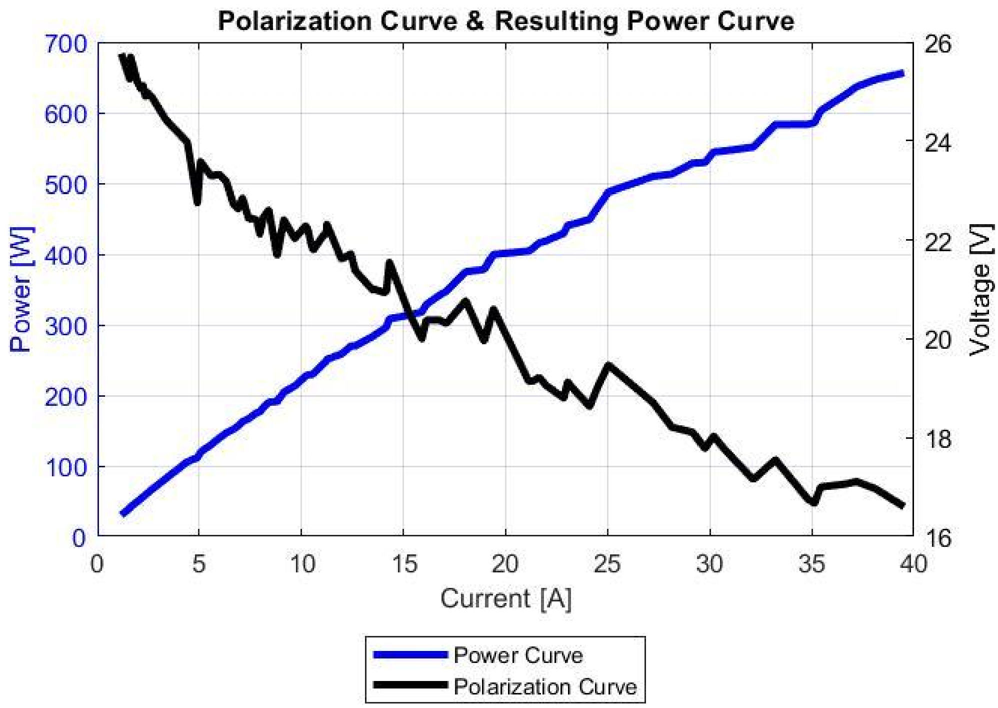

Figure 10: *The diagram above shows the experimental polarization curve for the fuel cell and the resulting power curve calculated from the polarization curve.*

The input for the fuel power was converted to the total current in the fuel cell stack, assembled of thirty cells, by interpolation according to the power curve. Thereafter, the power from the fuel cell was divided by the current in order to obtain the voltage from the entire stack. Afterwards, the voltage for each cell in the fuel cell stack was calculated and the extra required voltage from the height losses was then added, as explained below. The result was afterwards multiplied by the number of cells i.e. thirty in order to get the new total voltage for the stack and then divided by the initial power output in order to obtain the total current produced by the fuel cell.

Furthermore, in order to convert the current to hydrogen consumption the total current from the stack was multiplied by the number of cells i.e. thirty once more. Thereafter, by using equation 15 (see section 2.2.1) the amount of hydrogen moles consumed per time unit were obtained. By integrating over the time of the mission, the total amount of hydrogen consumed for each timestep was then obtained. Subsequently, the consumed amount was subtracted from the amount of hydrogen left in the tank and then divided by the initial amount in order to get a percentage of the fuel left in the tank. This was done to obtain a clear parameter of the consumption.

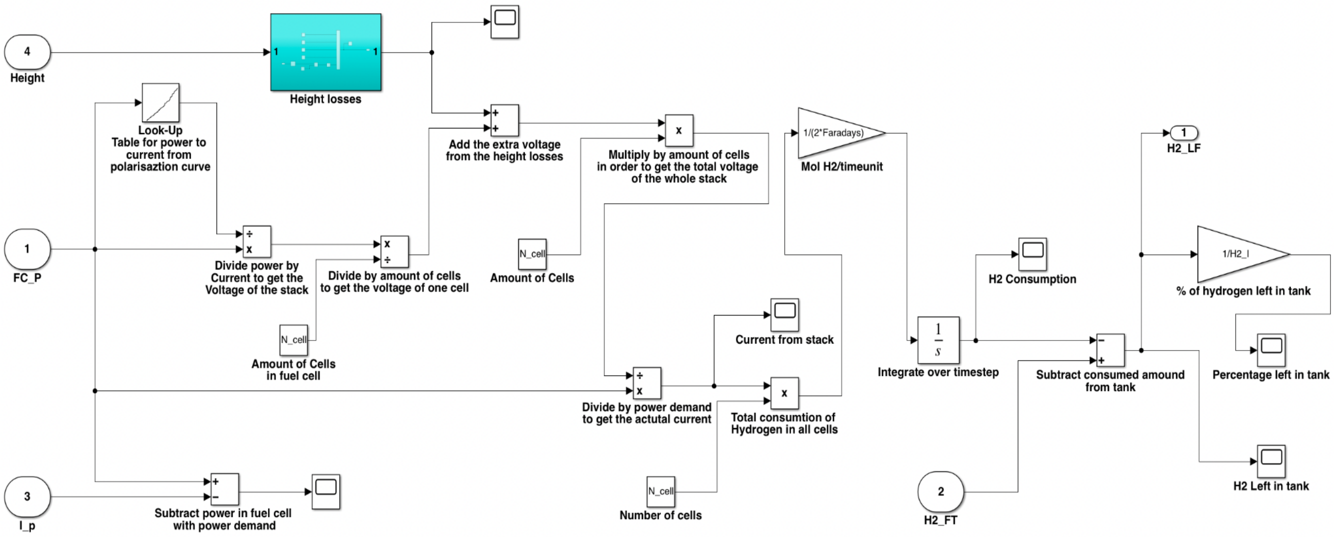

Figure 11: *The schematic above depicts the contents of the subsystem "Fuel Cell". The subsystem that input 4 connects to is the calculations for voltage losses due to height differences.*

From the Nernst equation described in the theory section (see equation 12), the extra required voltage to compensate for the pressure drop was calculated.

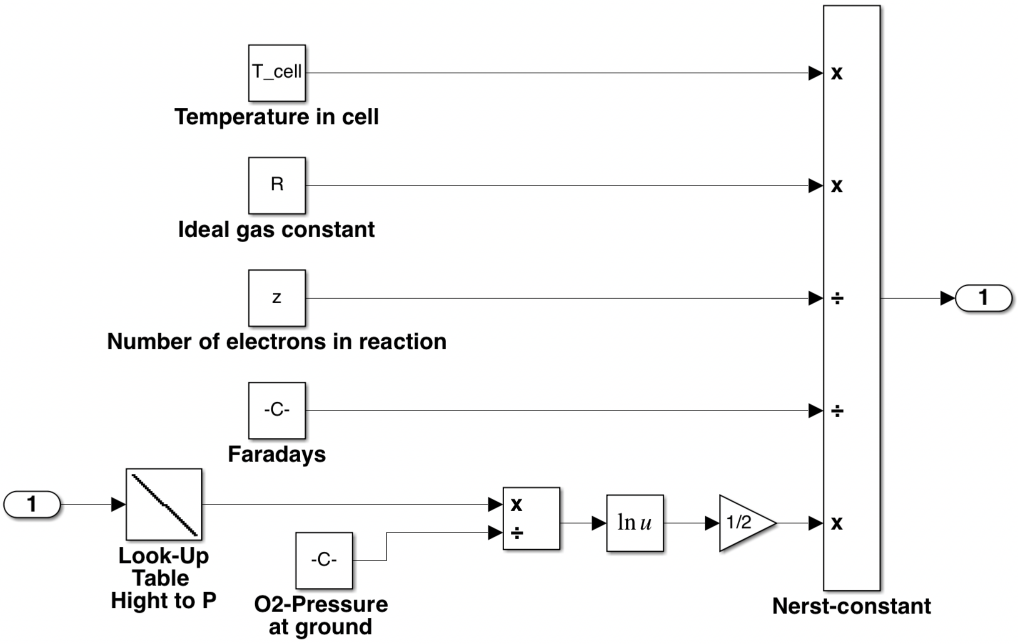

Figure 12: *The schematic above is taken from the subsystem of the height losses in the subsystem of the fuel cell in the Simulink model.*

Battery Subsystem

Two of the 5 inputs to the battery subsystem were used for the energy management regarding the battery pack. The inputs (see Figure 13 below) were outputs from the central function. Input one, *SoC*, is the state of charge of the battery pack at the specific timestep. The state of charge was multiplied by the total capacity of the battery pack in order to obtain the total charge at each time step. Input two, *Power_diff*, was divided by the voltage of the battery and integrated over time in order to obtain the added or drawn charge from the battery pack. These two values were then added together and divided by the total capacity of the battery pack to obtain the new state of charge of the battery pack at each time step.

3.3.4. Emergency Battery

The C-rate of the battery pack was obtained, using equation 17. Added or drawn current from the battery was calculated through dividing the Input two, *Power_diff*, by the voltage of the battery pack. The total capacity of the battery pack was also converted from As to Ah. The data obtained from the system illustrates the discharge C-rate and charge C-rate as a negative respective positive value.

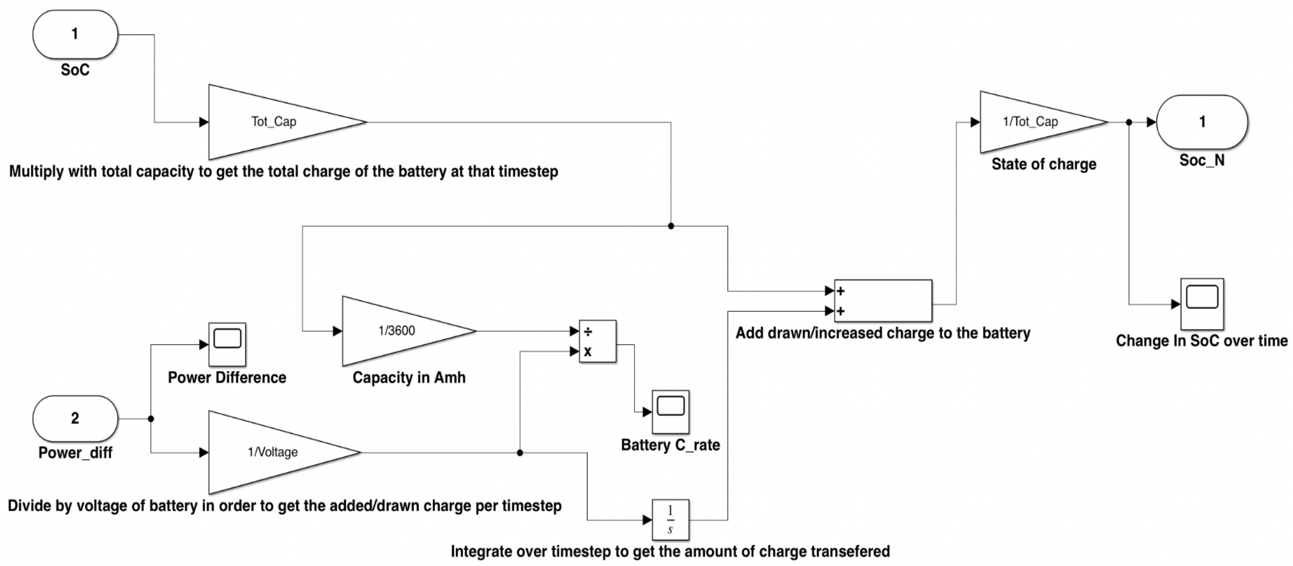

Figure 13: *The schematic above is taken from the subsystem of the batteries in the Simulink model. The flow scheme represents the calculations that were simulated for the inputs. The output, SoC_N is the new state of charge after the drained or added charge of the battery pack for the specific timestep, is directed back to the central function.*

In case there is a system failure with the drones propulsion system due to insufficient energy the central code will turn on the emergency power system called the black box. This system has enough power to land the drone safely. It works by assigning each possible state of the drone either a “0” or a “1”. All cases except one are assigned “0”. The state where there is no hydrogen left in the tank and the state of charge in the batteries is below 0,2 are instead assigned “1”. In the code this variable is known as the *Black_Box* variable and as seen in Figure 13 is multiplied with State of charge of the emergency battery (*SoC_Em*) and the power required to land the drone (*Power_Diff_Em*). This will power up the drone's engines with enough energy to land the drone.

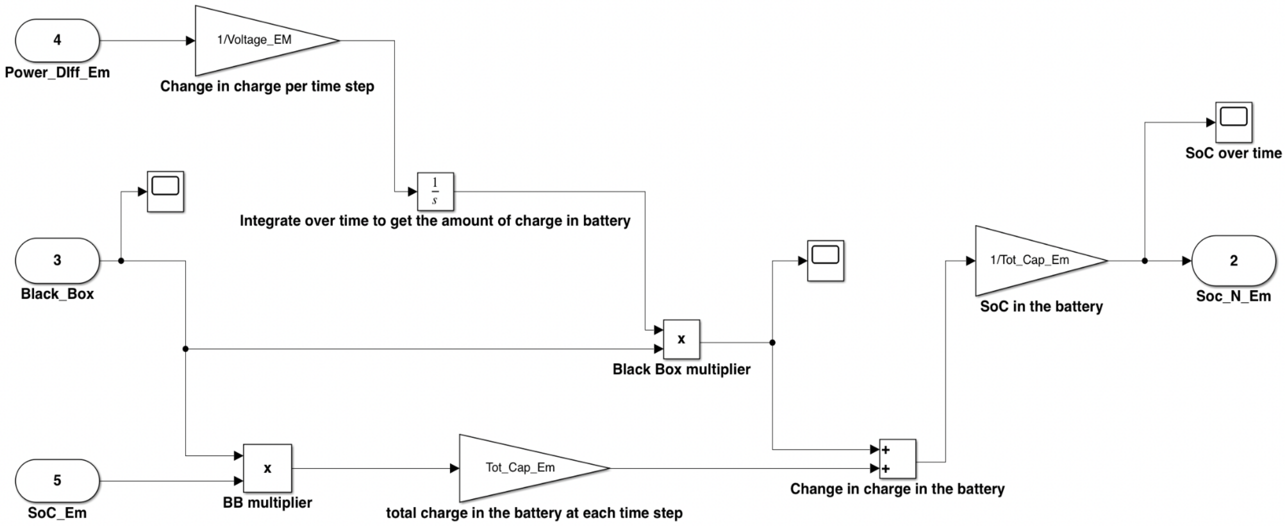

Figure 14: *Shows the schematic for the emergency landing. Power_Diff_Em is the power requirement for landing the drone, Black_Box input determines if we need to use the emergency battery or not, and SoC_Em is the state of charge in the emergency battery. Soc_N_Em is the new State of charge after each time step.*

Different Systems

To compare how the hybrid solution differs from a solution which is either powered just by batteries or hydrogen the code was augmented to examine the differences and similarities. This was done by reducing either the content of the hydrogen tank or the state of charge to zero and then compensate with the other power source to get a successful mission.

4. Result

The most efficient energy system solution for the mission was concluded to be the hybrid energy system consisting of a fuel cell run on the constant power output of 400 W and a battery pack consisting of two *Gens Ace 4* batteries. Additionally, one more battery of the *Gens Ace 4* was included in the model to handle the emergency landing in case of any error occurring during the mission. The mission is carried out at an altitude of 150 m. In the following section, the results of the simulations are presented and each choice made including the study of different scenarios are explained in depth.

4.1 Choice of Battery

Figure 15 illustrates the comparison between the state of charge, presented in blue, and the C-rate, presented in orange, of the battery types *Gens Ace 4* and *Gens Ace 3.7* on the graph on the left. The graph on the right represents the fuel cell power profile in orange and the fraction of the hydrogen left in the tank in blue. The fuel cell power profile is identical in both cases resulting in the same quantity of hydrogen being consumed. Therefore, the fraction of the hydrogen left in the tank is similar in both cases. The same set of information is illustrated in Figure 16 using a constant fuel cell power profile instead of a varied one.

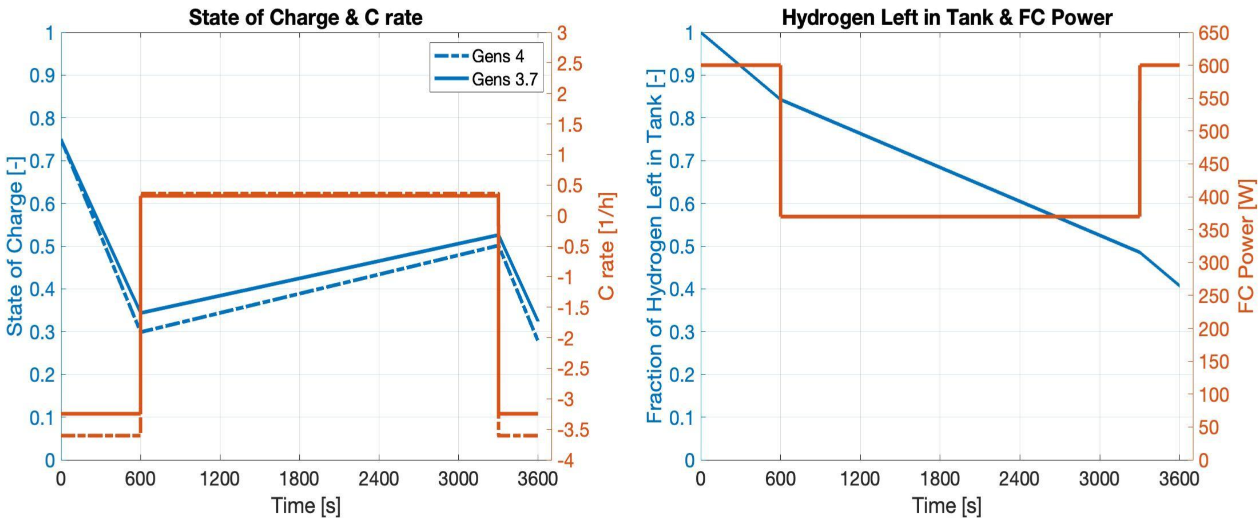

Figure 15: *The comparison between different battery solutions with a varied fuel cell power profile.*

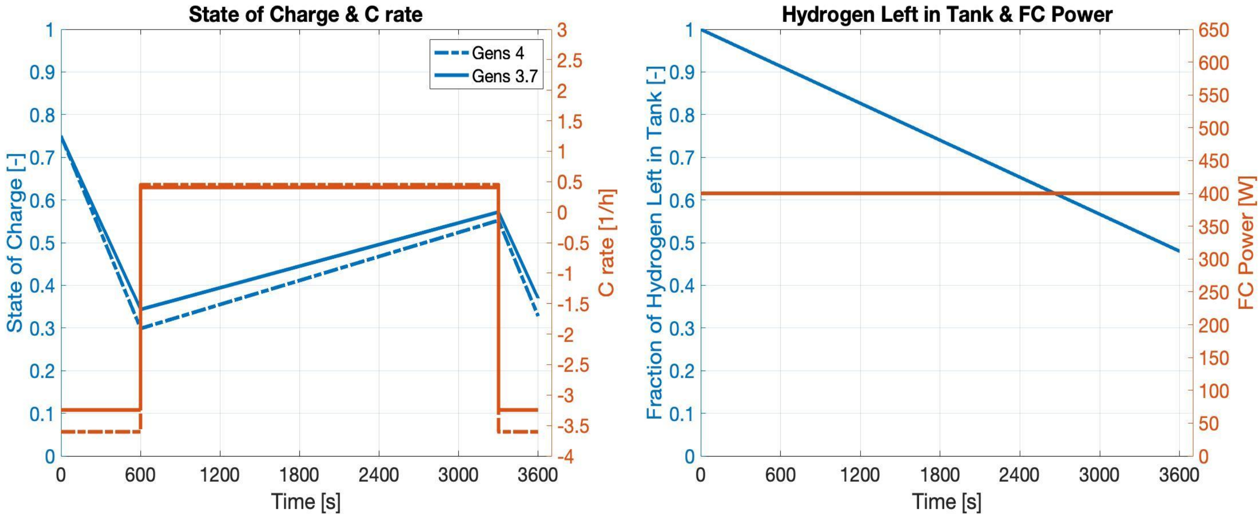

Figure 16: *The comparison between different battery solutions with a constant fuel cell power profile.*

The comparison between the weight and dimension of the two different battery solutions for the varied fuel cell power profile and the constant fuel cell power profile are presented in Table 3.

Table 3: *Comparison between different battery solutions with a constant fuel cell power profile and a varied fuel cell power profile.*

Battery	Quantity	Fuel cell Power $[W]$	Total mass $[g]$	Volume $[cm^3]$
Varied Power				
Gens Ace 4	1	600/370	477.6	233.43
Gens Ace 3.7	1	600/370	526.0	254.86
Constant Power				
Gens Ace 4	2	400	955.2	466.86
Gens Ace 3.7	2	400	1052.0	509.72

According to the results obtained by simulations, there were no substantial differences between the two battery solutions. *Gens Ace 4* provided a slightly higher discharge C-rate and a slightly lower state of charge in comparison to *Gens Ace 3.7* (see Figure 15 & 16). Additionally, the *Gens Ace 4* has a relatively smaller volume and a lower weight compared to *Gens Ace 3.7*. *Gens Ace 4* was selected as our battery solution in both cases. When using a constant fuel cell power profile, run on 400 W, two batteries were required to complete the mission while one battery was sufficient for the scenario with the varied fuel cell power profile i.e. baseline power of 370 W during the UAV flight and a power output of 600 W during take-off and landing (see Table 3).

4.2 Fuel Cell Power Output

The comparison between the different energy system solutions using a constant respective varied fuel cell power profile is illustrated in Figure 17. The simulations have been run using the *Gens Ace 4* battery which was concluded to be the most efficient alternative. The differences in the state of charge and in the fuel cell power profile is represented in the graph on the left in blue, respective orange color. Additionally, the graph on the right illustrates the differences in the fraction of the hydrogen gas left in the tank.

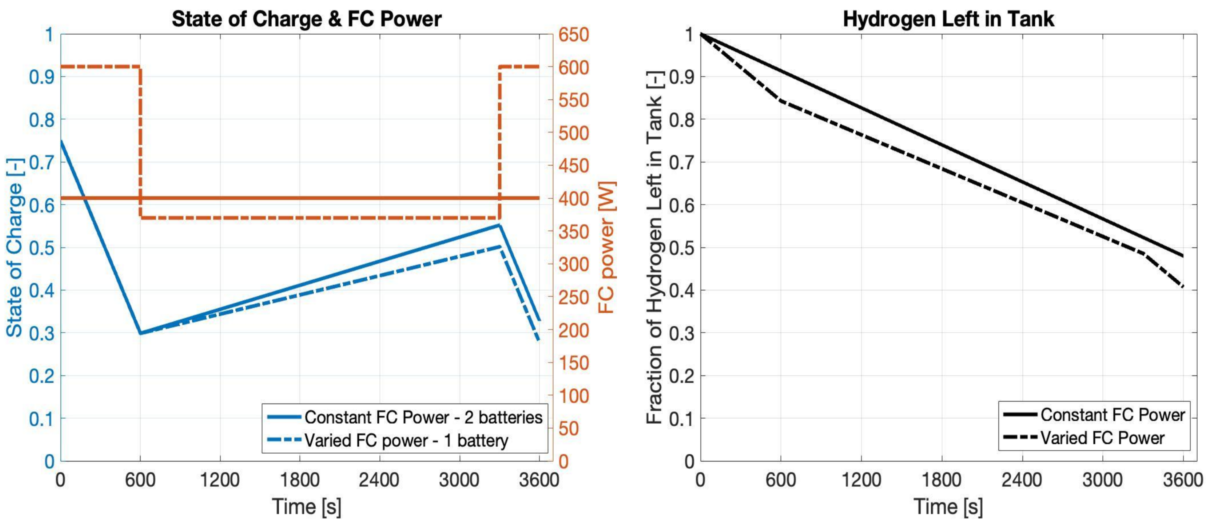

Figure 17: *The comparison between different energy system solutions with the constant respective the varied fuel cell power profile.*

The comparison between some of the properties of the two different energy system solutions i.e. using a constant and a varied fuel cell power profile is presented in Table 4 .

Table 4: *The comparison between different energy system solutions with the constant respective the varied fuel cell power profile.*

Fuel cell Power $[W]$	Battery quantity	Total mass of battery pack $[g]$	Volume of battery pack $[cm^3]$	Fraction of the hydrogen left in tank
400	2	955.2	466.86	0.55
600/370	1	477.6	233.43	0.41

The total charge used from the battery pack was different between the two cases as the power provided by the fuel cell was different. Additionally, the amount of batteries required for each scenario was also different (see Table 4). However, according to the results obtained by simulations, there were no substantial differences between the two energy system solutions regarding the state of charge of the batteries. Considering a constant fuel cell power provided a slightly higher state of charge at the end of the mission in comparison to considering a varied fuel cell power profile. Additionally, to be able to complete the mission with a constant fuel cell power profile two batteries were required while one battery was sufficient to complete the mission with a varied fuel cell power profile. This implies that double the weight and size for the battery pack is needed with the solution using a constant fuel cell power profile. Furthermore, 14% less hydrogen was consumed in the solution with the constant fuel cell power profile (see Table 4).

4.3 Different Energy Systems

When designing the system specifications such as weight and volume is of great importance as they both are very limited. The table below shows the difference in weight and volume of the different energy systems.

Table 5: *The comparison of the weight and volume between different energy system solutions*

Type of system	Weight (gram)	Volume (cm^3)
Hybrid	3066	5381,58
Battery	5736	2801,16
Fuel Cell	2110	4914,72

In a system only powered by batteries an additional ten batteries resulting in that twelve was required. If the system was solely powered by fuel cells, no change in the amount of hydrogen was required for a successful mission. However, the required power output from the fuel cell had to be varied over a significant range (350 to 800 W) in order to satisfy the power demand from the UAV. This is not possible as the max load on the fuel cell is 650 W so to satisfy the needed 800 W an other fuel cell with a higher output is needed.

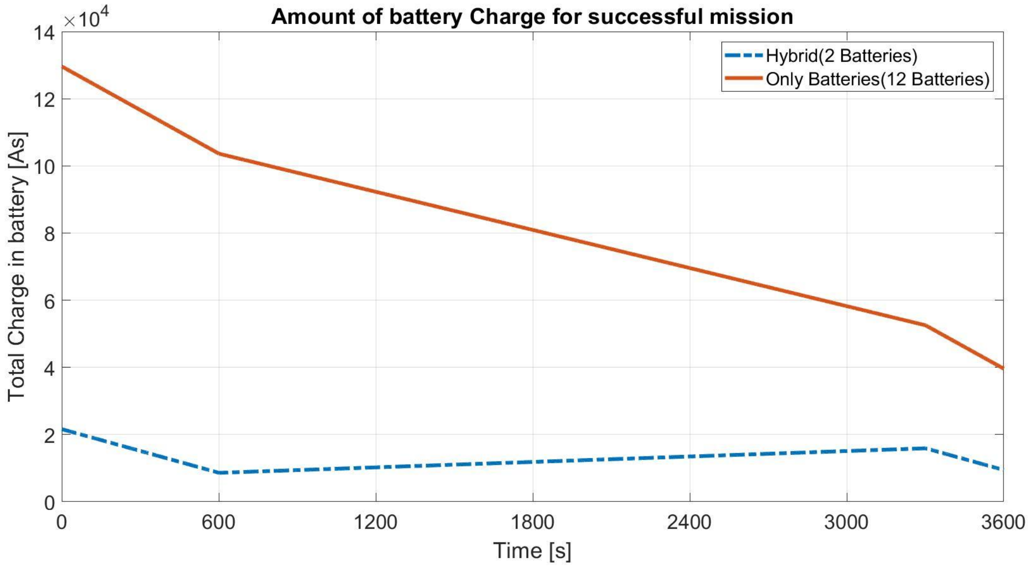

Figure 18: *The graph shows the total amount of capacity in the batteries required to complete the mission.*

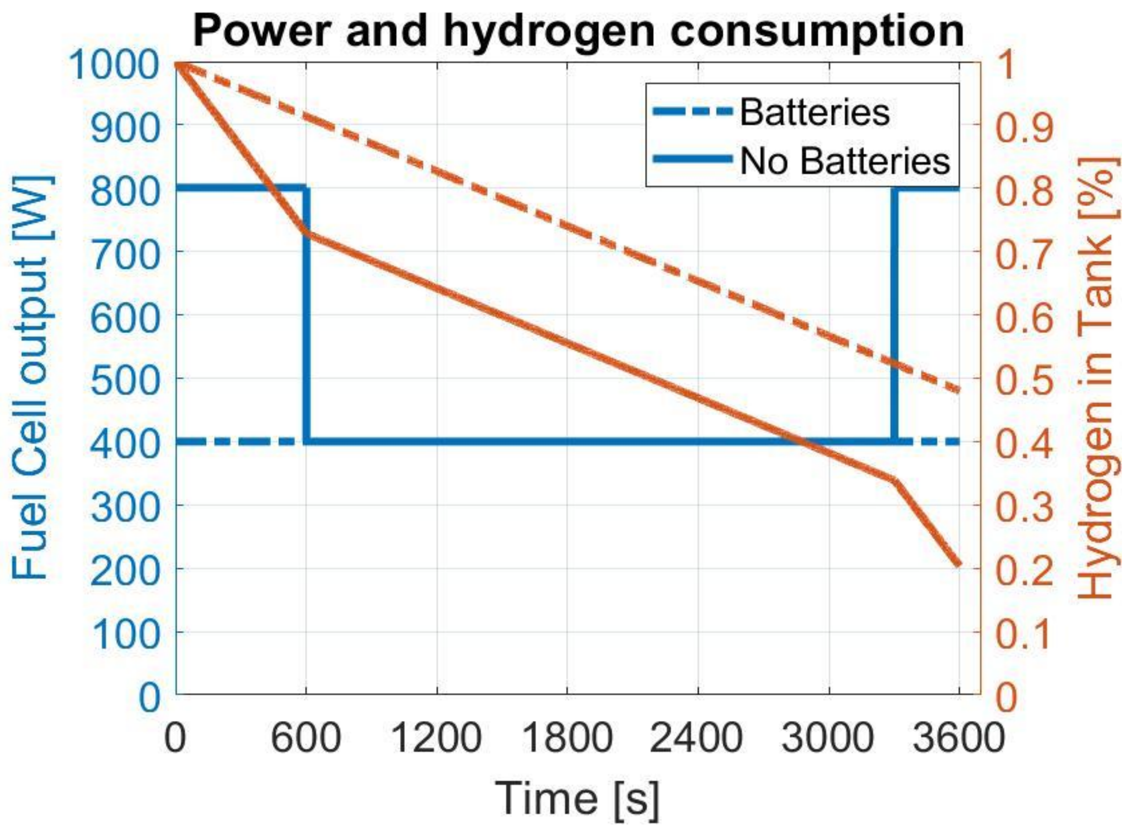

Figure 19: *The graph above shows how the hydrogen consumption and power output differ in a hybrid solution versus a pure fuel cell driven solution.*

4.4 Effects of Height and Speed

The simulation done at 150 meters confirmed that the system can perform throughout the entire desired mission layout with a full hydrogen tank, two battery packs with an initial state of charge of 0,75 and a constant power output from the fuel cell. As the power output from the fuel cell was constant (see Figure 20 below), the consumption of hydrogen was constant as well (see Figure 19 below). As a result, approximately 50 % of the hydrogen in the tank was consumed during the mission. This means that the battery pack was discharged for the additional power required during the climb and descend, as well as being charged during the cruise section when the power output of the fuel cell was larger than the power demand of the UAV.

The simulation for the cruise height at 300 meters failed initially when the system had the same components and parameters as the simulation for 150 m. This is a result of the batteries getting fully discharged during the longer time span of the climb section (see Figure 20 below). The simulation showed that the mission would fail before reaching the desired cruise height. Subsequently, the fuel cell power output had to be varied between 400 and 650 W throughout the mission in order to succeed. This resulted in a more rapid hydrogen consumption during the climb and descend (see Figure 19 below), and therefore roughly 80 % of the hydrogen was consumed during the mission. The battery pack was charged during the cruise section during this simulation as well.

The mission simulation at 450 m cruise height failed initially with the same system parameters as either the 150 m or 300 m parameters. The mission failed in the simulation due to the same reason as the 300 m mission failed using the system parameters from the 150 m mission. However, when using the system parameters from the 300 m simulation it failed due to the fuel tank running out of hydrogen in the descend section. This was a result of the longer time span of the climb section which resulted in a rapid consumption during a long time span compared to the entire mission time span. As the battery packs were charged during the cruise section, there was not enough fuel to fulfill the mission. In order to fulfill the mission with the chosen system, one simulation attempt was performed assuming that the battery packs had an initial state of charge of 1 and the power output from the fuel cell was varied between 350 and 650 W (which is the minimum power demand of the cruise section and the maximum power output from the fuel cell respectively). This resulted in the mission simulation succeeding. However, the hydrogen tank was almost 90 % depleted and the battery pack could not be charged during the cruise section.

To summarize, the maximum height of a mission for one hour (with some safety margins in fuel left) seems to be about 450 meters when incorporating one tank of hydrogen and two battery packs into the system. Furthermore, different strategies need to be employed to succeed in the mission.

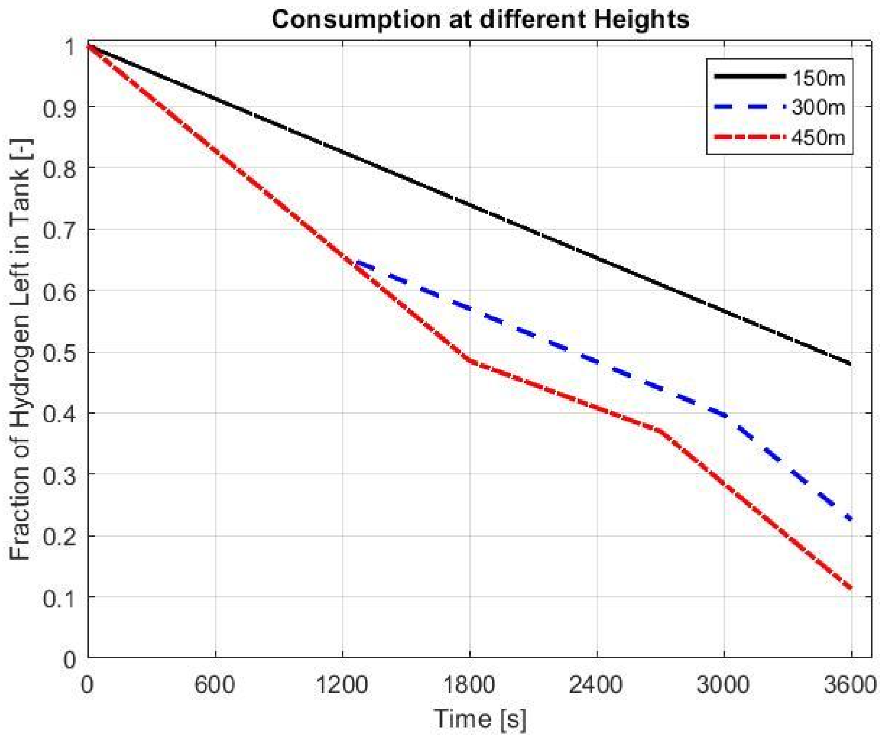

Figure 20: *The diagram above shows the consumption over time for the mission for three different cruise heights, namely 150, 300 and 450 m. The power output was varied for the mission simulation at 300 and 450 m, and constant for the mission simulation at 150 m.*

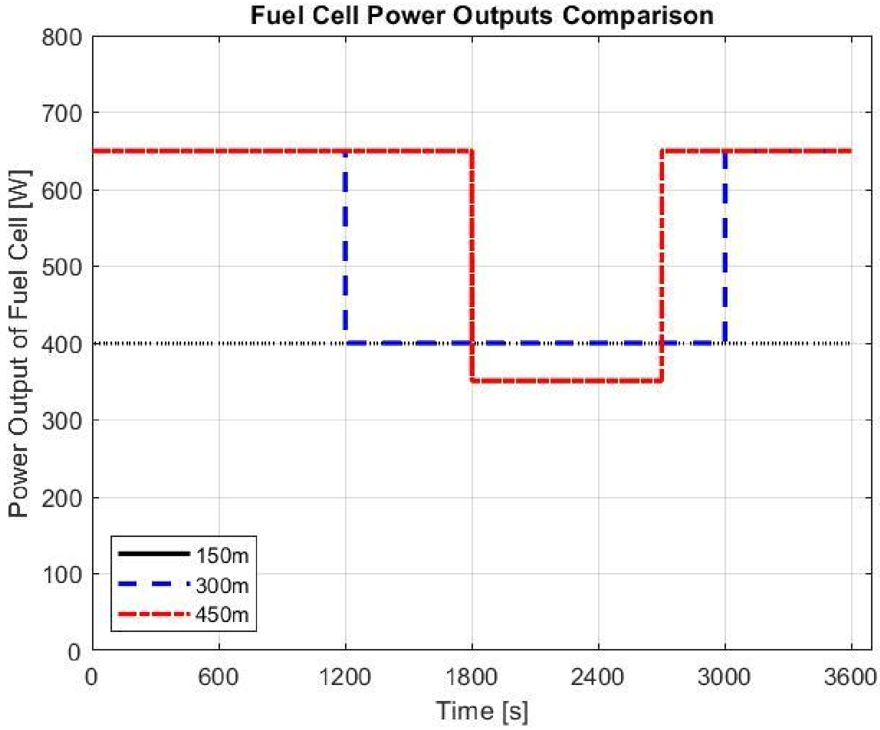

Figure 21: *The diagram above shows the power output of the fuel cell over time during the missions. Throughout the mission simulations at 300 and 450 meters, the power varied between 650 and 400 W and 650 and 350 W respectively.*

When the cruise height is increased, the total pressure of air decreases. This results in a loss of fuel cell performance. Taking into account the correction from the losses due to pressure differences (Nernst equation), the results from the simulations show that it is minimal. As the diagram in Figure 21 below shows, the corrected current (dashed line) does not differ significantly from the regular current (that does not take into account the pressure drop because it was calculated at the ground level). Therefore, in short, the effects on the required current correction due to pressure drop resulting from higher altitudes will be more significant at higher cruise heights, and negligible at the simulated heights (150, 300 and 450 meters).

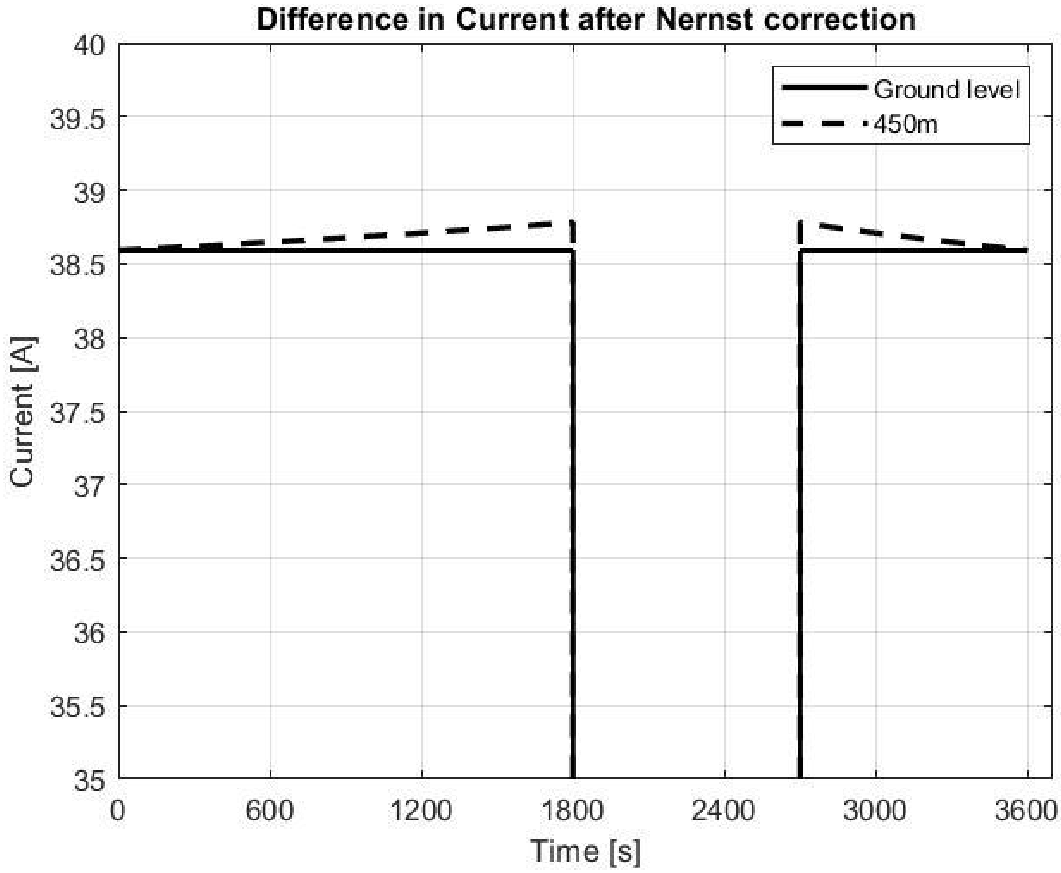

Figure 22: *The diagram above shows a comparison of current for the mission simulation at 450 meters. The dashed line represents the total current with the added correction from the Nernst equation for the losses due to pressure. The current correction increases as the drone climbs and is constant once it reaches the cruise height of 450 meters. Thereafter the current correction decreases again during the descent.*

4.5 Emergency Landing

In case of that the mission fails due to lack of energy from both the fuel cell and the main batteries onboard the drone there is a backup battery. The purpose of this battery is to have sufficient energy to land the drone and be as light as possible. Therefore any degradation of the battery due to any charge constraints are overlooked. This is because it will be less costly than to carry a lot of extra unnecessary weight or lose the drone. With this in mind the optimal number of batteries for emergency landing from 150 m which is our main scenario is one, as 94% of a battery is needed to land.

5. Discussion

On paper it may seem that a system solely powered by either batteries or fuel cells is the better of the options depending on the mission profile. It can be interpreted that the hybrid solution mostly highlights the negatives of both solutions by being both heavy and hard to refuel. However this is not the reality as the disadvantages of using only one source of power offers severe drawbacks. As mentioned, batteries are heavy for the amount of energy they can store which in turn limits the amount of cargo weight which can be carried. The difference in weight is more than 2 kg between the hybrid system and the battery system which becomes a large part of the total weight of the drone. It is more than 10% of the total weight of the drone.

The problem with a system purely powered by fuel cells is however not as apparent from our data. Fuel cells produce electricity by converting hydrogen gas and oxygen gas to water. As this is a chemical reaction it wants to run on as stable power production as possible. Our power profile as shown above can be considered an ideal condition to run a fuel cell only system as the change in required power only changes twice (climb to cruise and cruise to descent). A more realistic version would have several spikes due to environmental factors such as wind and air currents. These spikes are a problem for a fuel cell as it can't handle the change in required power very well which means that the degradation of the fuel cell greatly increases. Also as it is power is produced by a chemical reaction it is hard for the system to change the power output in these "spikes".

This is where the hybrid solution shines. It is resilient to the changes in required power output as well as being much lighter than a drone solely powered by batteries.

Batteries

Considering the fact that the batteries *Gens Ace* 4 and *Gens Ace 3.7* have a considerably higher energy density compared to the *Soar* variant, we decided to use one of the two formerly mentioned batteries since the optimal solution for the energy system is a higher energy and power output in relation to weight. Another important factor for the battery selection is the state of charge of the battery. The calculated C-rates of the both batteries required for completing the mission (see Figure 16) compared to the C-rates of the batteries documented from the specification sheet (see Table 2) indicates that both batteries are considered suitable for the mission. The *Gens Ace 4* discharges and charges with a slightly higher C-rate. It is true that a higher C-rate will cause further internal energy losses due to the energy conversion to heat. However, since the differences in the C-rates of the two batteries are not crucial for the mission, it did not influence our decision making.

We also took into consideration the total mass and volume of the battery solution since reducing the weight of the UAV model in general is desired and more energy efficient. *Gens Ace 4* was then selected owing to the fact that the mission can be completed with the battery solution that is lighter and occupies less volume in the model.

The combination of different battery types were also discussed and studied for incorporation in the model when having a varied fuel cell power profile; mostly to minimize the total mass and volume. To connect batteries with different ampere ratings in parallel is possible, however, in reality they have a slightly different cell voltage irrespective of what is written on their label. This can be problematic as batteries will then try to charge each other to balance these voltage differences. [22]

The simulations and calculations are based on the values documented in the specification sheets of the batteries. These values have not been experimented in the laboratorium to inspect if there are any variations in reality that can impact our results.

Fuel cell, Constant or varied load

A comparison between the energy system solutions using a constant fuel cell power profile and a varied one was made mostly to see if considerable weight and volume differences for the battery pack could be obtained which was not the case here (see Table 4). Keeping the fuel cell power profile constant throughout the mission was concluded to be of much greater importance considering that it can considerably affect the fuel cell's degradation and efficiency over time. The fuel cell is the expensive component in our energy system solution and therefore, the goal is to maximize its lifespan.

Height

Regarding the result from the different cruise heights, the maximum height of a system containing one hydrogen tank and two batteries seems to be around 450 meters with some safety margins. In order to reach higher altitudes another system could be tested with an additional hydrogen tank and/or several additional batteries. The possibilities of the system dimensioning are endless in the case of simulations. However, the amount of components becomes very important regarding their mass and volume as the drone cannot be too heavy to fly and there also needs to be space for the additional batteries or extra hydrogen tanks. The results from the simulations show that the pressure difference does not affect the performance of the fuel cell at such low altitudes. However, this will probably affect the performance at higher altitudes but more precise simulations are needed to determine how much.

Furthermore, the effects of temperature were not taken into consideration when constructing the model for the simulations. The decrease in temperature could affect the results due to the accumulation of product water in the fuel cell as well as produced water freezing inside the fuel cell if the drone reaches altitudes where the temperature has dropped significantly. This will most probably only be a large issue if the drone cruises at substantial heights (at around 2000 meters where the temperature drops below 0 ℃ [11]).

As the exhaust from a fuel cell is water there is a probability that it will freeze as soon as it leaves the fuel cell. This could cause a build up which in the long run would clog the outflow leading to build up in the fuel cell. To combat this some of the power produced could be used to heat the exhaust vents to reduce the risk of the build up. However, this would not be needed as the temperature at the height where the simulation has been done is rarely below the freezing point for water.

When it comes to having an emergency battery it depends on if the extra weight outweighs the risk of the drone crashing. To land the drone if all other energy sources fail a single extra battery is needed which adds 478 grams to the total weight of the drone. The benefits of having this battery on board should be worth it to cover its cost by preventing a crash. This is hard to determine as no calculation on flight cost has been done. However, the extra safety net is always good as it is hard to predict every senario the drone can be exposed to. Another solution than having an extra battery could be to continue to drain the main batteries to 0% instead of stopping at 20 % as we do now. However, this is too little energy to land the drone safely as the calculations done shows that we need at least 94% of a single battery to perform the landing sequence.

The whole argument that fuel cells are more environmentally friendly is based on the fact that hydrogen comes from a sustainable source, one example of this would be hydrogen gas produced through electrolysis of water using wind or solar power as the energy source. This would be the case if the most common source of hydrogen was not from fossil based sources, for example steam methane reforming (if the methane is from a fossil source) where the methane is used to produce hydrogen gas. With that said the system in this report has the potential of being environmentally friendly as it does not produce any CO_2 itself.

6. Conclusion

- The hybrid energy system solution run with the constant fuel cell power profile was concluded to be the best option considering that this can considerably affect the fuel cell's degradation and efficiency over time.
- *Gens Ace 4* was selected owing to the fact that the mission can be completed with the battery solution that is lighter and occupies less volume in the model. Less weight in general is desired and more energy efficient.
- The approximate maximum height that can be reached for the mission lasting one hour (with some safety margins in fuel left) is 450 m, utilizing two *Gens Ace 4* batteries with the initial state of charge of one and a varied fuel cell power profile that varies between 650 W and 350 W.
- The effects on the required current correction due to pressure drop resulting from higher altitudes will be more significant at higher cruise heights and are not substantial up to 150 m in which our mission is carried out.
- Fuel cells are more environmentally friendly than the traditional alternatives due to the fact that hydrogen comes from a sustainable source and that the only exhaust is water defined as zero emission.

7. References

[1] O. US EPA, “Sources of Greenhouse Gas Emissions,” Dec. 29, 2015. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (accessed May 20, 2022).

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8. Attachments

8.1 Code

Initializer Constants and Vectors

```
close all, clear all, clc
H2_I = ((0.002*300*10^5)/(8.314511*343)); %(mol H2) Initial amount of Hydrogen
FC_Volt = 23; % (V) Voltage of the whole Fuel cell stack
Faradays = 96485; %(C/(mol e-)) Faradays constant
Voltage = 18.5; %(V) Voltage of the battery
Cap_GentsACE40 = 4*3600; %(As) Total capacity of one battery
N_Batteries = 2; %Number of batteries
Tot_Cap = N_Batteries * Cap_GentsACE40; %(As) Total capacity of the battery pack
SoC_N=0.75; %Inital state of charge of the battery
N_cell=30
FC_Pow = 400; %(W) Set value of baseline-power of fuel cell
FC_Pow_MAX = 400; %(W) Maximum power produced in the fuel cell
H2_MinT = ((0.002*5*10^5)/(8.314511*343)); %(mol H2)  Minimum tolerance of
                                  %       that is required for
                                  %       the fuel cell to work
R = 8.314511; %ideal gas constant
z = 2; %number of electrons in the reaction
T_cell = 343;%(K) temperature in the fuel cell
P_O20 = 0.20265; %(bar) pressure of oxygen at ground level
Height_at_t = xlsread('Tabulated Data.xlsx',5,'A2:A602');
Pressure_height = xlsread('Tabulated Data.xlsx',7,'C2:C602');

FC_power = xlsread('Tabulated Data.xlsx',3,'B2:B79');
FC_current = xlsread('Tabulated Data.xlsx',3,'A2:A79');

%Extra Emergency battery
Cap_GentsACE40 = 4*3600; %(As) Total capacity of one battery
Voltage_EM = 18.5; %(V) Voltage of the emergency battery
Tot_Cap_Em = Cap_GentsACE40; %Total capacity of the emergency battery
SoC_Em=1; %Initial state of charge of the emergency battery
```

Central Matlab Function

```
function [FC_P, l_p,  Height, Power_Diff, Black_Box, Power_Diff_Em] = fcn(H2_LT, SoC_N,
Load_power, FC_Pow, H2_MinT, FC_Pow_MAX, Em_Power, Soc_N_Em, Load_height)
l_p=Load_power;
SoC_N1=SoC_N;
H2_LT1=H2_LT;
FC_Pow1 = FC_Pow;
FC_POWM = FC_Pow_MAX;
```

```
Height = Load_height;
Em_P=Em_Power;
%We rename the vairables

if (H2_LT > H2_MinT)
    if (FC_Pow1 > l_p && SoC_N1 < 0.6 && l_p <= FC_POWM)
        Power_Diff = FC_Pow1 - l_p;
        Power_Diff_Em = 0;
        FC_P = FC_Pow1;
        Black_Box=0;
        %We produce more power than needed and we can charge the battery
    elseif (FC_Pow1 > l_p && SoC_N1 >= 0.6 && l_p <= FC_POWM)
        Power_Diff = 0;
        Power_Diff_Em = 0;
        FC_P = l_p;
        Black_Box=0;
        %We produce more power than needed but we cannot charge the battery
        %We decrease the power output for the fuel cell to that of the
        %demand
    elseif (FC_Pow1 < l_p && SoC_N1 > 0.2 && l_p <= FC_POWM)
        Power_Diff = FC_Pow1 - l_p;
        Power_Diff_Em = 0;
        FC_P = FC_Pow1;
        Black_Box=0;
        %We do not produce enough power and we can draw power from the
        %battery, the demand is lower than the maximum tolerance on the
        %FC
    elseif (FC_Pow1 < l_p && SoC_N1 > 0.2 && l_p > FC_POWM)
        Power_Diff = FC_POWM - l_p;
        Power_Diff_Em = 0;
        FC_P = FC_POWM;
        Black_Box = 0;
        %We do not produce enough power and we can draw power from the
        %battery, the demand is higher than the maximun tolerance on the FC
    elseif (FC_Pow1 < l_p && SoC_N1 < 0.2 && l_p < FC_POWM)
        Power_Diff = FC_POWM - l_p;
        Power_Diff_Em = 0;
        FC_P = FC_POWM;
        Black_Box = 0;
        %We do not produce enough power and we cant draw power from the
        %batteries so we need to raise the FC_P to l_p
    else
        Power_Diff = 0;
        Power_Diff_Em = 0;
        FC_P = 0;
        Black_Box = 0;
        %The tolerance for the fuel cell is reached and we cannot draw
        %power from the battery/ies
```

```
        end
elseif (SoC_N1 > 0.2)
    FC_P =0;
    Power_Diff = -l_p;
    Power_Diff_Em = 0;
    Black_Box=0;
    %We do not have any hydrogen left but we can draw power from the
    %battery
else
    FC_P = 0;
    Power_Diff = 0;
    Power_Diff_Em = -Em_P;
    Black_Box=1;
    %We do not have any hydrogen left and we cant drain the battery anymore
    %so mission failure
end
```

8.2 Other

Polarization & Power Curve

Current [A]	Power [W]	Voltage [V]
1,166	30,04199	25,765
1,58	39,895	25,25
1,624444	41,74640767	25,69889
1,96	49,3724	25,19
2,15	53,836	25,04
2,24	56,2688	25,12
2,35	58,515	24,9
2,44	60,9756	24,99
2,53	63,0476	24,92
2,65	65,985	24,9
3,35	81,8405	24,43
4,41	105,7077	23,97
4,91	111,7025	22,75
5,06	119,3148	23,58
5,57	129,7253	23,29
5,99	139,6868	23,32
6,33	146,6661	23,17
6,68	151,8364	22,73

6,92	156,5996	22,63
7,12	162,692	22,85
7,44	166,8048	22,42
7,62	170,9928	22,44
7,83	175,392	22,4
7,97	176,2964	22,12
8,15	183,049	22,46
8,41	190,1501	22,61
8,81	191,177	21,7
9,13	204,6033	22,41
9,66	212,8098	22,03
10,2	227,358	22,29
10,31	228,882	22,2
10,49	229,5212	21,88
10,58	230,644	21,8
11,02	243,2114	22,07
11,21	248,1894	22,14
11,24	250,8768	22,32
11,95	258,359	21,62
12,17	263,6022	21,66
12,42	269,7624	21,72
12,63	270,0294	21,38
13,49	283,1551	20,99
13,52	284,0552	21,01
14,02	293,5788	20,94
14,16	296,652	20,95
14,31	308,3805	21,55
15,26	313,4404	20,54
15,91	318,2	20
16,12	328,5256	20,38
16,76	341,5688	20,38
17,11	347,5041	20,31
18,06	375,1062	20,77
18,95	378,242	19,96
19,4	399,64	20,6

21,13	404,4282	19,14
21,35	408,8525	19,15
21,65	416,113	19,22
21,97	418,7482	19,06
22,85	429,58	18,8
23,05	440,9465	19,13
23,2	441,728	19,04
24,12	449,3556	18,63
24,54	467,487	19,05
25,04	487,5288	19,47
27,23	509,4733	18,71
28,16	512,7936	18,21
29,17	528,2687	18,11
29,76	529,1328	17,78
30,18	544,1454	18,03
30,77	545,8598	17,74
32,13	551,0295	17,15
33,22	583,011	17,55
34,8	583,248	16,76
35,14	585,7838	16,67
35,44	602,48	17
36,67	625,5902	17,06
37,2	636,492	17,11
38,15	647,024	16,96
39,54	656,364	16,6

Height Data

Height [m]	Pressure of air [bar]	Pressure of oxygen [bar]
0	1,01325	0,20265
10	1,0125475	0,2025095
20	1,011845	0,202369
30	1,0111425	0,2022285
40	1,01044	0,202088
50	1,0097375	0,2019475
60	1,009035	0,201807

70	1,0083325	0,2016665
80	1,00763	0,201526
90	1,0069275	0,2013855
100	1,006225	0,201245
110	1,0055225	0,2011045
120	1,00482	0,200964
130	1,0041175	0,2008235
140	1,003415	0,200683
150	1,0027125	0,2005425
160	1,00201	0,200402
170	1,0013075	0,2002615
180	1,000605	0,200121
190	0,9999025	0,1999805
200	0,9992	0,19984
210	0,9984975	0,1996995
220	0,997795	0,199559
230	0,9970925	0,1994185
240	0,99639	0,199278
250	0,9956875	0,1991375
260	0,994985	0,198997
270	0,9942825	0,1988565
280	0,99358	0,198716
290	0,9928775	0,1985755
300	0,992175	0,198435
310	0,9914725	0,1982945
320	0,99077	0,198154
330	0,9900675	0,1980135
340	0,989365	0,197873
350	0,9886625	0,1977325
360	0,98796	0,197592
370	0,9872575	0,1974515
380	0,986555	0,197311
390	0,9858525	0,1971705
400	0,98515	0,19703
410	0,9844475	0,1968895

420	0,983745	0,196749
430	0,9830425	0,1966085
440	0,98234	0,196468
450	0,9816375	0,1963275
460	0,980935	0,196187
470	0,9802325	0,1960465
480	0,97953	0,195906
490	0,9788275	0,1957655
500	0,978125	0,195625
510	0,9774225	0,1954845
520	0,97672	0,195344
530	0,9760175	0,1952035
540	0,975315	0,195063
550	0,9746125	0,1949225
560	0,97391	0,194782
570	0,9732075	0,1946415
580	0,972505	0,194501
590	0,9718025	0,1943605
600	0,9711	0,19422
610	0,9703975	0,1940795
620	0,969695	0,193939
630	0,9689925	0,1937985
640	0,96829	0,193658
650	0,9675875	0,1935175
660	0,966885	0,193377
670	0,9661825	0,1932365
680	0,96548	0,193096
690	0,9647775	0,1929555
700	0,964075	0,192815
710	0,9633725	0,1926745
720	0,96267	0,192534
730	0,9619675	0,1923935
740	0,961265	0,192253
750	0,9605625	0,1921125
760	0,95986	0,191972

770	0,9591575	0,1918315
780	0,958455	0,191691
790	0,9577525	0,1915505
800	0,95705	0,19141
810	0,9563475	0,1912695
820	0,955645	0,191129
830	0,9549425	0,1909885
840	0,95424	0,190848
850	0,9535375	0,1907075
860	0,952835	0,190567
870	0,9521325	0,1904265
880	0,95143	0,190286
890	0,9507275	0,1901455
900	0,950025	0,190005
910	0,9493225	0,1898645
920	0,94862	0,189724
930	0,9479175	0,1895835
940	0,947215	0,189443
950	0,9465125	0,1893025
960	0,94581	0,189162
970	0,9451075	0,1890215
980	0,944405	0,188881
990	0,9437025	0,1887405
1000	0,943	0,1886