Life cycle assessment of hydrogen fuel in aviation

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Abstract

The aviation sector emits 2% of the global emissions caused by transportation. This is a problem for our global climate and has also shown to be an issue for the public after the Swedish boycott of airtravel, inspired by Greta Thunberg in 2019. Because of this, aviation will require to modernize and implement new technology that will cut these emissions.

The Life Cycle Assessment executed in this thesis gives positive results regarding the environmental impacts that would be prevented by a hydrogen-electric aircraft. The assessment considers the life cycle of a hydrogen-electric aircraft that uses a solid oxide fuel cell for propulsion. This aircraft is compared to the traditional kerosene-fueled aircraft. The results show that a hydrogen-electric aircraft prevents over half the Global Warming Potential caused by the use of traditional aircraft with kerosene propulsion as long as the fuel is defined as green hydrogen, i.e. produced with no CO_2 emissions.

Contents

Nomenclature

1.4-DCB	Dichlorobenzene
c_K	Kerosene fuel consumption
CFC-11	Chlorofluorocarbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
d	Distance travelled
DSB	Norwegian Directorate for Civil Protection
e_H	Specific energy, Hydrogen
e_K	Specific energy, Kerosene
FC	Fuel cell
Fe	Iron
GHG	Greenhouse Gas
GWP	Global Warming Potential
H_2	Hydrogen
HEV	Hydrogen Electric Vehicle
HFCEV	Hydrogen Fuel Cell Electric Vehicle
HTP	Human Toxicity Potential
IPCC	Intergovernmental Panel on Climate Change
KOH	Potassium hydroxide
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LH_2	Liquid Hydrogen
LNG	Liquefied Natural Gas
m_{K1}	Mass of kerosene burned at referenced distance
m_{K2}	Calculated mass of Kerosene
MDP	Metal Depletion Potential
NMVOC	Non-Methane Volatile Organic Compound
NO	Nitrogen oxide
NOx	Nitrogen Oxides
O_2	Oxygen
ODP	Ozone Depletion Potential
PEMWE	Proton Exchange Membrane Water Electrolysis
PH	Pumped Hydro
PM	Particulate Matter
PMFP	Particulate Matter Formation Potential
POFP	Photochemical oxidant Formation Potential
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
VOC	Volatile Organic Compound
WE	Water Electrolysis

1 Introduction

Today's fuel in aviation is based on fossil energy resources. Could hydrogen be the renewable alternative? My thesis will elaborate on the possibilities based on a life cycle assessment of hydrogen used as fuel in aviation.

A Life Cycle Assessment is a method for calculating emissions of a specific system over its lifespan, i.e. from cradle to grave. This method is well established in the research and academic society and makes it possible to compare different solutions to each other if the used assumptions are similar in both studies.

As stated by the Intergovernmental Panel on Climate Change (IPCC), something must change for human society, to stop or at least slow down global warming and not exceed the 1.5^{o}C temperature limit. To change, the world must make cuts in CO_2 emissions. The new report from IPCC stated that to achieve the goal of a maximum of 1.5 degrees, the world needs a major change, a change to a climate budget that has negative CO_2 emissions. [Intergovernmental Panel on Climate Change, 2013]

The aviation sector produces an amount of CO_2 emissions that is small compared to the rest of the transportation section. Aviation in 2014 was responsible for around 2% of the global energy-related CO_2 emissions with 0.71 Gt CO_2 while the rest of the transportation sector was responsible for 23% a total of 6.7 Gt CO_2. Still, considered that the demand for aviation only will increase with time it is forecasted to reach 3-4% within 2050. [Timmis et al., 2015]

The technology of hydrogen usage is not new. Not even within the aviation sector. The Soviet Union did accomplish to fly a hydrogen-fueled aircraft in 1988. This aircraft is known as TU-155 a/c. This was an aircraft that had its maiden flight 15^{th} of April in 1988. The fuel back then was liquified hydrogen but was later changed to liquefied natural gas (LNG). [Wikipedia - Soviet Union, 2020]

Why the Soviet Union chose liquefied hydrogen, when it is less energy-consuming to keep the hydrogen in a gaseous state, is not known. All though issues regarding the volume can be thought to be the reason. Fuel storage in an aircraft could be a problem because of the desirable low weight and limited space. However, hydrogen can be stored as a gas, liquid or in the surface of a material by adsorption, where the solution of liquid storage has the smallest volume [Baroutaji et al., 2019].

No matter how hydrogen is stored, the energy per mass ratio is the highest of any fuel, but the energy density varies. Since hydrogen has such a low boiling point, -252.8^{o}C it will require advanced technology to achieve high energy density. This could be solved by cryogenic temperatures, compression, a combination of the two or to be based in a material. [Energy dep, 2020]

Compressed hydrogen is already a solution for storage in hydrogen-electric vehicles. Several companies such as Hyundai and Toyota have each launched at least one model that is a hydrogen-electric vehicle. However, the usage of hydrogen in the public sector is also starting to grow. Scania and Esoro have made a partnership with different food chains, Asko and Coop, and plan to launch a truck that also is driven by fuel cell technology. [Hydrogenforum, 2019]

Libya is taking a step for the rest of the world when it comes to hydrogen in aviation. They have a test case of their aviation called “Hydrogen fueled airplanes”. They plan is to use liquefied hydrogen and based on that they will save the environment for 400 tons of CO_2 on each long-distance flight with a 747 aircraft. In addition to this, they state that the use of hydrogen will reduce the weight of the aircraft, which is beneficial for takeoff. [Bindra et al., 2016]

There are other reports written in and after 2016 on the same topic, hydrogen in aviation. A thorough assessment of hydrogen and other potential fuels was completed by Bicer, Dincer [2017] in 2017 where they used the Ecoinvent database and SimaPro for processing the collected data. They concluded that even though a fuel does not have emissions during use it is important to take into account in what way the fuel is produced. For instance, hydrogen can be produced from natural gas or by the use of geothermal energy. These two options have different amounts of emissions. Bicer, Dincer [2017] concluded that the emissions from liquid hydrogen produced with geothermal energy are as low as 0.014 kg of CO_2 per tonne-km, while the standard aviation fuel, kerosene, is 1.05 kg of CO_2 per tonne-km [Bicer, Dincer, 2017].

Still, the estimate of emissions using Ecoinvent and SimaPro in Bicer, Dincer [2017]’s report was based on using hydrogen in combustion engines, which releases NOx emissions in addition to water vapour during its usage. The hydrogen-electric fuel cells, on the other hand, does not have any other emissions than water vapour during operation. When using hydrogen in a fuel cell (FC) electricity is produced and used for propulsion as it is done in hydrogen-electric vehicles (HEV).

Safety of hydrogen use is important. Since hydrogen is the smallest element in size and weight and also has a low boiling point, it is under normal circumstances in a gaseous state, which makes the requirements of the technology and materials high. The overall safety precautions the manufacturer has made, connected to hydrogen in cars, are a controlled release valve in addition to protected fuel tanks. The tanks have three layers of polymer, carbon fibre and polymer reinforced with glass fibre. This technology does not leak and will absorb five times as much energy compared to steel in the event of a collision. The controlled release valve comes into play if the storage tank has taken too much damage. It will then release the fuel in a restrained manner out into the free air around and since hydrogen is lighter than air it will rise and spread in the atmosphere quickly. This will reduce the risk of the possibility of high damage if it ignites. [Toyota, 2020]

The safety measures taken in the HFCEVs could be applied to aircrafts as well. A controlled release of fuel, layered tanks and reinforced and enhanced technology should be beneficial. But other precautions might need some attention. The fact that the physical conditions higher in the atmosphere are not the same as on the ground. The temperature and pressure are lower, as well as the power and constraints set on the materials during takeoff, landing, flight and in the event of a crash landing, are more challenging.

To answer the question "Could hydrogen be the renewable alternative?" it is planned to base the results on models and theory. The idea is to be able to conclude whether or not hydrogen-electric aircrafts have lower emissions than the traditional aircraft. Some of the data that will be accumulated will come from former work on the subject. My contribution through this thesis will be an analytic assessment of a life cycle of hydrogen used as fuel in aviation.

2 Background theory

2.1 Climate

Our global climate is changing. This is not new, the climate on Earth has been changing since day one. The difference now is the speed of the change. The acceleration of global temperature change is immense. In the summary of the report titled *Climate Change 2013: The Physical Science Basis* published by the Intergovernmental Panel on Climate Change 2013 (IPCC) they write that the warming of the climate system is undoubtedly a fact. The ocean and atmospheric temperatures have increased, the onshore snow and ice are melting, which are a participating factor in the increase of sea level and least but not last the greenhouse gases (GHG) are raising [Intergovernmental Panel on Climate Change, 2013].

The atmospheric composition has been severely altered since the industrial revolution in the mid 18^{th} century. The concentration of carbon dioxide, methane and nitrous oxide have not been this high over the last 800 000 years. Carbon dioxide on its own has increased by 40% since pre-industrial times mainly due to carbon emissions but also because of land-use changes [Intergovernmental Panel on Climate Change, 2013].

The reason why this is alarming is that these gases, especially carbon dioxide prevent radiation/heat from escaping our atmosphere and so on contributes to a temperature increase in the atmosphere. The ocean assists the atmosphere by absorbing carbon. This leaves the ocean acidic and causes harm to the biodiversity [Intergovernmental Panel on Climate Change, 2013].

2.2 Hydrogen

Hydrogen is the lightest element found in our universe in addition to being the most abundant. Hydrogen is rarely found existing alone [Baharozu et al., 2017]. Hydrogen has a high chemical value that is released when binding between atoms occur. This chemical energy is possible to use as thermal energy or converting it to electricity. To do that the process has to be controlled and set to start when it is suited. This means that hydrogen must be separated from other components and then introduced to another component at the desired time. Hydrogen has a wast market potential, to mention two [Barthelemy et al., 2017];

- Fixed applications such as back-up power supply
- Fuel in the transportation sector. For example aircraft, maritime vessels, buses and cars.

To implement hydrogen in these sectors of the market the technology is needed to be up to today's standards of safety and efficiency.

2.2.1 Producing Hydrogen

Hydrogen can be generated in a variety of ways. It can be produced based on clean renewable energy or it can be based on fossil fuels. Today most of the total produced hydrogen is based on fossil fuel, whereas only 4% is produced using electricity for production by electrolysis. The electricity can come from renewable or non-renewable resources. These different production types of hydrogen have various *(i)* benefits, *(ii)* disadvantages and *(iii)* emissions.

Steam methane reforming

SMR is steam reforming of natural gas. The process consists of introducing natural gas, methane, for steam at temperatures between 700 ^{o}C and 1000 ^{o}C while at a pressure of 3-25 bar (0.30-2.50 MPa) in the presence of a catalyst [Liu et al., 2020]. *(i)* Amongst some of the benefits from this production, it is produced three molecules of hydrogen from each methane molecule, shown in eq.1. Also, using the methane is considered a benefit, since the alternative is to burn it for heat or just to release it into the atmosphere without using its full potential. *(ii)* A disadvantage of SMR is the byproduct of CO_2 which is not desired because of the lack of possible applications other than reentering the reservoir that the methane exited. Another disadvantage is the excess need for power when producing hydrogen from methane compared to release. Also, possible leakage in the construction resulting in methane emissions. *(iii)* the emissions of SMR are quite extensive, 9.26 $kgCO_2/kgH_2$ (more than nine kilos of carbon dioxide is produced for each kilo of hydrogen [Grote et al., 2014]. The consequences of CH_4 and CO_2 emissions are complex and many. To simplify, it is most important to look at how long the emission of each component will affect our climate. Methane has a high heating value of our atmosphere but will only consist for around 40 years while carbon dioxide has a milder impact per time, it will impact the atmospheric composition for centuries. To sum up, impact multiplied with the time of each makes them both highly dangerous.

The steps of SMR production can be explained by using eq. 1 and 2. Step one of the SMR process shown in eq. 1. Results are mainly carbon monoxide (CO) and hydrogen (H_2) and small amounts of carbon dioxide (CO_2). The second step is called the "water-gas shift reaction" where all components, carbon monoxide, steam and the catalyst, are subjected to another round to extract any additional hydrogen. This process is shown in eq. 2 where one of the byproducts is a supplement of heat [Liu et al., 2020]. The third step consists of purifying the hydrogen by removing all carbon dioxide and impurities leaving the final produced hydrogen at the quality of better than 99.999% [Liu et al., 2020].

$$CH_4 + H_2O + heat \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 + heat \tag{2}$$

As shown in eq. 1 and eq. 2 above, there are unwanted byproducts but the worst is carbon dioxide which is found after the second step.

Water electrolysis, WE

In contrast to SMR, electrolysis has negligible environmental emissions during production if the electricity used comes from renewable energy resources, for example, wind power, hydropower, geothermal, solar power and so on. In Bicer, Dincer [2017]'s results, the hydrogen produced from electricity from geothermal energy has the lowest global warming potential (GWP).

The oldest and most commonly used technology for water splitting is an alkaline electrolyser. This electrolyser consists of an anode and cathode that are submerged in an alkaline electrolyte and separated by a porous ceramic diaphragm. Another, more modern electrolyser is the proton exchange membrane water electrolyser (PEMWE). This does not have any liquid electrolyte but is made of a solid polymer membrane. The benefits of PEMWE are high purity of produced hydrogen, flexible operation and the elimination of potential leakage regarding KHO. [Bareiß et al., 2019]

(i) A benefit of applying the solution of PEMWE in Norway is the easily accessible resource of water for producing hydrogen. Besides, this could give Norway an advantage regarding global politics. *(ii)* Disadvantages are the need for new infrastructure and the regional scarcity of freshwater around the world. All though this is not an issue in Norway. *(iii)* Regarding the emissions of the production of hydrogen then there are none as seen in eq. 3. The only byproduct is the O_2-gas which is possible to use in hospitals or fish farming.

Eq. 4 and 5 shows the more detailed reactions within the electrolysis. The oxidation in eq. 4 at the anode where the water is split into oxygen gas and aquatic solute H^+. In eq. 5 the aquatic solution of hydrogen receives electrons and produces hydrogen gas.

$$2H_2O(l) + el. \rightarrow 2H_2(g) + O_2(g) \tag{3}$$

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^- \tag{4}$$

$$2H^+(aq) + 2e^- \rightarrow H_2(g) \tag{5}$$

2.2.2 Hydrogen storage and safety

Storage of hydrogen is an important factor when introducing and implementing hydrogen to the transportation sector. Hydrogen is not an energy source but an energy carrier and therefore a type of chemical storage. This can be compared to pumped hydro storage (PH) where excess energy is used to power the pumps that move water to a higher reservoir. When the need for power returns the potential energy stored in the water is released as kinetic through a fall controlled by pipes and converted to electric power by the combination of turbines and generators.

The produced hydrogen has to be stored under specific conditions. Since the hydrogen atoms are small the technology used has to be leakage proof. This is especially important regarding the explosion hazard that is highly present when working with hydrogen. Hydrogen can be held in compressed storage at a pressure as low as 20 MPa and up to 70 MPa which is what is used in today's hydrogen fuel cell electric vehicles (HFCEV) [Liu et al., 2020]. In Baroutaji et al. [2019]'s article *A comparison of storage options of the recent improvements and industrial perspectives* it is concluded with a new cryo-compressed solution. Still, they mention the mature technologies of the compressed and cryogenic storage technique. These will most likely be the preferred choices until the cryo-compressed solution has proven its worth.

2.2.3 Hydrogen conversion to electricity

The chemically stored energy in the energy carrier hydrogen can be used by converting it to electricity in a fuel cell. One fuel cell consists of two plates that are separated by a membrane. The membrane has a free passage for positive charges (protons) but prevents negative charges (electrons) to pass through. The fuel cell is fed by hydrogen on one plate and receives oxygen guided from the surrounding air. The positive charges of hydrogen will then travel towards the oxygen through the membrane. The electrons, on the other hand, will not be able to. This results in an unbalance of charges which causes the electrons to choose an alternative path around and generates an electric current. When the electron reaches the oxygen and positive charges of hydrogen they form H_2O, water vapour. Therefore the two results are electricity and pure water vapour and no other byproducts.

2.2.4 Hydrogen combustion

It is possible to burn hydrogen in the same matter as conventional fuels such as Jet-A, also known as kerosene, is most commonly used in aviation, and its traditional internal combustion engines. When hydrogen is injected into a combustion chamber it is mixed with oxygen before ignition. Several different engines use combustion, the newest might be the jet engine where the released thermal energy is used as a thrust and with a high enough force move the aircraft. In older cases, the thermal energy was used to produce mechanical power to rotate blades on a rotor engine to make thrust and the movement of the aircraft.

2.3 Aviation

The aviation sector receives a judgmental attitude due to their greenhouse gas emissions. Some airports in Stockholm, Sweden were affected by a movement called "flight shame". This resulted in a massive decline in passengers using air transport to travel. This happened in Autumn 2019, some claim that Greta Thunberg is responsible for the movement [Ripegutu, 2019]. This was an excellent example of how much consumers and private persons can affect the system and businesses.

As already mentioned the idea of using hydrogen for fuel in aviation has been thought of before. In addition to the Soviet Unions' experimentation, NASA has been looking into and used hydrogen in expeditions out of Earths atmosphere. For this reason, there should be a lot of data about efficiency and so on. All though the use is quite different. [NASA, 2020]

NASA uses hydrogen in a combustion engine to gain enough thrust to be able to lift the spacecrafts or satellites above earth atmosphere before the fuel tanks and combustion engines are released from the main vessel and then moves freely in outer space. This is of course not the goal in aviation. The goal is to have a permanent solution of aircraft design regarding storage, fuel usage and refilling technology. To have a permanent design of the aircraft that works regarding aerodynamics as well as volume needed for fuel to travel, there will most likely be necessary for design alterations. [NASA, 2020]

2.3.1 Electric aircraft

The electric aircraft will reduce emissions, noise and operating costs but are only available for short-distance flights with low passenger capacity. Non the less, these types of flights are well suited for Norway and the existing short-range flight pattern. These flights most often consist of a small amount of passenger need, which makes it convenient for the battery-electric aircraft. The range of the aircraft is dependent on the size of the battery in addition to passenger capacity or payload. The two aircrafts, Eviation Alice and Heart Aerospace ES-19, have a range of 1046km and 400km and passenger capacity of 9 and 19. [Baumeister et al., 2020]

Because of this short range and low capacity for passengers compared to the Boeing 787-8, the battery-electric aircraft will not be assessed in this LCA. The potential of hydrogen-electric will be viewed as a substitute for the battery-electric.

2.3.2 Status

Aviation today is based on fossil fuels and the Norwegian infrastructure of flights does not aid or promote the idea of new solutions. Also, the low costs of jet fuel prevent companies to invest their money in new technologies such as hydrogen-electric aircrafts. [Kåre Gunnar Fløystad, 2018] Still, some companies have an interest in evolving their fleet of aircrafts. Widerøe has joined a collaboration with the engine producer Rolls-Royce. They are working towards achieving the zero-emission target for Norway in 2030. [Widerøe, 2020]

2.3.3 Options of aircraft design change

Baroutaji et al. [2019] performed a comprehensive investigation of technology regarding fuel cells and hydrogen in aviation. Here they also mention the difference of location of fuel tanks within the airplane. The traditional location where the kerosene is stored is within the wings. Baroutaji et al. [2019] elaborate that the liquid hydrogen would not be suited to store in the wings due to the volume needed for storage. LH_2 in itself has a lower density than kerosene but when including the storage tanks and their needed insulation the wings would not have enough space. Therefore they pitch the possibility of either store the fuel above the passenger cabin in addition to the rear of the small to medium-range aircraft. The long-range aircraft will need more fuel and therefore more space. The tanks could be located behind the cockpit and a second at the far end of the passenger cabin. These solutions are illustrated in Fig. 1 [Baroutaji et al., 2019]

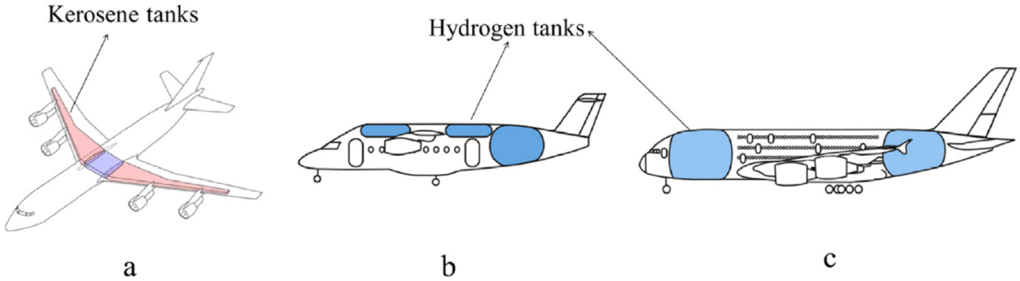


Figure 1: *(a) shows the traditional storage of kerosene tanks located in the wings. (b) is the proposed solution of short- and medium-range, while (c) is proposed for long-range flights. [Baroutaji et al., 2019]*

2.3.4 Safety and regulations

The safety regulations in Norway are supervised by the Norwegian Directorate for Civil Protection (DSB). Safety regarding hydrogen in aviation is an important question and an important factor to consider. Since a lot of aviation transportation is for the public it is important to have a good dialogue and communicate well with the community and making them feel comfortable with the technology and safety regulations. This will be something that might be an obstacle since the reputation of hydrogen has the public wary.

Since Jet-A (kerosene) still is less expensive than other fuels it is not much research regarding hydrogen safety in this aviation application. Therefore I imagine the safety measurements to be based on vehicle solutions. However, it is important to mention that the Orkney Islands have on-going testing of hydrogen-fuelled aircrafts, which can cause change for the hydrogen evolution in transportation sector [EMEC, 2019].

Safety in vehicles is based on a structure of compressed hydrogen gas stored in tanks that are specially adapted to storing hydrogen. Hydrogen is a small atom that could be hard to contain because there is a high probability of diffusion through materials if the technology is not advanced enough. These pressure tanks are in edition layered to withstand impacts in the event of a collision. In the case of the structure not being strong enough there is a safety mechanism that releases the hydrogen gas through valves that control the volume flow and releases the gas away from the car so that it would not be contained and be an explosive hazard but rise in the atmosphere. Since the density of hydrogen is so low compared to air the hydrogen will rise rapidly and will not linger at the surface unless it's contained in some way. [Barthelemy et al., 2017; Toyota, 2020]

2.4 Life cycle assessment, LCA

A life cycle assessment is an evaluation method that makes it possible to compare different components, production lines and services to one another. This is accomplished by assessing the impacts of raw material extraction, production processes, operation and maintenance, and waste management.

To assess these impacts several different impact methods can be implemented and are referenced to as LCIA. These LCIA's is mentioned further in chapter 3.2 Impact method. The Life cycle inventory (LCI) is the concept that regards all components, materials and transportation methods that are included in the LCA.

2.5 Focus and background for thesis choice

I chose to focus on aviation and its potential to cut environmental emissions because I believe that the society we live in today is not willing to give up on these beneficial transportation methods, and we should not have to either. With the speed of today's technology, I believe that in a short period, we have the means to complete this implementation. The main thing lacking is the willingness to change our ways and acknowledge that we as humans have left a bigger environmental footprint than Earth manages to reproduce if we continue business as usual [Intergovernmental Panel on Climate Change, 2013]. To receive the assistance of hydrogen solutions and implementation, I contacted Tomas Fiksdal at Greenstat AS - Hydrogen for guidance.

Recently, in 2018, I completed my bachelor thesis in Energy technology at the Western Norway University of Applied Sciences. The topic for this report was *Hydrogen production by electrolysis and waste heat* which was my first encounter with hydrogen as an energy carrier. After I finished this I applied for the Energy master at UiB.

This master consists of two years, the first year are based on six subjects while the second, and last year, are put aside for research and writing a thesis. In addition to using my bachelor's degree in Energy Engineering, the subjects that were used as a foundation for the thesis is;

SDG213	Causes and Consequences of Climate Change
ENERGI230	Environment and Energy
ENERGI210	Energy physics and technology
ENERGI200	Energy resources and use
Z-ENERGI	Life cycle assessment
GEOF105	Physics of the atmosphere and ocean

Table 1: *Subject content of the Master's degree*

3 Method

This thesis is a completion of a master in Energy from the University of Bergen. The literature research is based on articles collected from Science Direct and Google Scholar. The list of literature can be found in References.

The study assesses the environmental impacts of two types of aircrafts that are both based on the Boeing 787-8. Case-1 assesses the hydrogen-electric solution and Case-2 contains the traditional aircraft with the combustion of kerosene. The method that is used is a life cycle assessment (LCA). The LCA is supported by data from Ecoinvent, articles and Piano-X and processed by openLCA and Microsoft Excel.

Ecoinvent is a commercially accessible life cycle inventory (LCI) database. The Piano-X is an aircraft analysis tool that is used to provide data on fuel consumption and travelled distances. OpenLCA is a free software tool that is used to create a system and calculate the impacts of the LCA before the results are exported to Excel. The impact assessment method that is used is the ReCiPe midpoint (E)V1.13. The ReCiPe midpoint(E)V1.13 method consider 18 midpoints where in this study it was focused on GWP, ODP, HTP, PMFP, POFP and MDP. See the list in subchapter 3.1 Goal and scope.

3.1 Goal and scope

The goal and scope of this assessment are to estimate the environmental impacts of a hydrogen-electric aircraft in contrast to emissions caused by the traditional aircraft. The system boundary of the study is elaborated in chapter 3.3 System Boundary. The assessment of possible impacts caused by these emissions is evaluated by using the LCIA method, ReCiPe. The method is further explained in chapter 3.2 Impact method. The following categories are evaluated:

- Climate change (GWP)
- Ozone depletion (ODP)
- Human toxicity (HTP)
- Particulate matter formation (PMFP)
- Photochemical oxidant formation (POFP)
- Metal depletion (MDP)

3.2 Impact method

The impact method used in this study is the ReCiPe midpoint (E)V1.13. The ReCiPe method has 18 midpoint indicators and 3 endpoint indicators. These indicators are shown in Figure 2 where the connection between midpoint and endpoint also is illustrated. Since the goal of this study is to observe what impacts each case has on the environment it is best suited to apply the midpoint indicators with the factor of long term assessment based on precautionary principle thinking, the Egalitarian perspective. The other two choices were the Individualist; short term and optimistic that the future technology will solve the problems of the present, and the Hierarchist, the general agreement often used as default. An advantage of this impact method is a broad collection of midpoint categories. [PRé Sustainability, 2020]

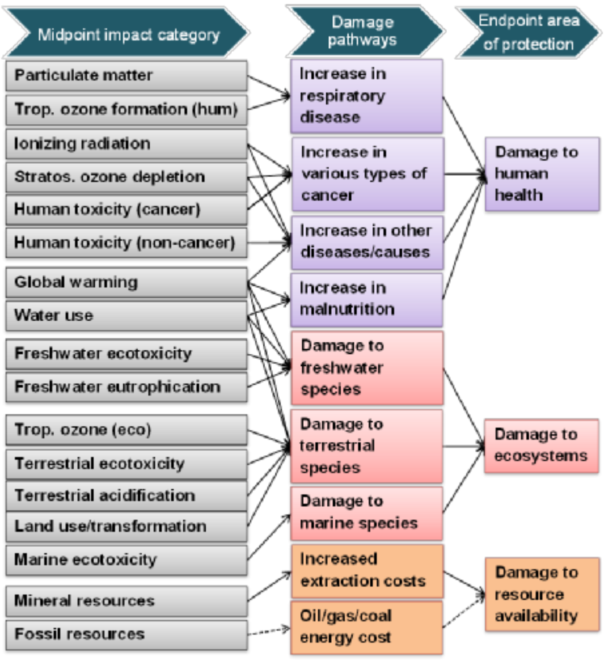


Figure 2: Structure of the impact assessment method, ReCiPe. [RVIM, 2020]

3.3 System boundary

The system boundary is decided based on current knowledge of the topic and the time limit of the study. In both Fig. 3 and the Fig. 4 the system boundaries are shown. The Cases are divided into three main categories; Production, Usage and Decommission. Both cases include consideration of emissions related to the production of the given fuel.

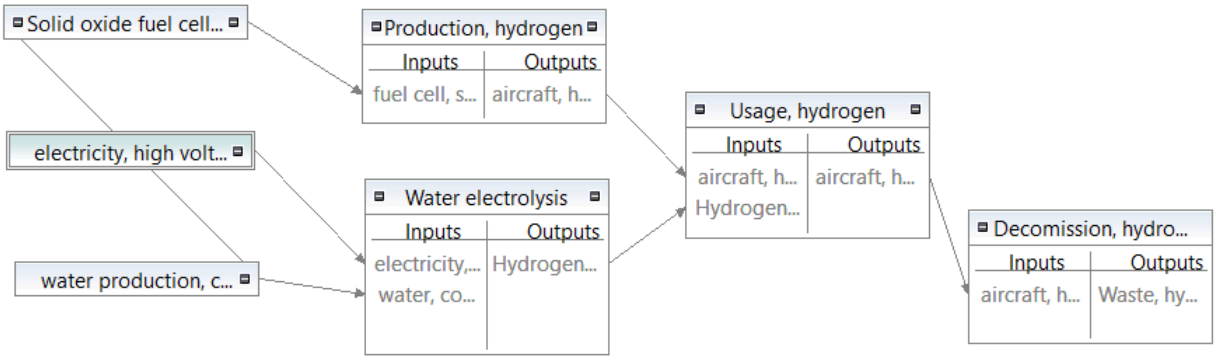


Figure 3: *System for Case-1: Hydrogen-electric aircraft LCA*

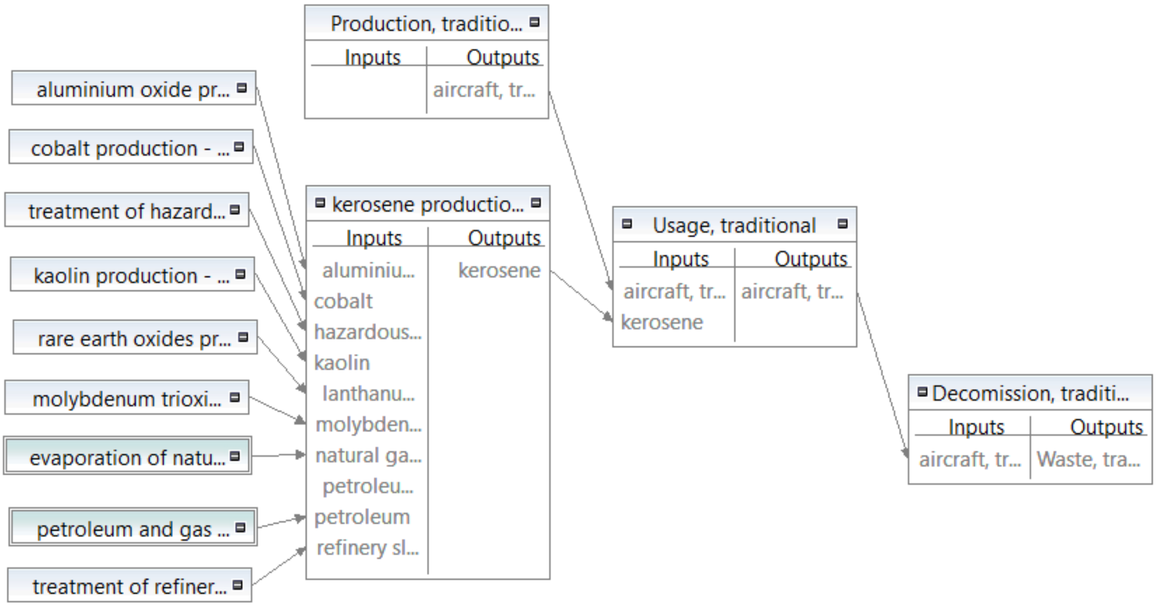


Figure 4: *System for Case-2: Traditional aircraft LCA*

3.4 Assumptions

The amount and type of material uses will most likely need to be altered when producing a hydrogen-electric aircraft. But, research on the topic hydrogen, alone and in combination with aviation still have gaps of knowledge. Therefore, in this study, it is assumed that the aircraft frame that is used in the hydrogen-electric aircraft is the same as the traditional and is therefore not included in the assessment.

Data containing what materials that are needed to produce a turbofan engine used in the traditional aircraft was not present in Ecoinvent's database. For that reason, the production of the engine necessary in the hydrogen-electric aircraft was not considered.

Since the engine data and the aircraft frame data was overlooked the emissions related to the possibly needed assembly of the frame and engine was automatically neglected. Also, the accessibility to how the internal system of an aircraft is designed is not open for the public and is therefore also overlooked.

The Norwegian electricity mix is set to be the provider of electricity for processing the water in a electrolysis to produce hydrogen.

Transportation of fuel from production to site is assumed to have the same travel distance and method of transportation. For that reason, transportation between fuel production and fuel use is ignored.

Since the study is based on specifications of the Boeing 787-8, the payload, passenger capacity and lifespan is assumed to be the same in each case and are therefore not taken into consideration. The total travelled distance through the lifespan of a 787-8 is calculated using the approximation shown in eq. 6 where range per flight equals 13 530 km and the number of cycles is 44 000. One cycle is defined as take-off and landing. [Boeing, 2020; Paur, 2010]

$$Total\ distance = "number\ of\ cycles" * "range\ per\ flight" \tag{6}$$

Maintenance during operation is normally included, but due to lack of accessible data, this is neglected for both cases. The fuel consumption is an approximation calculation based on simulation in Piano-X shown in Attachment #1. Where the efficiencies are neglected because of time limitations. Consumption, c_K, is calculated to be 5.30 kg$_K$/km by eq. 7 where d equals the distance travelled, 14 174km and m_{K1} equal 75 126kg, the mass of kerosene burned for this specific trip. Specific energy for kerosene, e_K, is 46.4 MJ/kg and for hydrogen, e_H is 141.8 MJ/kg. The mass of kerosene necessary for the entire lifespan of the aircraft, m_{K2}, is calculated in eq. 8. Calculating the mass of hydrogen is an approximation made of eq. 8 and using eq. 9. The hydrogen mass is shown in eq. 10.

$$c_K = d_K * m_{K1} \tag{7}$$

$$m_{K2} = e_K * c_K \tag{8}$$

$$E = e_K * m_{K2} \tag{9}$$

$$m_H = E/e_H \tag{10}$$

4 Results and Discussion

4.1 Results

The results are shown in Fig. 5 is imported from the assessment completed in openLCA. In the diagram in Fig. 5a the global warming potential (GWP) for both cases are shown. The GWP of Case-1 resulted in 316 000 tonne CO_2-eq. While the GWP from the traditional aircraft resulted in 755 000 tonne CO_2-eq which is over double the value over the same assumed period. It was expected that the difference between these two results would be larger. The reason why this is not the case will be discussed in chapter 4.2.1 Discussion.

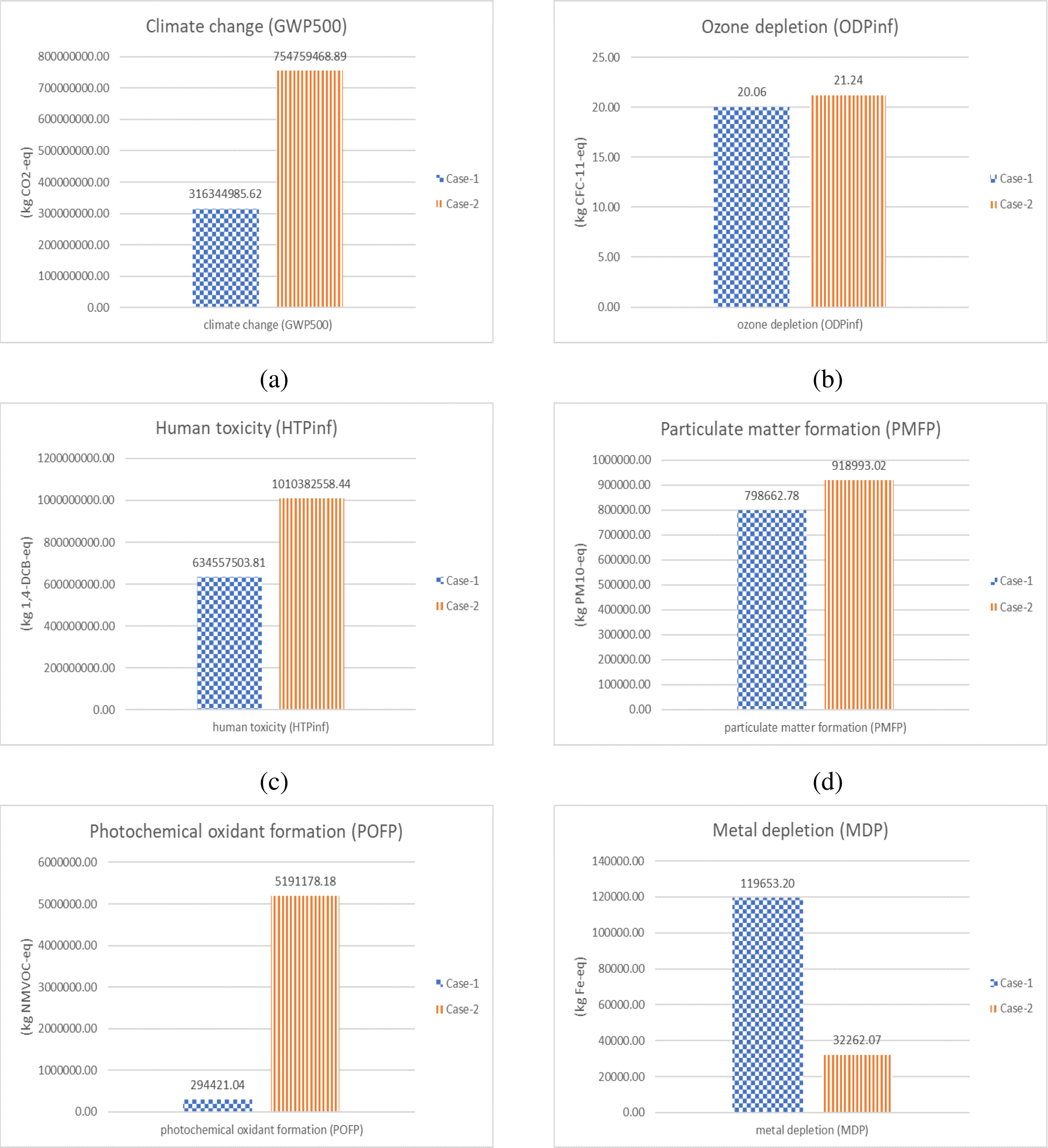
The value of ozone depletion is given in relation to kg CFC-11-eq which is a chlorofluorocarbon that dissolves the ozone (O_3) layer. The ozone depletion results are 20.1kg CFC-11-eq for Case-1 and sources from the electricity needed in the electrolysis of water. The process that is accountable for the ozone depletion of 21.2kg CFC-11-eq, for Case-2 is the off-shore petroleum production of kerosene.

The human toxicity results are measured by kg 1.4-DCB(dichlorobenzene) -eq and are a measurement of the chemical toxicity and its significance to human health. Both cases have a large amount of HTP but again Case-1, with 635 000 tonne 1.4-DCB-eq, have a smaller impact than the traditional solution, Case-2 with 1 010 000 tonne 1.4-DCB-eq. Still, Case-1 have an unexpectedly high value that seems to lead back to the energy mix used for the electricity in hydrogen production.

Regarding the PMFP, Case-1 emits 799 tonne PM10-eq while Case-2 emits 919 tonne PM10-eq. Also here it was expected to be a larger difference between the two cases. Since there is no combustion in the case of hydrogen-electric aircraft it would be reasonable to expect Case-2 to have a higher PMFP. This will also be further discussed in chapter 4.2.1 Discussion. The impact class of PMFP consider particles at 10 micrometres and smaller. In comparison to other assessment methods used it might consider particles at smaller than 2.5 micrometres. This is important to be aware of when comparing results, the PM10 should be higher than PM2.5 since it has a wider consideration.

Photochemical oxidant formation potential (POFP) is a measure of chemical reactions that occur between NO and VOCs. When looking at the results of POFP it was expected that the diagram would show a big difference between the two cases. This is because of the combustion of kerosene that is known as one of the main sources of VOCs. The traditional aircraft, Case-2, have 5 192 tonne NMVOC-eq while Case-1 have 294 tonne NMVOC-eq.

The results regarding metal depletion potential (MDP) is somewhat unexpected. Case-1 has a value of 120 tonne Fe-eq compared to Case-2 with 32 tonne Fe-eq. This can be explained by the fuel cell production that is exceptional for Case-1.



(a) (b)

(c) (d)

(e) (f)

Figure 5: *Results imported from openLCA. Case-1: Hydrogen-electric is coloured in a blue chess pattern while Case-2: Traditional is coloured in an orange striped pattern. Diagram (a) shows the global warming potential relative to kg* CO_2*-eq. (b) ozone depletion relative to kg CFC-11-eq. (c) Human toxicity relative to kg 1.4-DBS-eq. (d) Particulate matter formation relative to kg PM-10-eq. (e) Photochemical matter formation relative to kg NMVOC-eq. (f) Metal depletion relative to kg Fe-eq.*

4.2 Discussion and further work

4.2.1 Discussion

The results show that the hydrogen-electric aircraft is not without emissions either. Although, Case-1 has a lower impact relative to the ReCiPe than Case-2 in all most all categories. So, if the power used for producing the hydrogen comes from renewable resources in addition to using the WE method, the operation of the hydrogen-electric plane can be assumed to have an even lower rate of emission regarding the GWP.

An issue with WE, that's also mentioned in 2.2.1 Water electrolysis, is the scarcity of freshwater resources. This is something that Norway rarely have to consider but it is possible that if we continue to leave the same environmental footprint that we currently do, this can change. It is not so long ago, the spring and summer of 2018, that it was registered high temperatures and a shortage of rain in Norway [Ronald Toppe, 2019]. These two factors caused a shortage of food for livestock and a higher number of forest fires than usual. These events are expected to occur more frequently and become increasingly extreme in the future [Intergovernmental Panel on Climate Change, 2013].

To solve the issue of using freshwater for energy production instead of granting it for people, reverse osmosis can be a solution. The principal structure is a flow of water through a layered web-like membrane structure that removes all impurities. But then again this would cause a higher amount of needed energy and that could cause the hydrogen production to not be beneficial. [Greenlee et al., 2009]

The most likely needed design change for the aircraft frame of the hydrogen-electric solution would cause alterations in emissions regarding the plane's life cycle. There are not many but some test cases of this hydrogen-electric aircraft that shows some minor changes to the design onf the frames, for instance, ZeroAvia in the Orkney Islands [EMEC, 2019]. All though the battery-electric aircraft that is expected to be delivered in 2025 by Heart Aerospace [2020] does not have any major design alterations to its aerodynamic frame. I can not comment on the internal structure or battery placement but it is assumed to have a different structure than the traditional aircraft.

Today's status in aviation is believed to be haltered by the additional investment costs necessary to implement new structures by the airlines and the aircraft producers. Including the protocols regarding testing and certifications needed for new aircrafts. This might be the reason why some of the new innovative minds use the structure of traditional aircrafts since that will shorten the process by an extensively amount. [Smith, 2016] Besides, the DSB in Norway also has to approve of new technologies and that they are safe to implement into our infrastructure. [DSB, 2019]

The system boundary is an important factor when evaluating the results of LCA. In this study, it was set to cut-off at 3 links, shown in Fig. 3 and Fig. 4. That was partially due to shortage of time and some gaps in the database regarding aircraft engines etc. Another piece of information/data that I was not able to find was how SOFC are decommissioned. This is a possible emission that is not taken into account and weakens the study.

Since the total production of the aircraft, the transportation of fuel from production to operation site and the decommission of components was not included then the amount of emissions is not as important as the differences between the two cases. The assumptions mentioned in chapter 3.4 are also essential when comparing and evaluation of the results.

Coming back to the results in Fig. 5a and Fig. 5d it was expected to be a larger difference of the GWP and the PMFP of Case-1 and -2. This was because of the continuous combustion of kerosene during operation in Case-2, and the lack of combustion in Case-1. The reasons for this can be for instance a calculation error, wrong use of the imported database, not correct use of software or a flaw in the software. It cannot be excluded that there is an error in the calculation and incorrect use of the software.

4.2.2 Future research questions

I first thought of the use of hydrogen in aviation for my thesis topic in the Autumn of 2018. After only two short years there have been several publications on the topic of making aviation green by electrifying or finding other fuel options, like hydrogen. For instance, the article written by Collins, McLarty [2020] which was published in May 2020, assesses the possibility of lowering greenhouse gas emissions by suggesting a hybrid hydrogen-battery solution.

As mentioned, there have been many new publications after August 2018. Now, in May 2020, I got my hands on another report about aviation and hydrogen. This is written by McKinsey & Company with funding from the Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU [McKinsey & Company, 2020]. This report has an overall conclusion that states that hydrogen has a promising potential of propulsion fuel in future technology. They also state that the implementation of hydrogen will demands immense research and development, investments costs and adaptation and alteration of regulations. [McKinsey & Company, 2020]

When assessing the results it becomes noticeable that the database used for the Norwegian electrical power mix most likely includes a part of the petroleum production. This is because the emission that is present for Case-1: hydrogen-electric aircraft is almost in every aspect sourced back to the electricity consumption of producing hydrogen. This can be concluded with further research, a sensitivity analysis of source for consumed electricity in hydrogen production.

Also, it would be interesting to see research at which range it would be beneficial to use battery-electric or hydrogen-electric. The hypotheses are that the hydrogen is preferred for the medium- and long-range flights. But at what travel distance does this separation happen. Maybe it is necessary to reevaluate the classes of short-, medium- and long-distance flights.

A few more points of possible further research:

- Whether or not it is beneficial to use salt water for hydrogen production using reverse osmosis when considering the excess needed power.
- Altering the assumptions taken in this thesis.

5 Conclusion

The global emissions in aviation are responsible for 2% of the emissions caused by the transportation sector but are expected to increase to 3-4%. These emissions consist of large amounts of greenhouse gases and are contributing to global warming. The aviation sector will need to be innovative and adjust for alterations that will be needed in the future. A few factors that suspend the transition of green aviation is the costs of implementing new technology and production of other fuel options.

The results from this LCA study can conclude that the hydrogen-electric option in airtravel has less impact on our climate assessed by using the ReCiPe method. The CO_2 emissions are less than half that of the traditional aircraft. In addition to lower Ozone depletion potential, human toxicity potential, particulate matter formation potential and photochemical oxidant formation potential. The only impact class that the hydrogen-electric solution shows higher than the traditional, is regarding metal depletion potential. Also, the lack of decommission data of the solid oxide fuel cell could cause a deviation from these results.

Acknowledgement

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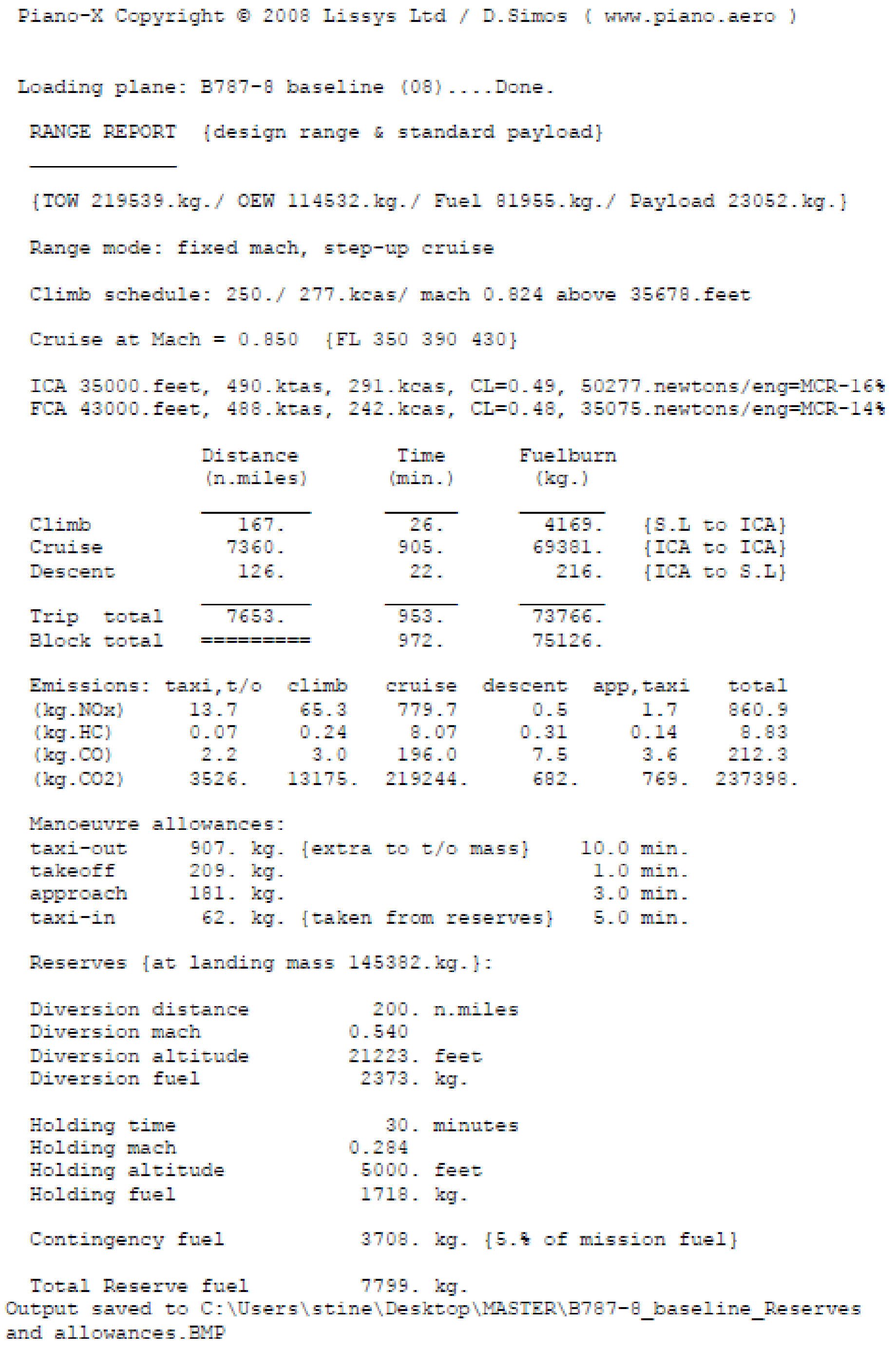
Attachments

Attachment 1



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 Piano-X Copyright © 2008 Lissys Ltd / D.Simos ( www.piano.aero )


 Loading plane: B787-8 baseline (08)....Done.

  RANGE REPORT  {design range & standard payload}
  ____________

  {TOW 219539.kg./ OEW 114532.kg./ Fuel 81955.kg./ Payload 23052.kg.}

  Range mode: fixed mach, step-up cruise

  Climb schedule: 250./ 277.kcas/ mach 0.824 above 35678.feet

  Cruise at Mach = 0.850  {FL 350 390 430}

  ICA 35000.feet, 490.ktas, 291.kcas, CL=0.49, 50277.newtons/eng=MCR-16%
  FCA 43000.feet, 488.ktas, 242.kcas, CL=0.48, 35075.newtons/eng=MCR-14%

              Distance        Time      Fuelburn
              (n.miles)      (min.)      (kg.)
              _________      ______     _______
  Climb           167.         26.        4169.   {S.L to ICA}
  Cruise         7360.        905.       69381.   {ICA to ICA}
  Descent         126.         22.         216.   {ICA to S.L}
              _________      ______     _______
  Trip  total    7653.        953.       73766.
  Block total ==========      972.       75126.

  Emissions: taxi,t/o  climb   cruise  descent  app,taxi   total
  (kg.NOx)     13.7     65.3    779.7     0.5      1.7     860.9
  (kg.HC)      0.07     0.24     8.07    0.31     0.14      8.83
  (kg.CO)       2.2      3.0    196.0     7.5      3.6     212.3
  (kg.CO2)     3526.   13175.  219244.    682.     769.   237398.

  Manoeuvre allowances:
  taxi-out     907. kg. {extra to t/o mass}    10.0 min.
  takeoff      209. kg.                         1.0 min.
  approach     181. kg.                         3.0 min.
  taxi-in       62. kg. {taken from reserves}   5.0 min.

  Reserves {at landing mass 145382.kg.}:

  Diversion distance          200. n.miles
  Diversion mach            0.540
  Diversion altitude        21223. feet
  Diversion fuel             2373. kg.

  Holding time                 30. minutes
  Holding mach              0.284
  Holding altitude           5000. feet
  Holding fuel               1718. kg.

  Contingency fuel           3708. kg. {5.% of mission fuel}

  Total Reserve fuel         7799. kg.
Output saved to C:\Users\stine\Desktop\MASTER\B787-8_baseline_Reserves
and allowances.BMP
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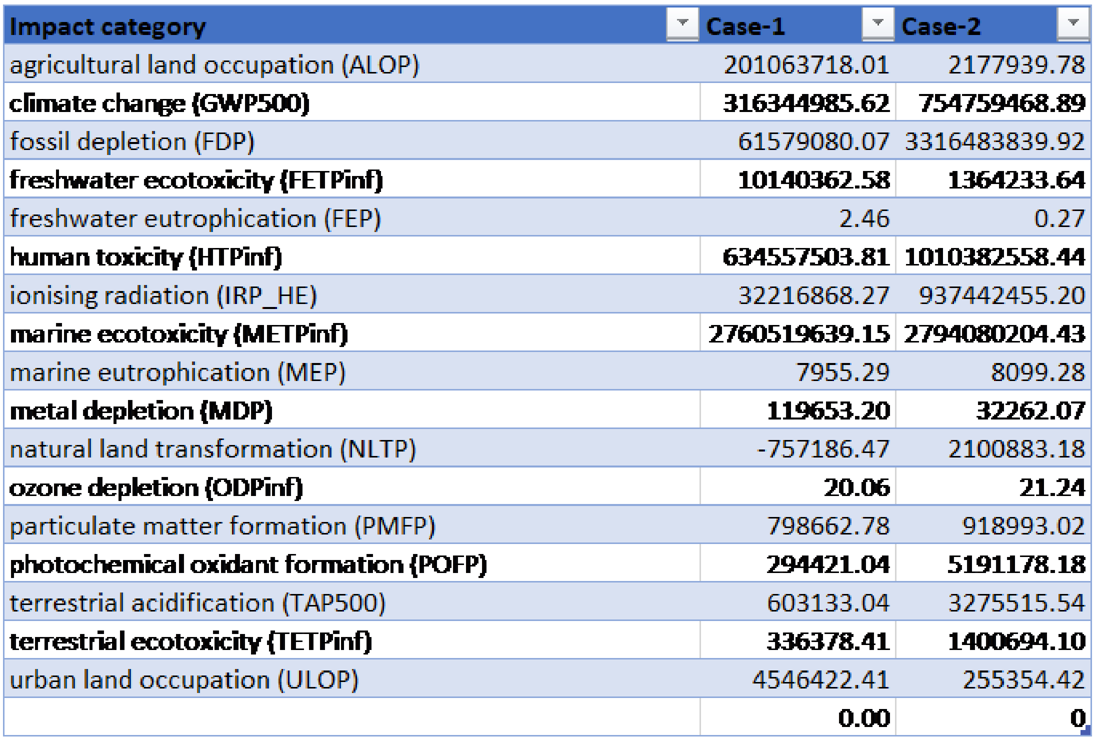
Figure 6: Flight simulation data exported from Piano-X

Attachment 2



Impact category	Case-1	Case-2
agricultural land occupation (ALOP)	201063718.01	2177939.78
climate change (GWP500)	**316344985.62**	**754759468.89**
fossil depletion (FDP)	61579080.07	3316483839.92
freshwater ecotoxicity (FETPinf)	**10140362.58**	**1364233.64**
freshwater eutrophication (FEP)	2.46	0.27
human toxicity (HTPinf)	**634557503.81**	**1010382558.44**
ionising radiation (IRP_HE)	32216868.27	937442455.20
marine ecotoxicity (METPinf)	**2760519639.15**	**2794080204.43**
marine eutrophication (MEP)	7955.29	8099.28
metal depletion (MDP)	**119653.20**	**32262.07**
natural land transformation (NLTP)	-757186.47	2100883.18
ozone depletion (ODPinf)	**20.06**	**21.24**
particulate matter formation (PMFP)	798662.78	918993.02
photochemical oxidant formation (POFP)	**294421.04**	**5191178.18**
terrestrial acidification (TAP500)	603133.04	3275515.54
terrestrial ecotoxicity (TETPinf)	**336378.41**	**1400694.10**
urban land occupation (ULOP)	4546422.41	255354.42
	0.00	**0**

Figure 7: Raw data, exported from openLCA