An environmental perspective on the feasibility of using existing PEMFC technology in general aviation.

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Abstract

The feasibility of using alternative energy solutions in general aviation is investigated; more specifically the usage of Proton Exchange Membrane Fuel Cell (PEMFC) technology, with the help of a constructed reference case. The constructed case is a modified Socata TB20 GT aircraft, equipped with PEMFC technology. Said reference case is then compared to the original 100LL setup with the help of analytical and numerical aerodynamic analysis, as to get a measure of the difference in performance. Additionally, a Life Cycle Analysis (LCA) is also performed on both the original and the reference case, in order to get a measurement of how “green” said green technology actually is.

Going by the methods used in the report, it is shown feasible to use existing PEMFC technology in order to get an air worthy aircraft, with performance matching the original setup, assuming some modifications were made. Firstly, due to restrictions in size and weight, the Socata TB20 GT was turned into a 2-seated plane. Secondly, the range of the new reference case was lower than the original, 100LL powered craft, yet still managing a flight time of 2h 30m on a maximum cruise speed of 310 km/h using adjustable propeller blades technology, or 280 km/h if making no modifications to the original propeller design.

Additionally, the use of PEMFC technology is also proven to be the better alternative from an environmental point of view, where the relative impact of 100LL fuel outweighs the comparatively larger production impact of the PEMFC setup even at minor usage. This was done by evaluating a constructed computer model using different usage patterns.
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Introduction

In modern history, each time has had its own struggles and goals in technical and engineering matters, ranging from the electrification of society to making lumps of metal fly and sending humans out into space and beyond. The questions and challenges of today are many. Going by international attention and awareness, few issues are given more space than the climate threat and the alarming possibility of global warming.

Almost every quarter, a new report is released pointing to both actual and possible rises in temperature across the globe, followed by agitated political debates arguing both the results and how big a part humanity has to play in it.

As a point of reference, in the United States between the year 1973 and 2010, the energy use in transportation has been slowly climbing from 24.6 % to 28.1 %, roughly a quarter of the total energy used. [1]. Of the total transportation energy consumption, petroleum products accounted for 95.8 % in 1974, versus 93.2 % in 2010 [2]. In addition, it can be noted that out of the total transportation energy consumption, about 20.2 % of those 28.1 % can be accounted to light vehicles, whereas buses and trucks account for the remaining 7.9 % of total energy consumption [3].

From the statistics mentioned above, it can be seen that significant reductions in environmental harm can be achieved, should one be able to use a source of energy other than petroleum. This goes for all modes of transportation, be it by ground, sea or air.

With all this in mind, a reasonable next step could be to pose the question: What can be done today, using existing technology? There will always be newer technology on the horizon promising to help us with both x, y and z which is of course good, however with the problem being that it answers mainly the questions of tomorrow, rather than the possibilities of today. In an effort to find out what is actually possible today, this report will focus on testing new technology in the field of general aviation. Although only contributing around 0.8 % to the total transportation energy use in 2009 [4], it serves as a powerful proof of concept, mainly regarding technological maturity, which is often seen to correlate with economic viability.

However, an eventual proof of concept of an up and coming “green” technology is not the only thing needed to be evaluated. Just as important, if not more, is an evaluation regarding the actual environmental benefits of said “green” technology.

Life Cycle Analysis (LCA) is a standardized approach for measuring how a product or systems impacts the environment during its entire life cycle, from conception to production, usage and grave. It has grown in popularity during recent years among both companies and governments due to being able to measure and compare different solutions from set parameters. This report will make heavy use of LCA analysis to evaluate just how “green” these eventual green technologies actually are.

A comment on the structure of this report: It’s divided up into parts. The first sections deals with the challenge of modifying an existing aircraft into an air worthy, "green" aircraft using technology available today. After coming up with an air worthy alternative, its performance is evaluated and compared to the original aircraft. Then follows the LCA section, which compares the modified aircraft with the original, getting a measure of environmental footprints. Lastly, the obtained results are discussed.

Project Description

Due to several reasons, including but not limited to environmental concerns, technological advancements, costs, political reasons, there is a need for more thorough investigations regarding the technological maturity level of so called “green” technologies.

The focus of this report is to evaluate the feasibility of using the technology of today (2013) in airborne personal transportation, as well as evaluating eventual feasible systems from a LCA perspective with the aim of gaining a more accurate assessment of how "green" said proposed green technology is.
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Technological background

Going by the statistics presented in the introduction, it’s easy to start putting blame everywhere for our current transportational, environmental impact; from politicians, to big oil companies, to human laziness. However, that would be ignoring the fact that right up until recently, there has really been no viable alternatives.

At its inception, fossil fueled engines spearheaded the field of thermodynamics, but could be constructed with the technological expertise of the past century. The technological threshold for some of the newer, “green” technologies is comparatively higher, and not until now starting to see real world applications, having tens of years of research behind them, rather than hundreds. There also exists no guarantee for more research to translate into a better technology.

Of course, the internal combustion engines of today are much more complex and thus stronger, more fuel efficient and lighter, compared to how they were at their inception, up to where they today are close to their limits. Internal combustion engines have a head start, and as will be discussed further when talking engine selection, fossil fueled engines are almost as good as they are going to get.

As such, focus has to be shifted elsewhere and it is just not for the environments sake. Auto manufacturers are very much aware of the limitations of fossil fueled engines - their inability of large, future growth, so if one manufacturer manages to make an alternative technology economically viable, they have a chance of making their competitor’s profits plunge.

Therein lies the problem of today; economic viability, which goes hand in hand with technological maturity. A lot of research and prototype projects are being conducted by major market players, all nosing on the new for when it will finally be able to compare to the old. Some performance losses will most likely be inevitable during the beginning of an eventual transition – fossil fueled engines have more than a century of research behind them and that will most likely require time to compensate for, if it even can be done. Politics also tries to shift the balance as much as it can, but as of today, fossil fueled engines are still very much the norm.

The following section will talk about fuel cells specifically, due to the soon to be shown relevance to this project.

The Fuel Cell

The main concept behind the fuel cell as a source of energy is not new. Already in 1839 the first fuel cell was built by the two physicists Ludvig Mond and Charles Langer using a mix of coal gas to create an energy output. However, for its time it was neither cheap nor powerful, prohibiting widespread use. And like a technological side track it stayed until the 1950s, when NASA in partnership with other scientific institutions produced fuel cells later used in the Space Gemini Program. The cells used were named Grubb-Niedrach Fuel Cells and were far too expensive for civilian use.

Fast forwarding to the 70s, talks about the need for a more “green” fuel started appearing in both political and economical debates. The sudden surge of cars during the past years had created pollution problems in cities all over Europe and the US. At this time, the first fuel cell vehicles were brought to the market by America, German and Japanese manufacturers, but could not carry their costs. It was a wide spread belief among auto makers of that time that fuel cells would be the technology of the next decade, a belief still alive to this day [5].

As of today, there are several different fuel cell setups – each version with its own advantages and drawbacks. What they all have in common is that they all transform chemical reactions into electric energy. As a comparative example, a battery is a stored chemical reaction waiting to happen, whilst a fuel cell might need both heating and supplied fuel from the outside. This is also the fuel cells greatest advantage – just like a combustion engine it will keep going as long as there is gas in the tank.

The fuel cell investigated in this paper is a so called PEMFC – Polymer Exchange Membrane Fuel Cell, a technologically advanced fuel cell used in many prototype automotive vehicles.
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and buses. Using hydrogen as fuel and taking oxygen from the environment, its exhaust is heat and water. Besides having a high energy efficiency\(^1\), it also does not require a high operating temperature – around 60 to 80 °C is enough. Technologically, what all fuel cells have in common is that the main parts tend to be an anode, a cathode, an electrolyte and a catalyst. What each of these parts do in a PEMFC is described below and pictured in figure 1.

![Figure 1: The insides of a PEMFC, courtesy of the U.S. Department of Energy.](image)

1. Hydrogen flows from the tank into the anode, where the electrons are separated from the hydrogen molecules using a platinum catalyst and transported away in the field flow plates used to contain and direct the fuel. In the PEMFC, a membrane is placed as an electrolyte between the anode and the cathode, letting protons through but keeping the hydrogen and oxygen from mixing. The anode reaction can be seen in equation (1).

\[
H_2 \rightarrow 2H^+ + 2e^- \quad (1)
\]

2. In the cathode, oxygen is splitted with the help of a catalyst, typically platinum although not being as efficient as when used in the anode.

3. The electrons released at the anode are lead around a circuit, producing electrical energy, before arriving at the positively charged cathode. The reaction can be seen in equation (2), resulting in water and heat.

\[
\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)
\]

\(^1\)The theoretical efficiency limit for a PEMFC is somewhere around 83 %.
Aircraft design process

Going by our primary goal, set out at the start of this project, it follows that there is a lot of decisions to be made regarding everything from performance trade-offs, to reasonable feasibility. The following sections follow the work process and the judgments made to reach a final concept, which is later to be evaluated first from a performance- and then a LCA perspective.

Prel. Decisions - Aircraft

Due to the current technological state of electrical vs. fossil propulsion systems, here speaking of the power discrepancy, said systems are generally not evaluated using the same platform. In aircraft design, keeping the weight down has always been an issue, but not at the levels needed for efficient electrical propulsion and it’s generally lower power per kg output.

Adding to this is the computational and simulational advances continuously being made, which opens up for the possibility of constructing the efficient solutions needed, something that due to cost concerns was not really possible before on the budgets allotted for civil flight development.

Due to the nature of gauging different technologies in any field, we have made the decision to apply different solutions to a pre-existing, somewhat modern personal aircraft. This opens up for the ability of actively comparing different technologies and drawing conclusion as to which system would be more preferable in this specific situation.

As part of the aircraft selection process, a few criteria were decided upon. The first was that the aircraft had to be somewhat modern, due to reasons including, but not limited to, alignment with project goals, avoiding eventual conflicts of standards and fairness of comparison.

The second criterion posed was that of performance. As a reference for this criteria, a quick comparison in fuel energy density between batteries and fossil fuel gives the following: If one was to buy a large batch of high energy density batteries today, you could for example buy the NCR18650A from Panasonic with a Capacity of 3100 mAh and a nominal voltage of 3.6 V, weighting around 45.5 g.

Converting into Watt hours (Wh)$^2$, we see that the selected battery has a total of 11.16 Wh. With a mass of 45.5 g, this gives a measurement of the energy density as 0.245 kWh/kg. This can be compared to in development figures by Panasonic stating they would have reached 0.265 kWh/kg by 2012 [7]. Converting into MJ/kg, we see that these batteries have an energy density of roughly 0.88 MJ/kg. This should be compared to oil derivatives such as Gasoline, LPG, Diesel, which has a energy density of around 46 MJ/kg [8]. Figures regarding MJ/L give similar numbers.

Going back to the performance criteria, we posed the requirement of a potential aircraft to be a comparatively long ranged aircraft, since going by the reasoning above; there is a possibility of a drastically reduced maximum range of the aircraft. Because of this, the decision fell upon the Socata TB20 GT, pictured in figure 2. Data can be seen in table 1.

Figure 2: Picture of the Socata TB20 GT in flight.

\[
2V \cdot \text{Ah} = \text{Wh}
\]
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<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max cruise speed</td>
<td>302 km/h</td>
</tr>
<tr>
<td>Rate of climb</td>
<td>6 m/s</td>
</tr>
<tr>
<td>Operating ceiling</td>
<td>6000 m</td>
</tr>
<tr>
<td>Stall speed</td>
<td>130 km/h</td>
</tr>
<tr>
<td>Take-off speed</td>
<td>126 km/h</td>
</tr>
<tr>
<td>Take-off distance</td>
<td>634 m</td>
</tr>
<tr>
<td>Max weight</td>
<td>1400 kg</td>
</tr>
<tr>
<td>Max range</td>
<td>2052 km</td>
</tr>
<tr>
<td>Power rating</td>
<td>250 hp</td>
</tr>
<tr>
<td>Available fuel</td>
<td>326 L</td>
</tr>
</tbody>
</table>

Table 1: Performance data of the original, unmodified Socata TB20 GT, as stated by the manufacturer. All values acquired with max certified weight and ISA conditions.

Prel. Decisions - Batteries

One of the first decisions that had to be made is regarding what kind of propulsion system that is to be tested. Using an electric engine to drive the propeller and thus the aircraft, the question is thus: How is the required electricity fed to the motor?

Since one of the project goals is aiming for a reduced environmental footprint during a whole life cycle, investigating different electricity sources becomes a necessity especially when thinking about using batteries, since the charge required is then built up using outside sources.

A lot of work in this has already been done. In his Master’s thesis, Ragnvald Alvestad at the Royal Institute of Technology, Sweden, [9] applied Life Cycle Analysis (LCA) on different setups of a ferry with the aim of investigating the benefits of using LCA in future ship design. One of Alvestad’s conclusions when using an electrical setup can be seen in figure 3 and its description, both authored by him. For more information about LCA, please refer to the relevant sections later in this report.

Going by numbers obtained by Alvestad, the source of electricity when using batteries will overshadow most other things by a large margin:

- At 2600 m with 75 % power.
- During level flight, not takeoff or landing.

Figure 3: 'A comparison of four different sources of electricity for case 4. Hydro power is, as expected, the best alternative with regards to environmental impact, whereas coal is worse off at 188 times larger impact when comparing only the energy consumption. Observe that the vertical scale is logarithmic.'

- Using fossil fuel generated electricity yields a total impact about 66 times larger than hydro power and 40 times larger than nuclear power for the modeled factors. This is three times worse than both diesel electric cases, and this points to that an environmental gain is only achievable if renewable or nuclear electricity is chosen to supply the ferry.” — Alvestad [9]

Since the actual source of electricity can never be pinpointed if using a countrywide power grid, and since the average environmental impact will vary both by weather, season and country, the possible use of batteries has been omitted from this paper. It is the authors’ opinion that even if all factors could be accounted for, there is a question regarding the scientific value of knowing a rough environmental impact of a specific flight route of a personal aircraft during a previous date, that has a non-linear variation with time.

In addition, if ignoring the LCA completely, the use of high energy density batteries could theoretically be viable – it’s the predominant choice of power in the few electric aircrafts existing today. However, as will be discussed in the following sections, these aircrafts generally tend...
to have characteristics such as less powerful engines, different designs or short flight times - and often a combination of them.

**Prel. Decisions - Motor**

The main decision regarding the motor is as to its power. How powerful does it have to be? Using a more powerful motor gives shorter flight times, but may also increase the range. A less powerful engine might increase the air time, but decrease range. In reality, this is an optimization problem involving speed, weight, range, acceptable takeoff and landing performance and maneuverability that the authors feel is outside the intended range of this report.

As a first step in combating the inevitable performance loss, the decision was made for a slight decrease in engine power. However, should the reduction in engine power be too large, the plane would retain neither the feel, nor any of the specifications of the original craft. Going with this, the chosen lower engine performance limit came from the decision that the new aircraft would still need to be able to achieve the maximum cruise speed of the original aircraft.

<table>
<thead>
<tr>
<th>Value</th>
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<tbody>
<tr>
<td><strong>Motor Name</strong></td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td><strong>Peak torque (at 360 A)</strong></td>
</tr>
<tr>
<td><strong>Continuous torque</strong></td>
</tr>
<tr>
<td><strong>Maximum speed</strong></td>
</tr>
<tr>
<td><strong>Peak Power (at 600 – 720 V)</strong></td>
</tr>
<tr>
<td><strong>Continuous power</strong></td>
</tr>
<tr>
<td><strong>Peak efficiency</strong></td>
</tr>
<tr>
<td><strong>Total Volume</strong></td>
</tr>
<tr>
<td><strong>Total weight</strong></td>
</tr>
</tbody>
</table>

Table 2: Original engine specifications [10].

According to the manufacturer [10], the Socata TB20 GT has a maximum cruising speed (at 8500 ft and 75 % power) of 163 KTAS. Transforming this into more general terms, the engine needs to output a total of 187.5 HP or 140 kW to reach a speed of 302 km/h at a height of roughly 2600 m. As such, any potential substitute engine would need an absolute minimum power rating of 140 kW.

Preparatory research for this report hinted at a small market for such engines. Modern prototypes and early design electric airplanes generally carry less powerful engines in harmony with current battery technology. The only feasible electrical aircraft engine found [11], developed specifically for aircraft use, was a prototype engine made for the NASA/CAFE Green flight challenge [12] of which Wired Magazine in 2011 wrote: “It is the most powerful electric motor seen thus far in an all-electric airplane design.” [11] Since using a one of a kind, prototype engine in our setup did not really fit in with the project goals - and also because no data could be found on it, focus had to be turned elsewhere.

Although not developed specifically for flight, the YASA-750H electrical engine developed by Yasa Motors provides the necessary power needed [13]. Originally developed for the Lola-Drayson B12/69EV prototype [14], record breaking [15], Le Mans racing car, which featured four YASA-750H engines, the engine is currently in production. It can also be optimized for different voltages and currents when placing an order.

<table>
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<tr>
<td><strong>Motor Name</strong></td>
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<tr>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td><strong>Peak torque (at 360 A)</strong></td>
</tr>
<tr>
<td><strong>Continuous torque</strong></td>
</tr>
<tr>
<td><strong>Maximum speed</strong></td>
</tr>
<tr>
<td><strong>Peak Power (at 600 – 720 V)</strong></td>
</tr>
<tr>
<td><strong>Continuous power</strong></td>
</tr>
<tr>
<td><strong>Peak efficiency</strong></td>
</tr>
<tr>
<td><strong>Total Volume</strong></td>
</tr>
<tr>
<td><strong>Total weight</strong></td>
</tr>
</tbody>
</table>

Table 3: YASA-750H electrical engine specifications [13].

Looking at the specifications given in table 3, continuous power is dependent on applied coolant. Due to placement right next to the two major air intake vents of the Socata TB20 GT and the high engine efficiency, cooling is not of major concern. It’s comparatively compact size, as seen in figure 4, also gives more options when designing a coolant system. The only real adaption that has to be made when installing the YASA-750H electrical engine is mandatory installment of reduction gearing, as the YASA-750H, just like the original 100LL
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A second possible engine choice is the Remy HvH250 HT high speed engine \[16\], should the YASA-750H not be available. This would add some additional engine weight as well as a smaller liquid cooling unit. The efficiency would drop by roughly 2 \%, but so would the price.

**Prel. Decisions - Power**

As has been previously stated in section on the subject of batteries, it’s not feasible to use batteries as a power source in this report due to its varying environmental impact. Even if one could technically get the Socata TB20 GT in the air using batteries, the comparatively powerful engine would make for a short range craft. See table 4 for flight times versus battery weight. Not included in this table is the flight time penalty for additional weight, which is considerable.

As can be seen from table 4, current battery energy density makes for much shorter flights when compared to the original aircraft and its 6+ hour maximum flight time, but the aircraft would still fly. However, since batteries are excluded due to difficulties including them in a LCA, other options have to be considered.

In the world of alternative energy, the most common types are solar-, wind- and geothermal energy, biofuel and ethanol, nuclear binding energy and hydrogen \[17\]. Excluding the first three, the choice is between different gases, ethanol and nuclear energy. As nuclear energy has yet to be accepted when going into space and beyond, the authors find it within reason to think that it will neither be possible nor legal for commercial aviation usage in the immediate future.

**Table 4:** Battery mass versus flight time. To be noted is that this is in an ideal scenario with 100 \% discharge possibility. Calculations made assuming 0.245 kWh/kg batteries and engine running at 135 kW.

<table>
<thead>
<tr>
<th>Battery weight [kg]</th>
<th>Flight time [minutes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>200</td>
<td>21</td>
</tr>
<tr>
<td>500</td>
<td>54</td>
</tr>
<tr>
<td>700</td>
<td>75</td>
</tr>
</tbody>
</table>

As can be seen in figure 5, if going solely on carbon dioxide footprint, using bioethanols might actually be worse than to keep using gasoline. And in the cases when it’s not, such as in Brazil and Mozambique, it’s still competing with food production and/or contributing to the

![Figure 5: Gram of Carbon Dioxide produced per Megajoule of energy, UK Government numbers \[18\].](image)
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continued deforestation of the rain forest. As such, both due to ethical and environmental concerns and the marginal gain towards a healthier environment, it is the authors’ opinion that the use of bioethanols is not a viable source of power in this project.

A more interesting source of power is hydrogen; more specifically hydrogen powered fuel cells. As was explained in detail earlier in this report, a PEM fuel cell has significant advantages compared to every other power source currently in existence – a 100 % clean working cycle, using hydrogen and oxygen to produce energy and water. The advantages and downsides of PEM fuel cells are further evaluated in the LCA later in this report.

Although being an emerging market, few portable PEM fuel cells exist that can output the power needed to propel the aircraft forwards. After being in contact with Ballard Power Systems, one of the world leaders in PEM fuel cell technology, it was discovered that their FCvelocity-HD6 fuel cell, originally developed and used mainly for buses, fits the power requirements. Currently, it has accumulated more than 200,000 hours of operation time in various buses and can be seen in picture 6. Specifications 5 can be seen in table 5.

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>150 kW</td>
</tr>
<tr>
<td>Estimated Lifetime</td>
<td>12000 h</td>
</tr>
<tr>
<td>Rated Current</td>
<td>320 A</td>
</tr>
<tr>
<td>DC Voltage</td>
<td>465 - 730 V</td>
</tr>
<tr>
<td>Cell efficiency</td>
<td>60 - 71 %</td>
</tr>
<tr>
<td>Weight</td>
<td>400 kg</td>
</tr>
<tr>
<td>Min. starting temp</td>
<td>- 40°C</td>
</tr>
</tbody>
</table>

Table 5: HD6 PEM fuel cell specifications, manufactured by Ballard Power Systems.

Figure 6: The FCvelocity-HD6 fuel cell system. Picture courtesy of Ballard Power Systems.

Compared to assorted oil derivates with an energy density of around 46 MJ/kg, hydrogen has a much greater energy density of 123 MJ/kg. However, hydrogen still has not been a viable fuel option until recently, due to its much lower density. And although possible in space applications, it’s not yet economically viable to use liquid hydrogen in airborne personal transportation. As such, the effective MJ/L when using 700 MPa tanks is 5.6 MJ/L, versus 26 – 36 MJ/L for oil derivates. More about this can be read in the following section.

However, the HD6 fuel efficiency is considerably higher than most internal combustion engines. For them, the laws of thermodynamics play an important role in the amount of combusted fuel that can be converted to actual work. Modern cars are getting closer to that limit of around 25 – 30 %, averaging around 20 % total efficiency [19]. Adjusting for these numbers, we get the numbers seen in table 6.

Prel. Decisions - Fuel tanks

Knowing effective fuel efficiency and fuel energy content, several fuel performance statistics can now be calculated. Even though a fuel cell equipped aircraft could have the same cruise speed as the original craft, it does so at a slight fuel efficiency cost, since the HD6 fuel efficiency drops when getting close to maximum power output.

Running at 80 % power, the HD6 fuel cell has an output of 120 kW or 0.120 MJ/s. To keep

5Additional specifications can be found in Appendix A.
6Official dry weight is 404 kg. In talks with Ballard a representative said 4 kg could be taken off with a bit of optimization.
7Assuming a good 4th generation tank, which would have a pressure of around 700 bar.
8Rough energy output numbers in a fusion reactor, entered as a comparison.
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<table>
<thead>
<tr>
<th>Fuel</th>
<th>MJ/kg</th>
<th>MJ/L</th>
<th>Efficiency</th>
<th>MJ/kg (adjusted)</th>
<th>MJ/L (adjusted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>123</td>
<td>5.6</td>
<td>60 %</td>
<td>73.8</td>
<td>3.36</td>
</tr>
<tr>
<td>Gasoline</td>
<td>46</td>
<td>36</td>
<td>20 %</td>
<td>9.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Propane</td>
<td>46.4</td>
<td>26</td>
<td>20 %</td>
<td>9.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Deuterium- Tritium</td>
<td>330000000</td>
<td>6368000000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6: Fuel energy density comparison in modern engine usage.

Using the engine running at that power for 1 hour, multiply by 3600 s. The total energy need to cruise at that power is 432 MJ. Using figures from table 6, that requires at least 5.8 kg of hydrogen, or using figures for tank volume, a tank of at least 128.6 L.

Using a 700 bar tank was something that was up until recently not possible. However, due to advances in the field of fiber composites, Type IV tanks are being sold today with a maximum constant pressure of up to 1000 bar, whilst being compact enough for mobile applications. The Tuffshell CNG fuel tanks seen in figure 7 from Lincoln Composites [20] come in customizable diameters and lengths, as seen in table 7.

![Figure 7: Cross section of a Tuffshell type IV CNG/hydrogen tank. Picture courtesy of Lincoln Composites [20].](image)

The Type IV tanks needed to get any decent mileage, as in, with a decent weight to liter ratio, are usually made out of a polymer and lined with some kind of carbon fiber or carbon fiber composite. As these materials are comparatively expensive, they are currently mostly used only for very high pressure tanks. Technically, they would decrease the mass and thus weight needed if say, used in a 200 bar tank usually made out of aluminum. But then there is often no reason not to up the pressure and drastically increase the amount of gas contained within the same area.

A detailed study by Argonne National Laboratory for the U.S. Department of Energy [21], using year 2008 numbers, showed a weight per liter figure of roughly 0.7 kg/L for a 700 bar system. It should be noted is that this was only a 5.4 % increase compared to a 350 bar aluminum tank, showing the advantages of using Type IV tanks to almost double the fuel contained in the same geometry, keeping similar weight. Using the same figures, predicted weight per liter is predicted to reach 0.5 kg/L in the near future.

Combining these figures, the total tank weight needed for a one hour flight at 80 % power equates to 90 kg using technology available in 2008. If taking into account the expected drop in kg/L in the near future, a one hour trip at 80 % power would only require a tank weight of roughly 64 kg for the same trip. As a crude point of reference, the original Socata TB20 GT fuel tanks carry a total of 336 L and weights around 275 kg filled up. Dividing by the roughly

---

9One of the most common polymers used are HDPE – High-Density Polyethylene.
6 hours of original flight time, would set the one hour flight time tank weight as a bit above 40 kg. As there is currently no thoughts about hydrogen tank kg/L performance going much below the estimated 0.5 kg/L \([21]\), the only way left to further enhance hydrogen tank performance would be to further increase the tank pressure. More about the future use of hydrogen can be read in the discussion.

**Prel. Decisions - Cooling**

Looking at the aircraft proposed in this report, there are two places where additional cooling is needed. The first is the engine. As seen back in table 3, the chosen YASA-750H electrical engine is very efficient. However, some heat will still be produced. Going by the only available data of 95% maximum efficiency, the motor will still develop up to 7.5 kW of heat\(^{10}\). As a point of reference, that is roughly the power of a normal sized\(^{11}\), electric sauna heater.

This might sound like a lot, but can easily be cooled by redirecting some of the air flowing into the large air vents in the front of the Socata TB20 GT, as can be seen in figure 2, and then directed out of the aircraft somewhere convenient. A smaller heat sink might need to be fastened to the engine, but the weight of this will not be of major concern, since some air flow will always be provided by the propeller blades as long as the engine is running.

Although not obvious at a first glance, fuel cells develop large quantities of heat. According to the specifications sheet, the HD6 fuel cell has an average efficiency between 60 - 71% depending on load. After additional contact with the manufacturer, safety margins require a cooling capacity of up to 135 kW. To translate, this would mean that at peak power, the efficiency could drop down to 52.6% before overheating would start to occur. This is something that in theory should never happen, but that the system is still required to handle.

\(^{10}\)Obtained by taking 5% of the maximum engine output of 150 kW.

\(^{11}\)8 kW is enough for around 7 - 13 m\(^3\) of isolated space.

This is a big issue. Having the capacity to cool off almost half of the energy required to fly an aircraft at it’s still very respectable speed requires serious engineering effort. To see if this was even possible, some preliminary calculations were made to see how much such an air cooling system would weight, if applied on the liquid based coolant unit which is bundled with a purchase of a HD6 fuel cell, transporting the heat out of the cell itself.

\[
\frac{dQ}{dt} = h_f A \Delta T
\]  

(3)

Using Newton’s law of cooling - equation (3), where \(dQ/dt\) is thermal energy per second, \(h_f\) the convection coefficient, for air convection being around 50 W m\(^{-2}\)K\(^{-1}\) for air speeds around 10 m/s, and having a fin height of 0.15 m and a length of 0.5 m, as well as taking into account that each fin will have air convection on both sides, we get the expression in equation (4), which can either be solved for the temperature \(T\) or the amount of fins needed \(x\).

\[
135 \text{ kW} = 50 \frac{\text{W}}{\text{m}^2 \text{K}} \times 0.15 \text{ m}^2 \times T \times x
\]  

(4)

Assuming we can, at maximum, run the system at temperature 100 K higher than ambient temperature, this would require a total of 180 fins\(^{12}\). However, the geometry also needs to be taken into account, as well as the air temperature gradually rising. Introducing the fin efficiency as the actual heat transferred by the fin, divided by the heat transfer of a hypothetical isothermal fin:

\[
n_f = \frac{\text{tanh} \left( \frac{mL_c}{mL_c} \right)}{mL_c} \quad \text{and} \quad mL_c = L_f \sqrt{\frac{2h_f}{t_f k}}
\]  

(5)

Using equation 5 with the values from table 8, this gives a total fin efficiency as \(n_f = 0.557\). This means that the amount of required fins would be 180/0.557 = 323 fins. Aluminum has a density of 2700 kg/m\(^3\) which gives the weight \(^{12}\)\(x = 180\) in equation (4).
An environmental perspective on the feasibility of using existing PEMFC technology in general aviation.

Table 8: Explanation of the terms in equation 5.

<table>
<thead>
<tr>
<th>Expression</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>201</td>
<td>Thermal conductivity, Au.</td>
</tr>
<tr>
<td>$L_f$</td>
<td>0.15 m</td>
<td>Fin height</td>
</tr>
<tr>
<td>$t_f$</td>
<td>4 mm</td>
<td>Fin thickness</td>
</tr>
<tr>
<td>$h_f$</td>
<td>50 $\frac{W}{m^2K}$</td>
<td>Convection coefficient, air</td>
</tr>
<tr>
<td>$mL_c$</td>
<td>1.673</td>
<td></td>
</tr>
</tbody>
</table>

per fin as 0.81 kg. This gives an absolute minimum weight of this setup as 261.63 kg, not counting the larger block of metal all the fins are connected by. As these numbers were far too high, we contacted the Division of Heat and Power at KTH for their input.

As an initial reaction, one of them said it probably wouldn’t work due to the pressure drop, whilst the other was more optimistic. Due to compressor limits whilst standing still on the ground, they kept the convection coefficient at 50 $\frac{W}{m^2K}$ and used Newton’s law of cooling to get the total convection area needed. Keeping $T$ as 100 K, this gives an area of 27 m$^2$. Two usable sides reduce it to 13.5 m$^2$.

Their solution however, was vastly different in one specific area; fin design. Whereas we had first been influenced by the larger fins sometimes present on combustion engine motor blocks, they instead pushed for a design more like the ones currently being used in modern cars. An ocular inspection down in their workshop concluded that no more than 1 mm of thickness was needed, with a narrow fin separation. The total fin weight is thus reduced to 36.45 kg. Additional weight such as mounting would give a total air cooling unit weight of around 50 kg, with far more manageable dimensions.

Prel. Decisions - Weight

One of the primary concerns in aircraft design is weight. Every extra kg equates to a large decrease in aircraft performance since that’s one additional kg that needs to be propelled and suspended in air for the duration of a flight.

As such, several design choices were affected during the modification of the original aircraft into a fuel cell driven one. The first weight related design choice made was reducing the 4 seated TB20 GT into a 2 seated one. This was done both to reduce weight, but also to make room for the hydrogen tanks, which due to geometry, cannot be stored in the wings like normal fuel. The second part was stripping the TB20 GT of all parts related to the original engine such as fuel filters and original fuel tanks, making sure no extra weight was present.

Having acquired the original flight manual, an accurate list of things removed and added can be found in appendix B. According to these figures, the total aircraft weight, assuming a one hour flight time, 40 kg of luggage and two 80 kg passengers, is 1308 kg, with a weight distribution as seen in table 9.

<table>
<thead>
<tr>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty weight</td>
</tr>
<tr>
<td>- Removed parts</td>
</tr>
<tr>
<td><strong>Skeleton weight</strong></td>
</tr>
<tr>
<td>Added objects</td>
</tr>
<tr>
<td>HD6 + Engine</td>
</tr>
<tr>
<td>Fuel [1 h]</td>
</tr>
<tr>
<td>Passengers [2]</td>
</tr>
<tr>
<td>Luggage</td>
</tr>
<tr>
<td><strong>New weight</strong></td>
</tr>
</tbody>
</table>

Table 9: Proposed weight distribution of the proposed one hour aircraft.

Subtracting the one hour aircraft reference case from the maximum takeoff weight shows that the plane could be loaded with an additional 92 kg and still meet regulations. Just having fuel for one hour, when the original craft had at least 6 cannot be seen as anything other than a failure of the technological maturity test, so more is added. If one was to fill up the entire remaining available weight that would be a total of 184 extra liters of 700 bar compressed hydrogen, bringing up the total fuel energy to 1.05 GJ, adjusted for fuel cell efficiency. As a crude measurement, that would keep the motor running at 70 % for 2 hours and 46 minutes.

As can be seen, this is a drastic decrease in performance, compared to the original aircraft.
It should be noted that the main reason behind this is not the weight of the fuel tanks or its supporting structure, but rather the large bulk weight of the HD6 fuel cell, which weights around 200 kg more than the original, 100LL fueled engine.

Due to the current weight of PEMFC technology, not only does one have to accept shorter flight times, but it also prohibits the possibility of making the aircraft a 4-seater again. This is strictly from a weight perspective, as there might not be enough room to put them back in with the hydrogen tanks installed, mainly since the aircraft dimensions have been designed with a comparatively more compact fossil fueled system in mind.
Performance analysis

An aircraft's performance depends on a plethora of variables, with the major ones being weight, engine specifications and aerodynamics. With the first two already being discussed in previous sections, it’s time to estimate the aerodynamic performance of the Socata TB20 GT. Only once that is done can any meaningful performance specifications be calculated, such as required takeoff strip length, or the new maximum speed.

The following sections are split up into parts. At first, some preliminary work is done in order to get the measurements needed. Once acquired, said values are used in the performance analysis for the modified aircraft. Lastly, the calculated values of the modified aircraft are compared to the values of the original aircraft, as given by the manufacturer.

Preliminary performance calculations

When talking aerodynamic performance, there are two major values that need to be specified; the parabolic drag polar $C_D$ and the zero-lift drag coefficient $C_{D0}$, seen in equation (6) and equation (7).

Starting with this, the first measurement to be calculated is called the $K$-factor, or the drag-due-to-lift factor. Shortly explained, it’s a factor related to the drag forces induced when generating lift force.

\[ C_D = C_{D0} + K C_L^2 \quad (6) \]

\[ C_{D0} = \frac{1}{S} \sum [C_{F,c} F_c Q_c S_{wet,c}] + C_{D,misc} \quad (7) \]

\[ K = \frac{1}{\pi e_0 \tau} \quad (8) \]

Using equation (8) to calculate the $K$-factor, values are needed for the effective aspect ratio of the main wing $\tau$ and the Oswald span efficiency factor $e_0$.

Using $\tau = \frac{b^2}{S}$, where $b$ is the overall length of the main wing and $S$ it’s main area, we get the following value:

\[ \tau = \frac{b^2}{S} = \frac{9.76^2}{11.90} \approx 8 \quad (9) \]

As the Socata TB20 GT is a straight-wing aircraft, with little or no sweep angle, the Oswald factor factor $e_0$ can be calculated using the empirical relationship [22] seen in equation (10).

\[ e_0 = 1.78(1 - 0.045 \cdot 0.68) - 0.64 \approx 0.8105 \quad (10) \]

Putting the values from equation (9) and (10) into equation (8), we get the value of $K \approx 0.04907$ m$^{-1}$.

Moving on, it’s time to specify the zero-lift drag coefficient $C_{D0}$, which as the name suggests relates to the drag induced during movement through the air. To get a value for $C_{D0}$ however, a detailed analysis over the geometric shape of the airplane is needed. For this, the plane is divided into five parts; the main wing(s), the fuselage, the horizontal stabilizers, the fin on top of the horizontal stabilizers and the engine nacelle. As a note to the reader, the following calculations are only briefly explained, but would require its own report for a full explanation. Further reading about the techniques deployed can found in literature [22].

Estimation of the wetted surface area $S_{wet}$ requires separate calculations for each part. Starting with the main wing, as $\frac{1}{\tau} > 0.05$, $S_{wet} = [1.977 + 0.52 \cdot \tau] S_{exposed}$, where $S_{exposed}$ is the exposed area of the wing. Looking at the Socata TB20 GT model, it is clear that the middle part of the main wing is “built into” the fuselage, which must been reduced from the total wing area. The $S_{exposed}$ is therefore $11.90$ m$^2$ - $1.80 \times 1.21801433 \approx 9.7$ m$^2$. The value of $\frac{1}{\tau}$ is known as the thickness chord ratio, which is different for every airplane model. For the Socata, it has been measured to 16 %. Combining this gives us the result as $S_{wet,wing} \approx 19.9839$ m$^2$.\[ \]

\[ V. Karlsson, D. Ahlmark \]

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Using equation (11), \( S_{\text{wet}} \) can be calculated for the fuselage. As the shape of the fuselage of the Socata TB20 GT is more circular than rectangular, the value of \( a \) is set to \( \pi \). \( A_{\text{top}} \) of the fuselage is calculated to 10.8 m\(^2\) and \( A_{\text{side}} \) is estimated to 5.4 m\(^2\). This gives the value as \( S_{\text{wet,fuselage}} \approx 25.45 \) m\(^2\).

Regarding the horizontal stabilizers and the fin, the same formula as for the main wing can be used, giving the results as \( S_{\text{wet,horiz}} \approx 5.69 \) m\(^2\) and \( S_{\text{wet,fin}} \approx 1.81 \) m\(^2\), as the area for the fin that is exposed to the air flow is 0.88 m\(^2\) and 3.68 m \( \cdot \) 0.75 m for the horizontal stabilizers. All the wetted surfaces can be seen in table 10.

<table>
<thead>
<tr>
<th>Area</th>
<th>( S_{\text{wet}} ) [m(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main wing</td>
<td>19.98</td>
</tr>
<tr>
<td>Fuselage</td>
<td>25.45</td>
</tr>
<tr>
<td>Horizontal stabilizer</td>
<td>5.69</td>
</tr>
<tr>
<td>Fin</td>
<td>1.81</td>
</tr>
<tr>
<td>Nacelle</td>
<td>6.84</td>
</tr>
</tbody>
</table>

Table 10: A summary of the calculated values of \( S_{\text{wet}} \) for the Socata TB20 GT aircraft.

Next up is the interference factor \( Q_c \). Estimations and discussions about \( Q_c \) can be found in [22]. For the Socata TB20 GT, the values can be seen in table 11.

<table>
<thead>
<tr>
<th>Area</th>
<th>( Q_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main wing</td>
<td>1.2</td>
</tr>
<tr>
<td>Fuselage</td>
<td>1.0</td>
</tr>
<tr>
<td>Horizontal stabilizer</td>
<td>1.05</td>
</tr>
<tr>
<td>Fin</td>
<td>1.05</td>
</tr>
<tr>
<td>Nacelle(^{14})</td>
<td>1.275</td>
</tr>
</tbody>
</table>

Table 11: Estimated values for the interference factor \( Q_c \).

\(^{14}\) \( Q_{\text{nacelle}} \) is between 1.25 and 1.30 if the distance between the nacelle and the main wing is less than the diameter of the nacelle, which holds true for the Socata TB20 GT.

To estimate the form factor \( F_c \) for wings and stabilizers, equation (12) is used with \( Ma = \frac{V_{\text{cruise}}}{V_{\text{sound}}} \). With the cruising speed of the Socata TB20 GT being around 69 m/s [10], \( Ma \approx 0.20407 \).

\[
F_c = \left[ 1 + \frac{0.6}{c_m} \left( \frac{t_c}{c} \right) + 100 \left( \frac{t_c}{c} \right)^4 \right] \cdot \left[ 1.34Ma^{0.18}(\cos \Lambda_m)^{0.28} \right] (12)
\]

Further, \( \frac{t_c}{c} \) is the maximum thickness normalized with the chord, previously calculated as around 0.16 for the Socata TB20 GT. \( (\frac{t_c}{c})_m \) is the chordwise position and is estimated to 0.3 for small subsonic airplanes and \( \Lambda_m \) is the sweep line of the wing, which is close to zero in our case. This gives \( F_{c, \text{wing}} \approx 1.395 \).

To calculate the form factor for the fuselage, equations (13) and (14) are used, with \( \ell_{\text{fuselage}} = 6.0 \) m and the maximum cross section area of the fuselage \( A_{\text{max}} \) being roughly 0.9 m\(^2\). This gives the value of the form factor as \( F_{c, \text{fus}} \approx 1.355 \).

\[
F_{\text{fuselage}} = 1 + \frac{60}{f^3} + \frac{f}{400} (13)
\]

\[
f = \frac{\ell_{\text{fuselage}}}{d} = \frac{\ell_{\text{fuselage}}}{\sqrt{\frac{2}{\pi}A_{\text{max}}}} (14)
\]

For the horizontal stabilizers and the fin, the form factor value is the same as for the main wing, 1.395. For the engine nacelle, the form factor is given by equation (15) with \( f \) from equation (14) with \( \ell_{\text{nacelle}} = 1.14 \) m and \( d = 0.95 \) m, giving the form factor as \( F_{\text{nacelle}} = 1.293 \). The full list of \( F_c \) can be seen in table 12.

\[
f = 1 + \frac{\ell_{\text{nacelle}}}{d} (15)
\]

The component flat-plate skin friction coefficient \( C_{F,c} \) depends heavily on the Reynolds’s number \( Re_f \) as given in equation (16). The reason for this is, depending on if the flow is
An environmental perspective on the feasibility of using existing PEMFC technology in general aviation.

<table>
<thead>
<tr>
<th>Area</th>
<th>$F_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main wing</td>
<td>1.395</td>
</tr>
<tr>
<td>Fuselage</td>
<td>1.355</td>
</tr>
<tr>
<td>Horizontal stabilizer</td>
<td>1.395</td>
</tr>
<tr>
<td>Fin</td>
<td>1.395</td>
</tr>
<tr>
<td>Nacelle</td>
<td>1.293</td>
</tr>
</tbody>
</table>

Table 12: A summary of the calculated values of $F_c$ for the Socata TB20 GT aircraft.

laminar or turbulent, the induced friction will be calculated differently. For high speeds or larger areas, the flow will be much more turbulent than it is laminar. As such, equation (17) will be used as an approximation, trying to calculate both scenarios in one go. The second term of this equation is used for correction purposes and goes towards zero when $Re_\ell \gg 5 \cdot 10^5$. A table of values for the constant $A$ can be found in table 13. It is to be noted that $C_{F,c}$ has to be calculated for each part of the aircraft, due to the geometrical dependency of $Re_\ell$. As a point of reference, $C_{F,tot} \approx 0.0028$ for the Socata TB20 GT on a height of 2600 m and a speed of roughly 300 km/h.

$$Re_\ell = \frac{\rho V l_c}{\mu}$$  \hspace{1cm} (16)

$$C_f = \frac{0.455}{[\log_{10} Re_\ell]^{2.58}} - \frac{A}{Re_\ell}$$  \hspace{1cm} (17)

<table>
<thead>
<tr>
<th>$Re_\ell$</th>
<th>$3 \cdot 10^5$</th>
<th>$5 \cdot 10^5$</th>
<th>$10^6$</th>
<th>$3 \cdot 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1050</td>
<td>1700</td>
<td>3300</td>
<td>8700</td>
</tr>
</tbody>
</table>

Table 13: Approximative values for the constant $A$, depending on the Reynolds transition number $Re_\ell$.

Lastly, the lift coefficient $C_L$ can be approximated during steady level flight using equation (18), where $V$ is the speed of the aircraft, $L$ the lift force (aircraft weight times gravity), $\rho$ the density of the surrounding atmosphere and $S$ the reference area, which for an aircraft is chosen as the projection in the horizontal plane of the planform of the main wing.

$$C_L = \frac{2L}{\rho V^2 S}$$  \hspace{1cm} (18)

It is now possible to calculate the drag polar $C_D$ using equation (6), where $C_{D0}$ is obtained through equation (7).

**Performance calculations**

First on the list of calculations was a comparison of a given scenario from the Socata TB20 GT specifications sheet. In the scenario, a speed and engine throttle was given during specific conditions, giving a good point of reference. For these calculations, computer assistance was needed, as the calculations where too big and with too many factors, for them to be done by hand. Additionally, since they had to be done for 5 different parts, the time required as well as the possibility of error made it unreasonable to do it any other way. For the calculations of $C_{D0}$ and $C_L$ (and thusly also $C_D$), a Python script was created, available on demand from the authors. Additional calculations were done using Matlab and to a lesser extent, Wolfram Alpha.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{D0}$</td>
<td>0.0200</td>
</tr>
<tr>
<td>$C_L$</td>
<td>0.3473</td>
</tr>
<tr>
<td>$C_D$</td>
<td>0.0259</td>
</tr>
</tbody>
</table>

Table 14: Calculated drag related values for the maximum cruise speed of the original aircraft; $V = 83.6$ m/s, $h = 2600$ m.

Using said python script with the values from preliminary calculations yielded the results in table 14. Inserting them into equation (19) yields $P_r \approx 85$ kW. Comparing this to the estimated output of the original, piston engine; 133 kW\textsuperscript{15}, yields an efficiency of $\frac{P_r}{P_{eng}} \approx 64\%$. From this, a conclusion could be drawn: The

\textsuperscript{15}75 % of 250 hp, and assuming 5 % mechanical losses.
Socata TB20 GT is in dire need of adjustable rotor capabilities.

\[ P_r = \sqrt{\frac{2W^3}{\rho S}} \frac{1}{C_L^{3/2}/C_D} \]  

(19)

An adjustable propeller blade setup is not free, but compared to the already high costs of the HD6 fuel cell, roughly gaining a performance increase of 10 to 20% without any increase in fuel consumption is a lot. Considering the comparatively shorter range of the PEMFC aircraft, a range boost of that size could be considered too good to give up.

Regarding the PEMFC aircraft, propeller efficiency is thusly assumed to be roughly 80%, a somewhat conservative estimate of tilt rotor capabilities. Again using equation (19) together with the python script, the maximum cruise speed of the PEMFC aircraft can be estimated. Electrical engines do not suffer from a drastic decrease in efficiency above 75% like combustion engines, but efficiency still tend to drop during the last percent. Also adding to the situation is how the YASA-750H electrical engine is optimized, since the 95% efficiency cannot be achieved through the entire throttle spectrum. Due to these reasons, the assumed maximum cruise speed of the PEMFC Socata TB20 GT is roughly 80%.

The new maximum cruise speed power output is thus around 114 kW. Inserting that into equation (19) and inserting the values of \( C_L \) and \( C_D \) as a function of speed, an expression between power and velocity is achieved. Combining this with the python script, an optimization problem is created, which can be numerically solved. Solving for this gives the new maximum cruise speed of the PEMFC Socata TB20 GT as 86.2 m/s, or 310 km/h.

Should instead the original, fixed blade propeller be used, the maximum cruise speed would end up as around 77.9 m/s = 280 km/h. Do note that this lower speed is without any environmental gain, compared to the 310 km/h speed.

Since simply stating the new aircrafts maximum cruise speed does not give that much information about the aircrafts performance, speeds were calculated as a function of engine throttle, as can be seen in figure 8. With this as a base, the maximum range of the aircraft could be plotted – as seen in figure 9. Since the modified aircraft is not using an internal combustion engine, conventional range calculations assuming a gradually reduced aircraft weight does not fit. Instead, the maximum range was assumed as how long the PEMFC aircraft could fly on 80% of total available fuel, as a function of engine throttle. Taken into account during range calculations is also that engine setup made as part of a purchase will provide extra efficiency in a set output area, meaning that a preferable output region will have to be specified to achieve the ranges seen in figure 9.

Figure 8: Steady level flight speed as a function of engine output, for the PEMFC aircraft.

Figure 9: PEMFC aircraft range as a function of speed, using 80% of available fuel.
An environmental perspective on the feasibility of using existing PEMFC technology in general aviation.

Using equation (20) together with equation (21) with values from the previous sections, it is possible to calculate figures for the climb performance of the modified aircraft. This gives \((R/C)_{max} = 4.27 \text{ m/s}\), which is the aircraft’s maximum vertical velocity, achieved during the optimal climb velocity \(V_{(R/C)_{max}} = 42.68 \text{ m/s}\). This means that during optimal conditions, it would take the PEMFC aircraft just over 10 minutes to reach its intended service height of around 2600 m.

\[
(R/C)_{max} = \frac{P_a}{W} - V_{(R/C)_{max}} \frac{4}{\sqrt{3}}(KC_D0)^{1/2} \tag{20}
\]

\[
V_{(R/C)_{max}}^4 = \frac{4}{3} \frac{K}{C_D0} \left(\frac{W}{S}\right)^2 \tag{21}
\]

In addition, the climb angle during maximum rate of climb \(\gamma_{(R/C)_{max}}\) can be calculated using equation (22), resulting in \(\gamma_{(R/C)_{max}} \approx 6.52^\circ\)

\[
\sin \gamma_{(R/C)_{max}} = \frac{P_a}{WV_{(R/C)_{max}}} - \frac{4}{\sqrt{3}}(KC_D0)^{1/2} \tag{22}
\]

Also of interest is takeoff performance, since both the engine and propeller has been modified. For civilian aircraft the certified takeoff range is decided upon as when the aircraft has taken off and reached a height of roughly 10 meters. As such, the calculation is split up into two parts.

\[
S_g = NV_{LO} + \frac{1}{2gK_A} \ln \left(1 + \frac{K_AV_{LO}^2}{K_T}\right) \tag{23}
\]

Starting with the ground roll distance \(S_g\) as given in equation (23), several factors need to be evaluated. The lift off speed \(V_{LO}\) can be calculated using equation (24) with \(C_{L,takeoff}^{max}\) approximated as 1.8, giving \(V_{LO} = 35.49 \text{ m/s}\). This can be compared to the Socata TB20 GT specifications sheet stating \(V_{LO} = 35 \text{ m/s}\) [10].

\[
V_{LO} = 1.1V_{stall}^{takeoff} = 1.1 \sqrt{\frac{2W}{\rho SC_{L,takeoff}^{max}}} \tag{24}
\]

The method used to calculate \(S_g\) is an approximation of a more difficult expression involving complex integration, requiring some knowledge in numerical integration. As such, the expression for \(K_T\) in equation (25) is to be evaluated for \(V_{LO}/\sqrt{2} \approx 0.7V_{LO}\). With the maximum propeller efficiency \(\eta_p\) set to 0.8, the engine efficiency at full power \(\eta_{eng}\) as 0.9 and the friction coefficient \(\mu\) set to 0.05, this gives \(K_T \approx 0.268\).

\[
K_T = \frac{\eta_p\eta_{eng}P_a}{VW} - \mu \tag{25}
\]

With \(C_L\) set to 0.1 during the ground roll distance, \(K_A\) can be calculated using equation (26) where \(\Phi\) is an added term to \(C_D\) induced by ground interference, given by equation (27). Here \(h\) is the wing height above ground and \(b\) the wing span of the aircraft, giving \(\Phi = 0.49\) and \(K_A \approx -0.000101\).

\[
K_A = \frac{\rho}{2W/S} \left(\mu C_L - C_{D0} - \Phi C_L^2\right) \tag{26}
\]

\[
\Phi = \frac{(16h/b)^2}{1 + (16h/b)^2} \tag{27}
\]

Inserting these into equation (23), with \(N = 3\) s being the average time a plane spends on its back wheels during take-off and \(C_{D0}\) calculated as 0.1904, this gives a measure of the ground roll distance for the modified Socata TB20 GT as \(S_g \approx 434 \text{ m}\).

Having previously obtained figures for climb performance means the airborne part of the take off can be calculated. The beginning of the climb can be approximated as a circular movement with the radius \(R = 596.7 \text{ m}\), as given by equation (28).

\[
R = \frac{V^2}{g(n - \cos \sigma)} \tag{28}
\]

Here, \(n\) is a load factor of lift \(L\) generated at this speed, divided by the downwards force \(W\), giving \(n = L/W = 1.2097\) and \(\sigma\) is the climb angle, approximated by taking the value from

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equation (22)\textsuperscript{16}. With $R = 597$ m and $h = 10$ m the altitude gain needed, using equation (29) this gives the airborne part of the take-off distance $S_a = 109$ m.

$$S_a = \sqrt{R^2 - (R - h)^2} \quad (29)$$

Combining the distances $S_g$ and $S_a$ then gives the total, estimated take-off distance of the PEMFC Socata TB20 GT as 543 m.

### Performance comparison

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1400 kg</td>
<td>1400 kg</td>
</tr>
<tr>
<td>Max cruise speed</td>
<td>301 km/h</td>
<td>310 km/h</td>
</tr>
<tr>
<td>Rate of climb</td>
<td>6.1 m/s</td>
<td>4.3 m/s</td>
</tr>
<tr>
<td>Take-off distance</td>
<td>635 m</td>
<td>543 m</td>
</tr>
<tr>
<td>Range</td>
<td>2000 km</td>
<td>750 km</td>
</tr>
</tbody>
</table>

Table 15: Performance comparison between the original values as stated in performance sheets \textsuperscript{10} and calculated values for the modified, PEMFC aircraft.

Looking at table 15, it can be seen that the PEMFC version holds up fairly well despite a slightly less powerful engine and even out performs the original aircraft in a few categories. This can be attributed to the adjustable propeller blades of the PEMFC aircraft. As a result of this, the estimated take-off distance is 14.5 % shorter, and the maximum cruise speed 3 % higher.

But as can also be seen, the range of the modified aircraft is significantly worse, only having 37.5 % of the original, making the PEMFC aircraft unpractical for longer distance flights. For an aircraft, range is generally a more important factor compared to other forms of transportation, meaning that the reduced range is concerning. But even though unfeasible for long range flights, if going by the numbers in table 15, the modified, PEMFC Socata TB20 GT still seems to be a very air worthy craft.

Regarding the short range of the PEMFC aircraft; whereas 100LL range is not predicted to increase that much in the future, PEMFC range is. Higher pressure hydrogen tanks, as well as enhancing the efficiency in the actual fuel cells, will most likely result in an increased range in the following years. And as mentioned during the aircraft design process, current range is made with current, comparatively high, fuel cell weight.

Taking performance for present electric airplanes in regard in the aspect of range, it is even more obvious that fuel cell airplanes may be an option in aviation propulsion systems in the coming decades, due to the continuing strive to move away from fossil fueled engines. However, after looking at the performance comparison, it is clear that making adjustable propeller blades available in the market for smaller aircrafts is a necessary step if one wants to enhance the efficiency for a greener aviation, in small aircrafts’ perspective.

Lastly, the rate of climb is reasonable for a small aircraft, but is still a lot lower. It also hints of a possible problem, should the usage of PEMFC technology spread to larger airplanes. Engine performance might be decreased slightly, but doing so inflicts direct penalties on important performance statistics, such as a commercial airliner flying on considerable higher altitude. But as the Socata TB20 GT keeps its cruise flight during normal conditions on a rather low altitude\textsuperscript{17}, it is not any significant problem in the specific case investigated in this report.

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\textsuperscript{16}For small angles, the cosine term could be approximated as 1 without losing much - if any, precision.

\textsuperscript{17}The restriction of airspaces tend to apply above 3 km.
Life Cycle Analysis

As seen in previous sections, from an engineering perspective a fuel cell-driven Socata TB20 GT appears feasible. But just because something is possible, it does not automatically follow that it’s also something that should be done. As stated in the project description, any feasible alternative technology should also be evaluated from a so called "green" perspective. So that begs the question; just how green is this proposed fuel cell driven Socata TB20 GT? In order to shed some light on this, a so called Life Cycle Analysis (LCA) will be performed on both the original and the modified aircraft.

LCA, sometimes also called cradle to the grave analysis, is a set of standardized evaluation methods aimed towards creating a measure of how harmful different engineering setups might be. Although shifting a bit between standards\(^\text{18}\), a LCA often tend to consist of a few main sequences:

1. **Raw material extraction.** What materials are needed in order to produce said product? How are they extracted and what tools are needed to do it? How much energy and effort does it take to bring the metals and other crucial materials to the factory for further refinement and processing?

2. **Production.** Once all required materials and tools have been made available, how much harm does the actual manufacturing process and construction do to the environment? As an example, even if a vehicle runs on what is branded as a green technology, is it worth the emissions during production, or has the harm just been moved from usage to production?

3. **Usage.** During a products lifetime, how is it used and how does that usage effect the environment? Does it use resources and if so, how do they in turn affect things?

4. **Disposal.** Can it be recycled and if it can, is it being recycled and in what way? Reusability or used up? Just because something is not harmful if recycled properly does not mean it does not result in consequences. A good example are batteries, which if handled properly generally are of little harm, but depending on how big a portion is not being recycled can pose a big problem.

With these steps forming the core of a LCA, where the standards tend to differ is mainly on how the damage is assessed. What constitutes as damage and how severe is said damage rated to be? In order to shed light on this, different standards adopt different categories, where weighting is possible. As a result of this, there will always be a judgment component to a LCA as one has to divide and structure up different data posts in order to arrive at meaningful conclusions.

What all this means is that a LCA is only as good as the data on which it is based. Complicating things further is that there are still so many things yet unknown to us. Processes can be both better or worse than predicted by current research. A lot of variables are missing and even if data is acquired, there is still no guarantee that it is accurate. Producers have every incentive to put processes in better light and trade secrets and competition might force silence even if no ill intent is present. As such, any and all LCA done will always be approximative. It is neither an exact science, nor an absolute.

However, that in no way means LCA is useless. On the contrary, LCA can be of major assistance. But as seen during research made in preparation for this report, LCA tools tend to be marketed for internal use, with good reason. It is common knowledge to any and all PR-departments that you yourself want to control the flow of information. What this in real terms means is that companies would not mind knowing the environmental impacts of their products, but maybe not share it with others unless to, as an example, strengthen brand image.

Due to this, making a LCA as an outsider has its difficulties. Enormous work has gone into the creation of databases so that most common processes have more or less accurate values from a plethora of different viewpoints. A process that is ever going and evolving. If the whole production chain is known, this can produce

\(^{18}\)Different standards are often aimed at answering slightly different questions.
fairly reliable results, but as in the case of this report, it requires a fair share of guess work. The chosen fuel cell is made by one of the market leaders and as such has more than a few trade secrets surrounding it. But as will be shown in the following sections, that does not necessarily prevent the acquisition of relevant conclusions.

Regarding standards and methodology for the LCA made in this report; the productions of both the original and the modified Socata TB20 GT was evaluated and put through two different usage patterns. The evaluation was done using software, capable of matching against two different evaluation standards; ReCiPe [23] and it’s converted CO₂ equivalent utilizing IPCC 2007 methods.

The ReCiPe method utilizes the standards ISO 14040 and 14044 for a general framework. It’s main objective is to transform the often very long list of so called Life Cycle Inventory results into a limited number of indicator scores which each express a relative impact severity in different categories [24]. Appendix C shows the full list of indicators and their relations to each other. In short, lower relevance indicators together influence higher valued indicators, which all builds up to present a final value. Purposefully discarding a level of detail opens up the possibility of cross field comparisons, which is what is being sought in this report. Due to the sacrificed level of detail, caution is advised whilst drawing eventual conclusions.

The software used extensively in this report is called ECO-it [20] - version 1.4, marketed as a quick screening tool for designers to make informed decisions. Developed by the same company that makes Sima Pro, the current market leading LCA software, it gives faster answers and can be used with only intermediate LCA knowledge. This also means that the high level of detail present in the latest version of Sima Pro and the possibility of evaluating individual contributing factors, as well as changing the importance of each factor, is not available.

What this means in regards to this report is that the level of detail in the interiors of the avgas engine and fuel cell respectively, are crude at best. On their own, it’s the authors' opinion that they do not qualify to the levels of scientific rigor sought in this report. However, as shall be seen in the following sections, this turns out to be of no major importance due to reasons soon to be explained. But before that, the following sections explain the procedure of arriving at said results.

Preparing the LCA

As previously explained in this report, regarding materials, a PEM fuel cell can be divided into four major parts; the membranes, the flow field plates, the platinum infused anodes and cathodes and lastly the controls and casing. Estimations for the different parts of the HD6 fuel cell follows in order of ReCiPe magnitude.

1. Used as a catalyst for facilitating the splitting of atoms in both hydrogen and oxygen, platinum is currently a critical part behind the high efficiency of the HD6 fuel cell. The electricity producing, chemical reaction requires around 0.5-0.8 g/kW [25]. In this report, the higher value is assumed due to the relatively high efficiency of the HD6 fuel cell, compared to market competition.

2. Flow field plates are used both for maintaining an even flow for the Watt per area dependent reactions to occur, but they also need to be corrosion resistant, collect and transport the produced free electrons and hold the structure together [26]. Since high conductivity is a must, graphite has so far been the standard material, but since it is brittle and has relatively poor mechanical properties, heavy refinement and post-processing is a necessity. Using current figures of around 1 W/cm², the HD6 would need around 15 m² of active area. Looking at HD6 dimensions, 20 – 25 plates are assumed with an assumed thickness of 0.6 cm, since much smaller plates were of at least 0.3 cm thickness [26]. This makes for a total of 234 kg of graphite inside the HD6, or roughly 60 % of the weight.

This is not too unreasonable, since the smaller

---

19. An indicator might be deemed of lower relevance both due to uncertainty or be perceived less danger.

20. A free trial version can be found at: http://www.presustainability.com/eco-it
average automotive cell roughly contains around 80 kg of graphite [27], and there are few other components in the HD6 fuel cell to make up for the 400 kg dry weight.

3. The most common membranes are made by Naifon. Polymer film is used and bathed in chemical solutions. At least 15 m² is needed and impact is calculated by assumed chemical requirements per m².

Also adding to the fuel cell scenario is the air cooler, hydrogen tanks and the YASA-750H electrical engine. Such a high W/kg engine requires the use of powerful neodymium magnets, a known hazard mainly due to China’s monopoly and unregulated mining industry [28] [29]. Using Vestas figures for their high end generators [30] and scaling it down hints of roughly 10 kg of Nd magnets in the 25 kg engine. Using values from table 16 estimates around 3.3 kg Nd and 6.6 kg Fe. With the CO₂ equivalent being known [32], Nd can be estimated in the ECO-it software using other similarly rated values.

Lastly, the values for the original engine to serve as a comparison have been acquired by rough estimation of raw material composition.

<table>
<thead>
<tr>
<th>Elements in NdFeB alloy</th>
<th>Amount [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neodymium (Nd)</td>
<td>29 - 32</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>64.2 - 68.5</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>1.0 - 1.2</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>0.2 - 0.4</td>
</tr>
<tr>
<td>Niobium (Nb)</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>Dysprosium (Dy)</td>
<td>0.8 - 1.2</td>
</tr>
</tbody>
</table>

Table 16: Estimated material composition of high end neodymium magnets [31].

Going from production into usage, two different test scenarios were posed with different usage times. The full reasoning can be seen in Appendix D and table 17. Data for Hydrogen production was present in the ReCiPe database but 100LL was not, and was assumed as its components of normal, unleaded petrol with it’s 0.5 g/L of neurotoxic and otherwise banned Tetra-ethyl-lead (TEL) used to up the octane rating, added on top. More about the use of TEL in aviation can be read in the discussion.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Amount [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>21750</td>
</tr>
<tr>
<td>Petrol</td>
<td>164250</td>
</tr>
<tr>
<td>+ TEL</td>
<td>82</td>
</tr>
</tbody>
</table>

High consumption scenario

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Amount [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>9048</td>
</tr>
<tr>
<td>Petrol</td>
<td>68328</td>
</tr>
<tr>
<td>+ TEL</td>
<td>46.5</td>
</tr>
</tbody>
</table>

Low consumption scenario

Table 17: Estimated fuel consumption for the two test scenarios.
Results of the LCA

In this section, the results of the LCA are presented. Please refer to the discussion for a more in depth analysis of the results.

As a comment on the vertical scale in the ReCiPe figures, lower is better. The unit kPt is $10^3 \cdot \text{Pt}$, where Pt is the ReCiPe indicator value.

A breakdown of the factors behind the production value in figure 10, can be seen on the next page in figure 13. Please also note the different vertical scales in figure 10 and figure 11.

Figure 10: Full Life Cycle Analysis of the HD6 fuel cell system. The two different usage patterns correspond roughly with active hobbyist or traveler (2.9 kPt), and commuter (7 kPt). Usage is calculated over a 10 year period.

Figure 11: Full Life Cycle Analysis of the original, avgas powered engine. The two different usage patterns correspond roughly with active hobbyist or traveler (18 kPt), and commuter (42 kPt). Usage is calculated over a 10 year period. Software estimations put the TEL part of avgas as increasing usage kPt by roughly 2 - 4 %.

Figure 12: Full Life Cycle Analysis of the original and fuel cell setups, displayed as CO$_2$ equivalent emissions. C and E refers to the commuter- and enthusiast usage scenarios. For more information on them, see Appendix D.
An environmental perspective on the feasibility of using existing PEMFC technology in general aviation.

Figure 13: Production values for the HD6 fuel cell. As can be seen in this table, the high demands on the flow plates and the platinum used as a catalyst cause by far the biggest impact. The neodymium magnet powered engine is still over 5 times less harmful than the impregnated flow plates, and almost 17 times less harmful than the roughly 0.12 kg Pt used in the fuel cell.

Table 18: Summary of ECO-it results using ReCiPe method. Lower value is better. Values within brackets correspond to percentage of total. C and E refer to the two different usage patterns commuter and enthusiast. For more information on usage patterns, see Appendix D. Note that the disposal unit is in Pt, where kPt = 10³·Pt.
Discussion

The Life Cycle Analysis

As has been previously stated, LCA is no exact science. A majority of the time spent doing it – even with the help of software, is taken up by making educated guesses and approximations. As such, some values, specifically those regarding the original engine, but also fuel cell production, risk not being all too accurate. The authors would like to point out the fact that this is only for the production part – the fuel consumption for both 100LL and Hydrogen can be seen as fairly accurate, assuming no software errors.

On the topic of this, a question that deserves to be raised is regarding the use of the ECO-it software during the LCA. Due to economical constraints, the use of Sima Pro was not possible. This prohibited the acquisition of more in depth, layered data which would have been a welcome addition to pinpoint the exact causes that factor into the different results. Do note that it is the opinion of the authors that the use of Sima Pro would not have resulted in different results; both ReCiPe and Sima Pro are based on large databases built by large teams of environmental scientists. Although of course the odd error is always present, the databases have been constantly updated over large periods of time, minimizing the possibility of at least larger, more noticeable errors. The difference would instead be that the results would not immediately have been summarized into a final, weighted value.

Moving on to the results of the LCA study; looking at figure 13, some clear patterns emerge. The first and the most obvious is the catalyst, which is simply modeled using 0.12 kg of unprocessed platinum. As such, the actual impact of the Catalyst in any current PEM fuel cell might be even higher. If fuel cell production is ever going to be both economically and environmentally viable, the use of Platinum ought to be discontinued, or at the very least drastically lowered. Due to the monetary value of Pt, it should be noted that a large portion of it (as with the Nd magnets) are assumed to be recycled and reused, mainly since it is a very lucrative thing to do.

Looking at figure 10, it can be seen that even under moderate usage, hydrogen consumption accounts for a large majority of the total environmental impact. The main reason for this has to do with today’s state of hydrogen production which is what the software uses, since a fuel cell is virtually exhaust-free whilst in use. If fuel cell usage is to be commonplace, future improvements in hydrogen production is strongly advised. More about this can be read in the section "The cost of hydrogen". Additionally, since around 70 % of the total production impact of the HD6 fuel cell is from the use of platinum as a catalyst, the relative impact of hydrogen compared to total fuel cell impact is predicted to be even higher in the future, as fuel cells probably will not be economically viable as long as larger amounts of platinum is required. Research in this, as well as in improvements regarding flow plates is ongoing, more of which can be read in subsequent chapters.

When comparing figure 11 with figure 10, the environmental advantages of using a PEM fuel cell setup is made clear. Even in an optimal scenario for the 100LL alternative, with perfect combustion efficiency and no TEL added, a PEM fuel cell will still be the better alternative by a very large margin. From a LCA perspective, in ReCiPe Pt-points, the PEMFC setup performed 4.5 times better with medium usage and 5.2 times better during heavy usage. This is with technology available today, heavily reliant on platinum where the hydrogen was modelled using today’s figures of hydrogen production, which will most likely be discontinued in favor for much more clean methods of production in future Fuel Cell usage. Also, the main eventual error source, the LCA modeling of the original, 100LL powered engine, could have an error margin of 1000 % and still result in the same conclusion.

It should also be mentioned that since any comprehensive LCA will take several different categories into account and weigh their importance against each other when drawing conclu-
sions, specifics sometimes tend to be overlooked. One such thing that is overlooked is the use of tetraethyllead (TEL) in leaded avgas (100LL); TEL is effectively banned over the entire world for use in automotive fuel.

The reason for this is because TEL is a generally unpleasant [33], neurotoxic substance that among other things has been shown to interfere with brain development in children. One of the major reasons why 100LL fuel is not banned yet is due to the fact that a lot of older aircraft engines cannot run using any other fuel. Some engine manufacturers, such as the producer of the current engine used in the Socata TB20 GT – Lycoming, does not create 100LL exclusive engines anymore, but cannot do much about the engines already in use.

Looking at all this, the authors cannot do anything but recommend a more in depth evaluation of possible PEMFC usage in future transportation projects.

The design process

A lot of the design process has been discussed in relevant sections, but there are a few additional aspects about the proposed PEMFC aircraft that requires further inquiry. One of them is regarding safety. There are several areas where a full safety review would have to be conducted before an all clear is given. One such aspect is the tanks, which both to setup and use vary greatly from the 100LL tanks present on the original Socata TB20 GT.

Firstly, the tanks have to be thoroughly tested and certified for the larger pressure gradients not normally present during use. Not because of a catastrophic failure in the form of a (violent) rupture, but because of fatigue. Most modern tanks today are required to start leaking before they rupture unless very heavy blunt force is present. But for all intents and purposes, a loss of fuel during flight has a high likelihood of ending just as badly.

Secondly, the fuel feeding system will also have to handle and work with the large pressure coming from the fuel tank, making a controlled expansion into workable fuel pressure and regulating outflow. If a catastrophic failure would appear, it is likely that it would manifest somewhere between tanks and fuel cell due to wiring, joints and similar being under great stress both from temperature and pressure gradients from the outside, but also being subject to considerable vibrations and turbulence. As such, both tanks and fuel feeding system will have to be incorporated into regular inspection schedules, and the fuel feeding system will have to be made out of costlier, more reliable manufacturers/materials.

Moving on from safety to performance; there is a possibility that a DC-DC converter might be needed if the setup cannot be calibrated adequately to produce a harmonized VDC output, to remove the risk of induced efficiency penalties in some throttle regions. Additional testing regarding the efficiency spectrum of the full PEMFC setup is advised.

The maximum weight of the original Socata TB20 GT of 1400 kg has been a self imposed limit during this project. This might not be the best solution. Due to the weight distribution of the PEMFC setup with its large zero fuel weight, additional range does not carry as large a penalty. Approximately, if going 5 % overweight, around one additional flight hour at maximum cruise speed could be gained.

However, going above the certified maximum limit might pose a serious risk during long time use and as such requires reclassification of the aircraft. To get it reclassified for a higher maximum takeoff weight, it is not unreasonable that some alterations would have to be made. If such a reclassification is made, going more than marginally above the original maximum takeoff weight of the Socata TB20 GT is not recommended. This because of the inherit performance penalty of a higher weight and the project goal stating that the modified Socata TB20 GT should not be too different from the original in the eyes of a pilot.

First brought up during the performance calculations, the technology of radially adjustable propeller blades will be incorporated into the PEMFC aircraft. Already standard on many aircrafts, the ability to shift the angle of which
the propeller moves through the incoming air flow has a large efficiency benefit. If the radially shifted angle is set as a function of indicated air speed, propeller thrust efficiency could be as high as 85 % [34] for a large part of the thrust spectrum.

There is a possibility that some weight and space might be saved on engine cooling. According to the manufacturer, continuous motor output depends a lot on cooling. However, neither proper figures nor numbers on that dependency has been found. As such there is no way to refute nor prove the possibility of extending the liquid cooling system utilized in the HD6 fuel cell system to the YASA-750H electrical engine. With its original design goal being Le Mans, eventual cooling issues would more likely manifest during long time, continuous high power output, rather than during acceleration phases.

Project feasibility

All in all, a lot of effort has been made into obtaining reasonable results, such as not doing overly optimistic estimations or using too shallow reasoning. However, there are still sections where the validity could come in question.

The first, and probably the most critical point is regarding the actual usefulness of the proposed air cooling system. To get decent numbers regarding absolute feasibility, at the least thorough computer simulations are needed which feeds back into an evolving design process. As mentioned in talks with the Division of Heat and Power at KTH, there might be difficulties in handling the pressure drop. If that turns out to be the case, the cooling system needs to be redesigned around it.

The size, and thusly, the weight of the coolant system might be lacking in dimensions. A quick assumption made at the start was that the heat sink was allowed to reach a temperature 100 K above air temperature. At takeoff, this temperature might be above the threshold causing fuel cell overheating.

This is something of a fundamental problem for the entire project. Air cooling works wonders when travelling at several hundred kilometers per hour at high altitudes where air temperatures are low, and with few moving parts it’s close to an ideal system. But when on the ground, it’s the opposite. As such, a scenario with the proposed aircraft idling on the tarmac needs further, in depth investigations, as the propeller together with the compressor might not be able to produce the large air flow needed for coolant unit not to overheat. As such, the total aircraft weight might be increased due to specific ground cooling. Additional ideas to combat tarmac overheating might be siphoning some engine power and/or fuel cell power for added air flows. Such a solution would not cost too much from a weight perspective, and might even be a good addition even if the proposed coolant system gets by on its own, as high operating temperatures generally makes for low lifetimes. Additionally, it might reduce the total aircraft weight by lowering the heat sink size. This is possibly something important, as there is a possibility that the proposed coolant system is simply too big to fit into the aircraft unadjusted.

Due to the uncertainties regarding the state of cooling, it is also not possible to give a final say as to the weight distribution throughout the aircraft. Since the placement of the center of gravity in an aircraft is no small matter, there is a small possibility that the placements of the main wings might need slight modifications – or a redesigned cooling process. If looking at individual parts, starting with the heaviest object – the HD6 PEMFC; its design makes shifting the placement comparatively easy, assuming it’s not hindered by the cooling system, since the two of them might not fit in the nose of the aircraft. It might also require the pilot seats to be shifted slightly backwards. Assuming theorized placements are roughly the same, the fuel tanks would need to be placed as far back as possible so as to not move the center of gravity too much forwards. Since the rear seats have been removed, slightly adjusting the pilot seat backwards in order to help with this would also be a possible solution.

Assuming that the modified aircraft works within parameters, this in no way indicates that
everything is ready for anyone to convert their aircraft, should they have the money. Whereas you are always limited by airport placements, the usage of an uncommon fuel will disqualify a lot of possible landing sites, further restricting aircraft usage. This is something that will change as soon as a new fuel becomes more common, but it makes for a rough transition period and more about the usage of hydrogen can be read in the next section.

The cost of hydrogen

Looking simply at the PEMFC reaction – using hydrogen and oxygen to create an electric flow with heat and H₂O being the only byproducts, it cannot get much better than that. Two readily available, for most intents and purposes harmless substances used as fuel, with clean water as a byproduct. At a first glance, PEMFC technology not just in general aviation, but in all kinds of transportation, has the possibility of combating a large share of the downsides of modern society and how we’re to a larger or lesser extent poisoning ourselves in the name of prosperity.

That is, if one is just looking at the reaction itself. If instead doing a LCA on hydrogen, it becomes clear that it’s not as a perfect technology as one might assume. Saying this, it is not the authors’ opinion to paint a dark picture of a promising and emerging technology – already today, as seen in the LCA performed in this report, using hydrogen is strongly preferred over common oil derivatives. With that in mind, if world hydrogen consumption should rise considerably, as it will if PEMFCs become common place, hydrogen production will and should come under scrutiny. If PEMFCs become common place, we will be talking about the Hydrogen economy instead of the oil economy.

Looking at the situation today, a large part of the worlds produced hydrogen is directed towards the production of ammonia to be used in fertilizers, using the so called Haber process. The other large area of use is in what is commonly referred to as hydro cracking²¹, mainly within the oil industry, producing mostly jet fuel, diesel and LPG. In 2002, over 90 % of the world’s hydrogen production came from fossil raw materials [35] and current figures seem to be similar [36].

What this means is that around 90 % of the current production capacity of hydrogen is unusable, if one wants rid society of the problems of using fossil fuels, since by current production processes, emissions and greenhouse gases are simply shifted from usage to production [37]. Out of the technologies available today, the most promising one is the production of hydrogen through electrolysis. Currently amounting to roughly 5 % of total production [36], it has two advantages. Firstly, it’s the same reaction being used in a fuel cell, easily achieving the purity levels needed for effective use. The second benefit is that it’s thusly CO₂ free.

The main reason behind its relative unpopularity is the price tag; present in all steps of a possible hydrogen economy, the high costs amounts to a major road block currently standing in the way of major usage.

Assuming hydrogen production is done by the comparatively very clean (and currently quite costly) high pressure electrolysis, another possible problem appears. Current figures estimate a production efficiency of around 50 – 80 % depending on size [38], as in a kilo of hydrogen with an energy density of 123 MJ/kg would require between 154 and 246 MJ of electricity to produce. This does nothing but shift the burden further down the line of production and beds for the following conclusion: A large scale, emission free hydrogen economy is only possible using a clean production mix in national power grids around the world. Essentially, the hydrogen used for PEMFCs would in a best case scenario be something of a gaseous and clean, high energy density battery.

²¹Cracking is the process of splitting large molecules into smaller, more useable ones.
Future improvements

Already looking like a possible and reasonable endeavor assuming prices go down, there is still a lot of room for improvement. But first a comment about the price; it really is imperative that it goes down, a lot. In a study made by Bent Sorensen at Roskilde University [39], PEMFC equipped cars would retail at an average of €80k, compared do around €15k for gasoline driven vehicles. To further understand some of the costs, the main materials for the HD6 fuel cell is taken as an example.

Using standard bipolar plates as a reference, as of April 2013 and if buying in large quantities [40], the plates alone would account for $ 4500. However, this is for standard plates of much smaller size. Assuming battery grade flakes, the current cost is around $5 to $20 per kg [41]. That would put the cost of graphite needed for a HD6 alone to around $1200 to $4700, before heavy processing, labor costs and so on. Additionally, using a current Platinum price of roughly 1500 USD/oz [22], the amount of platinum used in the HD6 costs around $6400.

Although being burdened by large costs as of writing, considerable work is being done at getting the technology market ready, i.e. reducing the price tag. Already in 2006, Vojislav R. Stamenkovic et al. opened up for other substances when they managed to show a 10 fold increase in oxygen reaction mixing Pt up with Ni(111) [42]. In 2007, Strasser et al. came up with a platinum based alloy that reduced platinum dependency by 400 % [25], showing that feasible market solutions are within reach. As the cathode reaction is already the limiting factor in efficiency, once incorporated into an actual product, costs are predicted to decrease whilst at the same time raising efficiency. Additionally, the problem of uneconomical flow plates was being actively discussed already in 2006 [26].

Taking all this into account, it is clear that PEMFC technology will require additional time before being able to actively compete with modern engines, be it in aviation or automotive usage. If widespread use in the near future is desired, targeted government stimulants and/or customized taxes might be needed.

Not as much related to economy as to performance; tank pressure is climbing. With the total tank weight per liter tank estimated to stabilize around 0.5 kg/L, increased operating tank pressure could be immediately translated as additional flight time. As an example, if hydrogen would be kept under a pressure of 1000 bar, like modern (stationary) storage tanks, the flight time of the modified Socata TB20 GT would be increased by roughly half an hour [23], assuming maximum cruise speed. For long range use, it might be a long time before PEMFC technology will be a serious contender, assuming no major breakthroughs or technology shifts.

One such technology shift could be to use liquid hydrogen, often used as rocket fuel. The benefits of this would be a large increase in range, already utilized in some modern submarines [24]. However, the range increase is not as big as one might imagine due to the already advanced technological level of fuel tanks. Comparatively, liquid hydrogen has roughly a 35 % higher energy density compared to hydrogen stored at 700 bar.

Still, a 35 % increase in distance, as well as removing the need for a cumbersome air cooling system for the PEM fuel cell are significant upgrades, instead hindered by other factors. One of them is the need for a tank coolant system. Any tank wall weight removed due to a lower fuel pressure would likely be consumed by cooling systems. For a larger application like a submarine, this added bulk weight is of little issue, but this might not be the case for a smaller aircraft.

Tank weight aside: The main issue with liquid hydrogen is the same no matter the application – storage. Since it needs to be kept at a temperature of maximum 33 K, active cooling systems are needed which is not ideal when considering general aviation scenarios. Depending on storage configuration, boil off rates are

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[22] Rough, 60 day average spot price, spring 2013.

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in the ranges of 1 – 3 % a day [43] which can be further reduced by active cooling. Due to the characteristics of general aviation such as comparatively sporadic usage, the usage of liquid hydrogen is likely to see widespread usage in other transportation sectors before eventual implementation in general aviation.

The role of liquid hydrogen in general aviation is still uncertain, but what is not uncertain is the weight; more specifically that the weight will decrease. Albeit comparatively expensive to normal aluminum, the use of composite materials has risen rapidly in the past years with manufacturers ranging from Cessna to Boeing. However, simply changing out the relevant parts of the Socata TB20 GT is far from an ideal solution. Some gain can be achieved, but if extensive usage of composite materials is sought, the better option most likely is to design an aircraft from the ground up with the strengths and weaknesses of the respective materials in mind.

A part that can and should be improved upon however is the field flow plates inside the HD6 fuel cell. The density of graphite (roughly 2.15 g/cm$^3$) is comparatively low$^{25}$, but weight is accumulated due to the thickness of the structure. As previously mentioned in the report, graphite is brittle and has poor mechanical properties, meaning that if a more suitable material is found, the flow plates could be made thinner and thus significantly reduce fuel cell weight, and to a smaller degree, fuel cell size. The gained weight could then go a long way in achieving the same performance as the original, unmodified Socata TB20 GT.

Final words

To summarize, it has been shown in this report that the possible use of PEMFC technology has its advantages and that further inquiry is recommended. It is not without its difficulties, where the subjects of cost, safety and surrounding infrastructure have been discussed. Assuming these challenges can be dealt with; the benefits of PEMFC technology could go a long way in reducing the environmental impact of modern society.

Initial applications have been shown to be viable, albeit not on par with current, fossil fueled solutions, mainly manifested in a reduced maximum range.

Additionally, it has been shown that from a LCA perspective, the possible usage of PEMFC technology really would result in a reduced environmental burden and that it will most likely be an even larger comparative reduction in the future, assuming continued development and research.

Ending this report, the authors would like to thank Arne Karlsson of the Dept. of Aeronautical and Vehicle Engineering at KTH, both for his enthusiasm and his help and guidance during this project, particularly regarding aircraft performance. The authors would also like to thank the friendly staff at the Dept. of Heat and Power at KTH for their help and insight regarding the difficulties of adequate cooling.

$^{25}$The density of aluminum is roughly 2.7 g/cm$^3$. 
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References


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Accessed April 2013.


Accessed April 2013.

Accessed April 2013.

Accessed April 2013.

Accessed April 2013.

Accessed April 2013.

[32] A. Tharumarajah, P. Koltun, Cradle to gate assessment of environmental impact of rare earth metals, Figure 2, CSIRO Division of Process Science and Engineering, 2011.

[33] toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+841
Toxicology Data Network site on TEL. Accessed April 2013.

[34] Figures obtained from handouts during lecture by Arne Karlsson in spring 2013, Dept. of Aeronautical and Vehicle Engineering, KTH.


Accessed April 2013.

[37] physicstoday.org/journals/doc/PHTOAD-ft/vol_57/iss_12/39_1.shtml
Accessed April 2013.


Accessed April 2013.

Accessed April 2013.

[42] http://www.sciencemag.org/content/315/5811/493

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Appendix A - HD6 specifications sheet

**FCvelocity-HD6**

**Ballard Experience**
Since 1992, Ballard Power Systems has developed and demonstrated five generations of heavy duty fuel cell modules for bus applications. Demonstration programs and field trials have been held in the US, Canada, Western Europe, Iceland, Australia and China. Ballard powered buses have accumulated more than 200,000 hours of operation, covering more than three million kilometers and transporting more than seven million passengers.

**6th Generation Module**
Based on the state of the art automotive fuel cell stack, Ballard’s FCvelocity-HD6 fuel cell module offers a design ideal for integration into bus applications.

With the next-generation Ballard fuel cell at its core, the FCvelocity-HD6 establishes a new standard for cost, through design for volume manufacturing, and compatibility with customer system requirements. The heavy duty power module features a control unit that can interface with a system controller, making it a plug and play product for any fuel cell or hybrid fuel cell bus platform.

This next-generation module also offers significant advances in durability, power density and fuel efficiency.

**Availability**
Please contact any of the following Ballard representatives for discussions regarding Ballard’s next-generation heavy duty fuel cell module.

- Daljit Bawa (daljit.bawa@ballard.com)
- Jeff Grant (jeff.grant@ballard.com)
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Appendix B - Weight modification table

<table>
<thead>
<tr>
<th>Removed parts</th>
<th>Weight [lbs]</th>
<th>Added Parts</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>438.7</td>
<td>Engine</td>
<td>25</td>
</tr>
<tr>
<td>Fuel pump</td>
<td>4.9</td>
<td>Engine heat sink</td>
<td>5</td>
</tr>
<tr>
<td>Fuel filter</td>
<td>1.3</td>
<td>Air compressor</td>
<td>30</td>
</tr>
<tr>
<td>Rear cabin lightning</td>
<td>0.3</td>
<td>Air cooling heatsink</td>
<td>50</td>
</tr>
<tr>
<td>Oil</td>
<td>27</td>
<td>AC extra margin</td>
<td>10</td>
</tr>
<tr>
<td>Oil cooler</td>
<td>3.1</td>
<td>Fuel cell</td>
<td>400</td>
</tr>
<tr>
<td>Rear seats</td>
<td>28</td>
<td>FC – air filter</td>
<td>4</td>
</tr>
<tr>
<td>Rear seat belts</td>
<td>1.1</td>
<td>FC – liquid cooling</td>
<td>25</td>
</tr>
<tr>
<td>Rear bench</td>
<td>19.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel tank (x2)</td>
<td>128</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric generator (x2) (used for ignition)</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylinder probes</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starter</td>
<td>11.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starting engine</td>
<td>19.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC generator</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fuel flow indicator</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>328 kg</strong></td>
<td><strong>549 kg</strong></td>
<td></td>
</tr>
</tbody>
</table>
Appendix C - ReCiPe indicator map

Figure: Relationship between LCI parameters (left), midpoint indicators (middle) and endpoint indicators (right) in ReCiPe 2008. Picture from http://www.lcia-recipe.net
Appendix D - Usage scenarios

In preparation of this report, two different transportation scenarios were posed to be used in the LCA. The two scenarios were of moderate and high usage. A possible low usage case was omitted since it would not have added much to the report that simple logic could not.

The high usage scenario - the commuter

Assuming that the aircraft is being used as a commuter vehicle, there stands to reason that the distance is long enough so that there is benefit in using a plane instead of a car. Assuming a distance of 200 km one way, that makes for 400 km a day, 5 days a week for maybe 45 weeks a year. Also, don’t forget that one wants to buy a new Fuel Cell after a bit over 10k hours, and that one might want to buy a new plane at least every 10th year.

Assuming a commuting speed of around 240 km/h (around 80 % or so power output for the fuel cell), that makes for around 375 hours a year in commuting time. During those 10 years, the total energy requirement adds up to 3750 h · 0.8 · 150 kW = 450 000 kWh. With one kWh being equal to 3.6 MJ, this becomes 1620 GJ. The original engine is assumed to travel at the same speed for simplicity, so as to not make speed a factor in this. In reality, the avgas Socata TB20 GT would probably be travelling slightly faster and thus being slightly worse from a ReCiPe LCA point of view.

For hydrogen, the value of roughly 5.8 kg/h from the report is used times 3750 hours = 21750 kg. For 100LL, using values from table 6 in the report, it adds up to 164250 kg fuel and assuming 0.5 g/L of TEL and a total of 225000 L of 100LL, 82 kg of TEL.

The moderate usage scenario – the active enthusiast

Assuming that the aircraft is being actively used mostly for recreational purposes such as weekend trips and for fun, that could equate to around 3 hours of usage a week, on average. Doing this for 10 years before buying a new aircraft, every week of the year adds up to 1560 hours.

For hydrogen, that’s 1560 h · 5.8 kg/h = 9048 kg of hydrogen. For 100LL, that is 1560 hours of 120 kW, meaning 3.6 · 120 · 1560 = 673920 MJ / 7.2 = 93600 L. Using density of 100LL as roughly 0.73 kg/L and TEL for 0.5 g/L, this becomes: 68323 kg petrol, 46.5 kg TEL.