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The Hydrogen Fuel Pathway for Air Transportation

Author
Li, Guozhen

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The Hydrogen Fuel Pathway for Air Transportation

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GUOZHEN LI

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Approved:

Joan Ogden, Chair

Daniel Sperling

Yueyue Fan

Committee in Charge

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ABSTRACT

This thesis is a preliminary investigation into the technical feasibility and cost effectiveness of a hydrogen-fueled aviation system. A review on hydrogen aircraft reveals that designing and manufacturing hydrogen-powered aircraft is technically feasible. Major hydrogen supply technologies are available, but their capacity is far below the need of a hydrogen aviation system. A large airport such as San Francisco International Airport (SFO) can consume over 3000 metric tons of hydrogen per day, if its air traffic is entirely fueled by hydrogen. Such an energy flow could support over 3 million typical hydrogen fuel cell cars' normal use. Airport liquid hydrogen cost modeling provides an estimation of hydrogen fuel cost as an aviation fuel. The cost is found to be 20%-90% higher than conventional jet fuel on a per energy basis, and supplying liquid hydrogen creates major electric power and land use challenge to the airport. The economies of scale are limited when hydrogen is supplied at an airport level scale, given hydrogen production, liquefaction, delivery, and storage technologies available today. Compared to other alternative aviation fuels (e.g. biofuel and LNG), hydrogen is highly costly but offers huge GHG saving potentials.

Keywords: alternative aviation fuel, hydrogen, airport, zero emission aviation

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1. Introduction

1.1. Motivation

The aviation sector contributes about 2% of global anthropogenic CO_2 emissions, and about 12% of the CO_2 emissions from all transportation sources (ICAO, 2010). Despite this relatively small share in all greenhouse gas (GHG) sources, air traffic is rapidly growing and is projected to grow at an annual rate of 5% at least until 2030 (Airbus, 2007; C. A. Boeing, 2013). Given this fast growth in air traffic, although the efficiency of air transport is constantly improving over time, aviation GHG is still expected to grow in the upcoming decades. The International Civil Aviation Organization (ICAO) projects the amount of CO_2 from aviation to grow at a rate of 3%-4% per year. In addition to the global impacts of GHGs, aviation also affects the local environment by emitting air pollutants and noise.

In response to the fast growing climate impact from aviation, the industry has set targets to mitigate aviation CO_2 emissions. The International Air Transport Association (IATA) targets to achieve (1) 1.5% per year average improvement in fuel efficiency, (2) carbon-neutral growth by 2020, and (3) a reduction in net aviation CO_2 emission of 50% relative to 2005 levels by 2050. A portfolio of strategies for achieving these goals include aircraft technology improvements (e.g. airframe and engine), operational improvements, economic instruments (e.g. market-based carbon cap-and-trade systems), and alternative fuels. Figure 1 shows the United States' action plan for reducing aviation GHG in response to the ICAO goals (FAA, 2015b). It points out that aircraft technology and operational improvements alone, even in an aggressive improvement scenario, are not enough to achieve the industry's targets. Aviation alternative fuels are a key for ensuring GHG reduction from aviation.

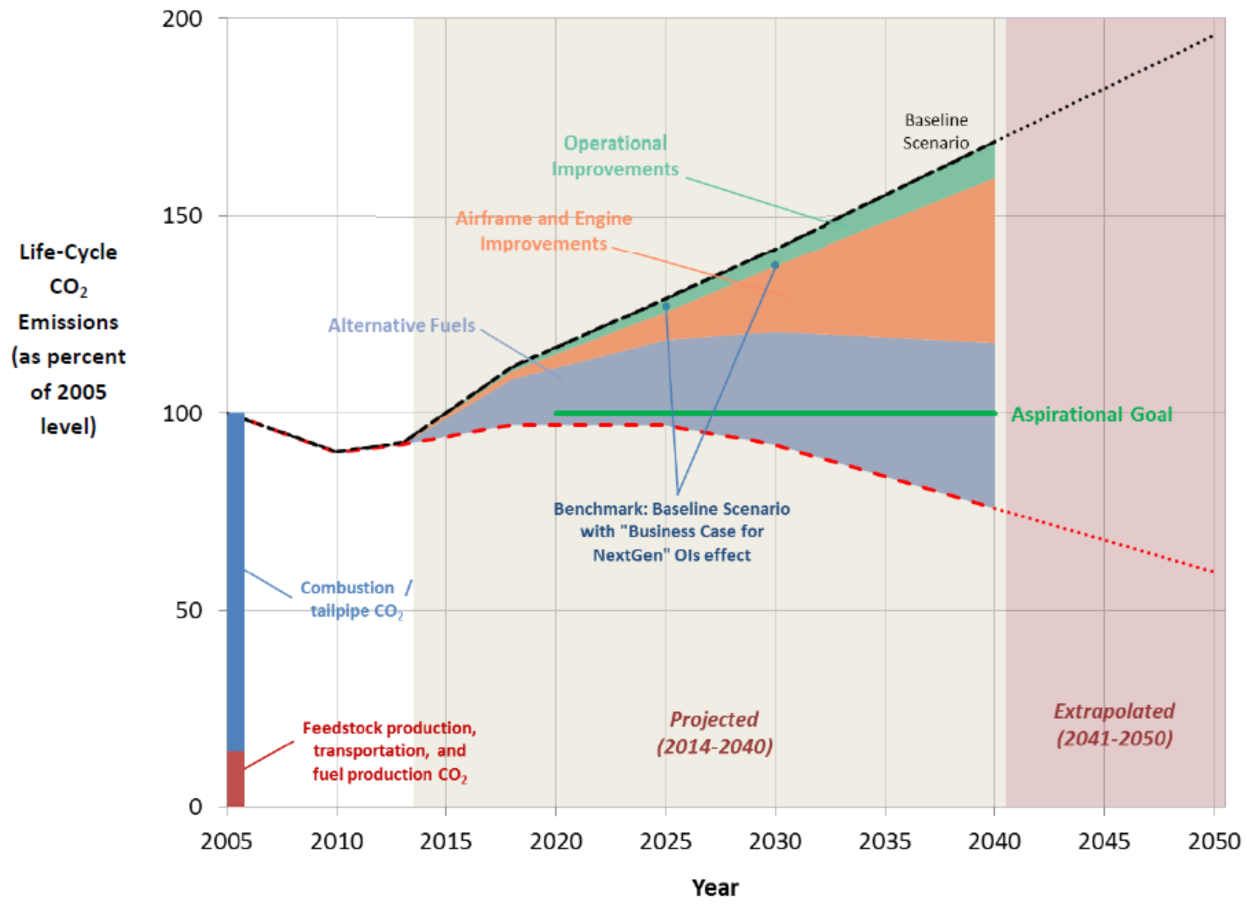


Figure 1 United States projected life-cycle CO_2 emissions impacts - aggressive system improvement scenario (FAA, 2015b)

The aviation industry has relied almost entirely on fossil fuels for over a century since its birth. However, the industry is also seeking alternative fuel options, mainly motivated by three major concerns: (1) uncertainty in future petroleum fuel prices, (2) environmental impacts of burning fossil fuels including emissions of air pollutants and greenhouse gases, and (3) energy security concerns.

Recently, aviation biofuels are emerging in the air transport market, because of their potentials in reducing aviation carbon emission. Fischer–Tropsch synthetic paraffinic kerosene (FT SPK), Hydro-processed esters and fatty acids SPK (HEFA SPK), and synthesized iso-paraffins (SIP) have been approved for commercial use with specified blend limits with kerosene jet fuel (ASTM-International, 2014). Longer-term solutions such as liquefied natural gas (LNG) and liquid hydrogen (LH2) are also under consideration (Bradley & Droney, 2012).

Among all alternative fuel options, LH2 has been recognized as an important candidate for long-term solution. Pioneering aero technology studies indicated LH2 fueled aircraft are technically feasible. However, the infrastructures and supply systems for aviation LH2 fuel are less well understood. First this study reviews the existing efforts in hydrogen aircraft development, and status of large-scale hydrogen infrastructure. Then an engineering/economic model is developed to estimate the costs to provide LH2 fuel for aircraft. After that, hydrogen is compared with other prospective aviation alternative fuels in terms of their economic and environmental benefits and costs.

1.2. Background: features of hydrogen fuel

Hydrogen has the highest specific energy (energy content per mass) among all energy carriers. Liquid hydrogen (LH2) contains 2.78 times as much energy as kerosene jet fuel of equal mass. In terms of volume, however, liquid hydrogen occupies 4 times as much space as kerosene of equal energy content (Table 1 and Figure 2).

Table 1 Energy content of liquid hydrogen and kerosene

	Liquid hydrogen	**Kerosene**	**Ratio (LH2:kerosene)**
Specific energy (MJ/kg)	120	43.1	2.78
Energy density (MJ/L)	8.49	33	0.25

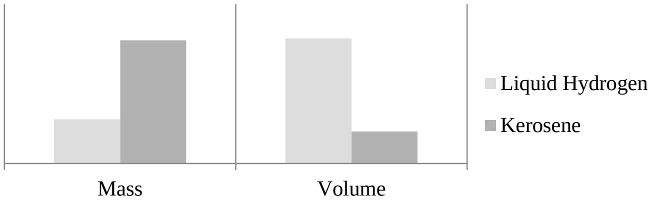


Figure 2 Comparison of mass and volume of LH2 and kerosene with equal energy content

There are three possible ways to store hydrogen: gas, liquid, and metal hydride. Each of them has certain advantages and disadvantages (Table 2), some of which are more critical in aircraft applications.

Table 2 Disadvantages for different hydrogen storage methods

	Gaseous hydrogen (GH2)	**Liquid hydrogen (LH2)**	**Metal hydride**
Weight	Light	Light	Heavy
Volume	Large	Medium	Small
Pressurized vessel	Required	Not required	Not required
Insulated & cryogenic vessel	Not required	Required	Not required

With weight, volume, and cost all taken into account, liquid hydrogen (LH2) is found to be the most suitable way to store hydrogen on-board aircraft, because GH2 poses higher weight and volume penalty when stored at high pressures, and metal hydrides present excessive weight problems (Mital et al., 2006).

The boiling point of hydrogen is 20.28K, which means liquid hydrogen must be stored below 20K (-253°C or -423.67°F) in a cryogenic fuel storage system.

When storing and operating LH2, special attention is needed on three special phenomena:

- **Permeation**: the hydrogen molecule is so small that it can permeate the tank wall. A metal tank wall is preferred to slow down permeation, though it cannot be entirely eliminated.
- **Boil-off**: liquid hydrogen expands rapidly when turned into vapor by ambient heat. This feature of LH2 causes unavoidable fuel loss in the order of 0.5% (mass) per day when in

storage, and up to 5% per event while loading (USDRIVE, 2013). Special treatments (e.g. venting) are also necessary to prevent dangerous pressure buildup in the LH2 tank.

- **Hydrogen embrittlement**: Hydrogen embrittlement is observed in hydrogen storage tanks and transmission pipelines. Various metals become brittle and fracture after exposure to hydrogen, posing a major safety hazard if used on an aircraft. At least two types of preventative measures have been explored in the hydrogen industry: protective coatings and gaseous inhibitors (Raymond, 1988).

Hydrogen is chemically highly interactive, thus has high flammability. Figure 3 illustrates the controllable flame ranges for hydrogen and kerosene. It shows that a hydrogen flame operates at leaner mixtures than a kerosene flame. Leaner burning usually means lower flame temperature, which offers the opportunity to reduce NOx and unburned fuel in the exhaust gas.

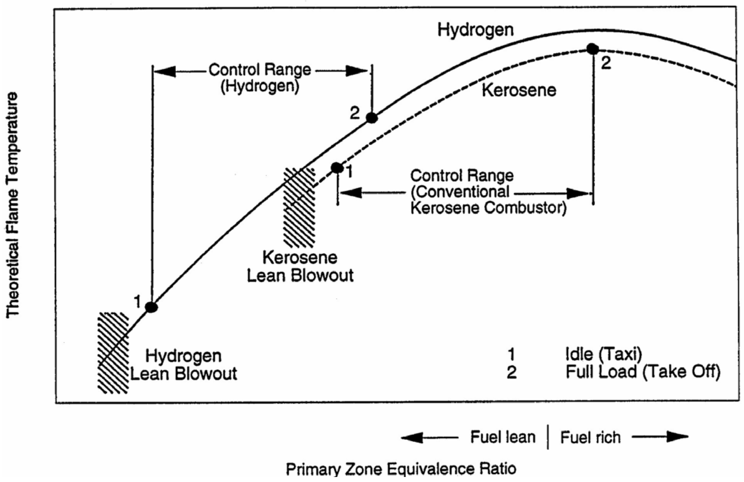


Figure 3 Temperature characteristic of hydrogen vs. kerosene in combustion chamber primiary zone (Ziemann et al., 1998)

2. A Review on Hydrogen Aircraft

2.1. A history of hydrogen aircraft studies

164 published studies on hydrogen aircraft between 1955 and 2013 are reviewed. These studies are listed in Appendix I, and depicted in Figure 4. In this figure each study is represented with a round disk, and labeled with its publication year and author's last name. All of them are lined up in a circle in the order of publication year (starting at 12 o'clock position, and clockwise from 1955 to 2013). The size of a disk represents its number of times being cited within these 164 studies. Each curved line in Figure 4 is a citation between two studies. The color indicates in which region the study was primarily carried out. A number of studies were conducted in joint efforts among various European countries, including Germany, Sweden, United Kingdom, Greece, Italy, and Spain. Most European studies on this topic are related to Airbus and the Cryoplane projects, so no distinguish was made among these European countries and they are uniformly coded as "EU" in blue color. Some other studies are coded as "null" in magenta because their exact regions are unclear.

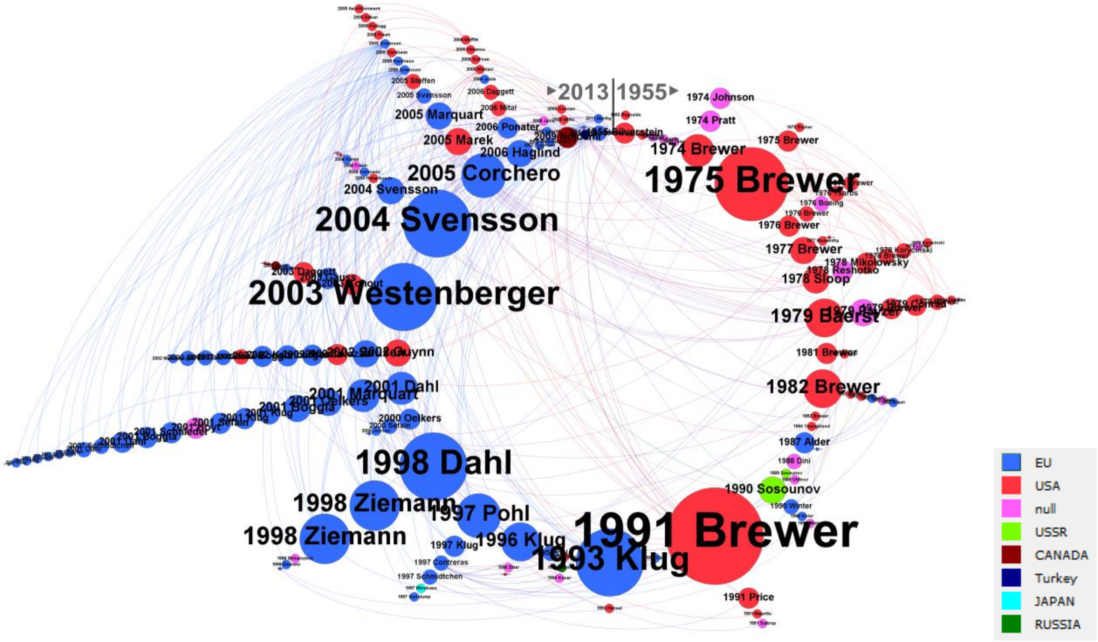


Figure 4 Studies on hydrogen aircraft, 1955-2013

With Figure 4 we may easily spot some of the most influential studies ever done in this area, e.g. the *Study of the application of hydrogen fuel to long-range subsonic transport aircraft* by Brewer (G. D. Brewer, Morris, Lange, & Moore, 1975), the book *Hydrogen Aircraft Technology* (G. D. Brewer, 1991), the 1998 paper *Engine Control And Low-NOx Combustion For Hydrogen Fuelled Aircraft Gas Turbines* (Dahl & Suttrop, 1998), the final report for the Cryoplane Project *Liquid Hydrogen Fuelled Aircraft–System Analysis* (Westenberger, 2003), and *Reduced Environmental Impact By Lowered Cruise Altitude For Liquid Hydrogen-Fuelled Aircraft* (Svensson, Hasselrot, & Moldanova, 2004). These studies received the most citations within the hydrogen aircraft research community, and represent some of the best knowledge and original work in the area.

Figure 4 also reveals some trend in the spatial shift of the interest in hydrogen aircraft studies. From 1950s to 1980s, the USA (mainly led by the NASA and the Lockheed Company) was the dominant contributor to hydrogen aircraft researches. This boom coincides with the 1970s oil crisis, where high oil prices motivated the world to seek alternatives for jet fuel. Efforts in this period included designs of subsonic and supersonic hydrogen-fueled aircraft, and other approaches such as enhancing efficiency with advanced turboprop engines. Later, however, when oil crisis had past, attentions in the US on hydrogen aircraft faded out in the late 1980s. In 1991, Daniel Brewer published his book *Hydrogen Aircraft Technology*, which is a comprehensive summary of past achievements in the area, and marked the end of the era when USA led the world in hydrogen aircraft explorations.

The Soviet Union had some noticeable achievements in the exploration of hydrogen aircraft in the 1980s. They are the first to test-fly a modified TU-154 (renamed TU-155) aircraft (Figure 5) running on hydrogen fuel.

Starting from 1990s, European countries took over the leading role, mostly owing to the Cryoplane Project. This project originally started as “a German-Russian joint project investigating the use of hydrogen in civil aviation" (H. W. Pohl & Malychev, 1997). This project grew larger in the 1990s and 2000s, joining many European countries (Germany, United Kingdom, Sweden, etc.) and Europe-based manufacturers (e.g. Airbus and Daimler-Benz). The Cryoplane Project left the world with a huge treasure by thoroughly investigating almost all aspects of hydrogen-fueled air transportation systems, covering not only the aircraft, but also ground infrastructure and transition scenarios.

In recent years, the US has introduced new prototypes such as hydrogen-powered unmanned aircraft the Boeing Phantom Eye (Figure 6), and the AeroVironment Global Observer (Figure 7). In 2008, Boeing test flew the first fuel cell manned aircraft in Spain (Lapeña-Rey, Mosquera, Bataller, & Ortí, 2010) (Figure 8).

A brief timeline of hydrogen aircraft researches/practices:

- In aeronautics, hydrogen was first used to inflate balloons (as lifting medium), rather than being burned as a fuel.
- The Hindenburg disaster in 1937 ended the heyday of rigid airships, and left a negative image of hydrogen to the public, although it was later revealed that the fatal factor in that accident was the airship's frame and coating rather than hydrogen gas, which rose and dissipated rapidly after catching fire.
- 1970s: the oil crisis led to renewed interest in hydrogen as a fuel. This resulted in a significant research effort from the US in 1970s and 80s on designs of subsonic and supersonic hydrogen aircraft.
- In 1988, the Soviet Union modified a TU-154 (renamed TU-155) and tested it with one engine (of two) running on hydrogen (Figure 5) (H. W. Pohl & Malychev, 1997).
- 1990s: German-Russian joint project on LH2 in civil aviation, known as the CRYOPLANE Project.
- 2000s: European Commission's Cryoplane project.
- 2006-2010: Green Freighter project, led by Hamburg University of Applied Science. It aims to investigate "environmentally friendly and cost effective freighter aircraft with unconventional configuration". (Seeckt, Heinze, & Scholz, 2010)
- 2010s: LH2 powered drones for non-commercial use, e.g. Boeing's Phantom Eye, and AeroViroment's Global Observer.

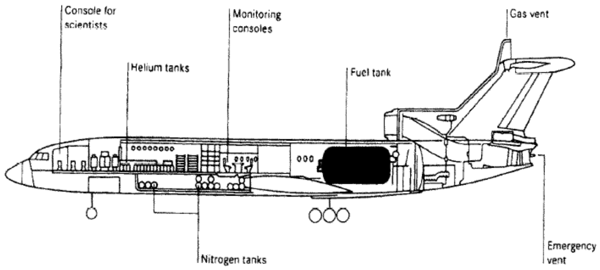


Figure 5 TU-155 experimental aircraft (H. W. Pohl & Malychev, 1997)

Figure 6 Boeing Phantom Eye (NASA, 2013a)

Figure 7 AeroVironment Global Observer (AeroVironment)

Figure 8 Boeing's fuel cell demonstrator airplane

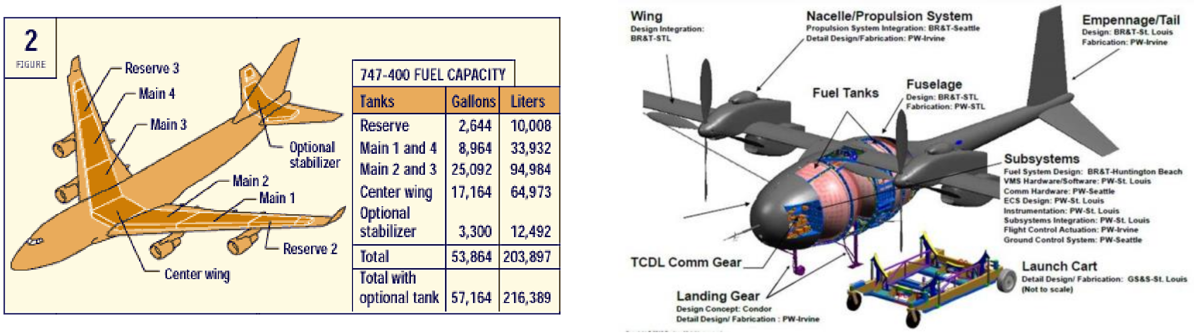
2.2. Technical features of hydrogen aircraft

2.2.1. Overview

Features of the liquid hydrogen fuel require modifications or redesigns of conventional aircraft. First of all, the aircraft configuration needs to accommodate LH2 tanks, which would occupy 4 times as large a volume of jet fuel to carry an equivalent energy content, and have to meet certain geometric requirements. Secondly, the aircraft needs to get propulsion either from modified jet engines or fuel cell and electric motors. Thirdly, the LH2 tank calls for reliable and cost-effective insulation technologies. Finally, an additional heat exchanger system is needed to heat liquid hydrogen to gaseous state before injection to the combustion chambers.

2.2.2. Aircraft configuration

The key challenge in LH2 aircraft configuration is the placement of fuel tanks. Today's commercial airplane typically use wing tanks to store fuel, as shown in Figure 9. However, this configuration cannot be directly transferred to liquid hydrogen aircraft, on one hand due to the extra storage volume required by LH2, and on the other hand because of the high surface area per volume ratio of wing tanks. To store liquid hydrogen, the surface area to volume ratio must be minimized in order to prevent boil-off. A spherical tank would be ideal to minimize this ratio (as applied on Boeing's Phantom Eye, Figure 6), but is spatially less efficient, especially for a space-sensitive application like commercial airplane. In most existing designs of LH2 aircraft, cylindrical tanks (or similar shaped ones) were selected for on-board LH2 storage.



747-400 FUEL CAPACITY

Tanks	Gallons	Liters
Reserve	2,644	10,008
Main 1 and 4	8,964	33,932
Main 2 and 3	25,092	94,984
Center wing	17,164	64,973
Optional stabilizer	3,300	12,492
Total	53,864	203,897
Total with optional tank	57,164	216,389

(a) (b)

Figure 9 (a) Wing fuel tanks (Colella & Zimmer, 2000) and (b) spherical LH2 tanks (Boeing)

Conventional configurations

Throughout decades of studies on hydrogen aircraft, conventional tube-and-wing configuration has been found most appropriate for commercial transport use. Obviously, "there are sound technical reasons why current subsonic aircraft look the way they do." (G. D. Brewer et al., 1975) In the conventional configuration, LH2 aircraft have similar exterior look as a typical jet aircraft. Fuel tanks, however, are placed inside the fuselage space instead of being integrated in the wings.

Under a conventional tube-and-wing configuration, 3 different layouts were found to be promising: (a) aft tank(s); (b) aft & on-top tanks; and (c) fore & aft tanks. See Figure 10.

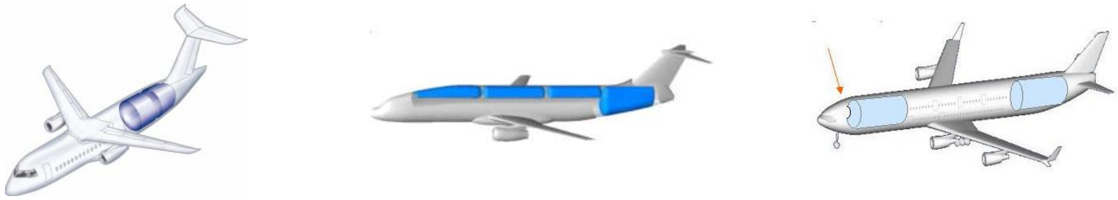

(a) (b) (c)

Figure 10 Conventional configurations for LH2 aircraft (Courtesy: Reference (Westenberger, 2003))

In 1970s, the Lockheed Company (G. D. Brewer et al., 1975) studied a range of configuration concepts (Figure 11), and preferred the configuration with two tanks, one fore and one aft of the double-deck passenger compartment, for its designated mission (Mach 0.85 speed, 400 passengers, 5500 nautical miles range). The USSR TU-155 test airplane used a single aft tank for their experiments (Figure 5). The Cryoplane project explored all three conventional configurations, and recommended different choices of them for different flight missions (Westenberger, 2003). For example, aft tank configuration is suitable for small aircraft such as business jet or regional transporter; aft & on-top tanks are suitable for short/medium range aircraft; and fore & aft tanks are best for long or very long range aircraft.

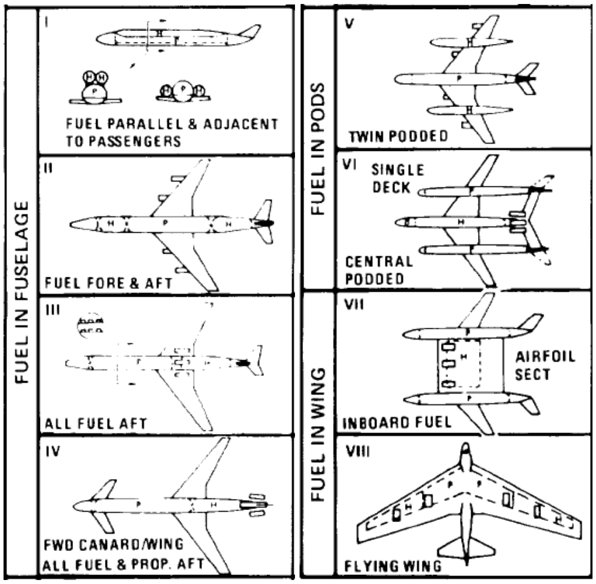


Figure 11 Aircraft configuration concepts studied in Reference (G. D. Brewer et al., 1975)

Table 3 lists comparison of some characters of these configurations.

Table 3 LH2 aircraft configurations

	Aft tanks	**Aft & on-top tanks**	**Fore & aft tanks**
Aircraft center of gravity (CG)	CG travel	-	Two tanks balance each other
Weight and wetted area increase	Medium	Most	Least
Efficiency	-	Less efficient than other two, due to weight and profile drag penalty (Westenberger, 2003)	
Growth potential	Limited by CG travel	OK	OK
Passenger Safety (crash & emergency)	Exposed to fuel on aft end only	Max exposure to fuel	Exposed to fuel on fore and aft ends

Unconventional configurations

In addition to the conventional “tube-and-wing” configurations listed above, some unconventional configurations are also considered as candidates. For example, blended wing body (BWB) configuration “promises significant improvements regarding the structural mass and the aerodynamic efficiency of an aircraft compared to the conventional aircraft configuration.”(Seeckt et al., 2010) With wings and airplane body smoothly blended, this configuration enables the body to take the shape of an airfoil and therefore produce lift. The extra lift results in potential increase in aircraft efficiency and range. The extra space inside the structure also allows deployment of multiple cylindrical tanks (Figure 12).

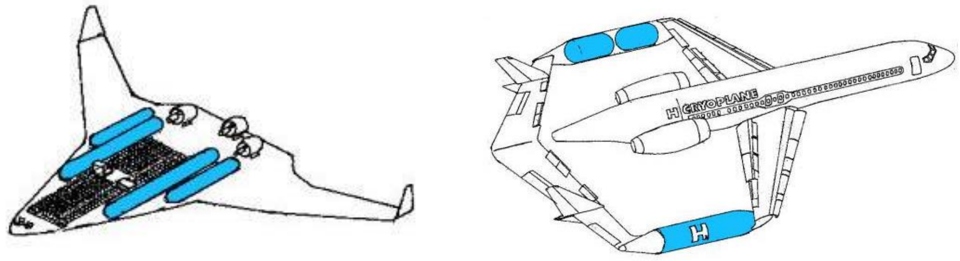


Figure 12 Blended wing body (left) and twin boom configuration (right) (Westenberger, 2003)

A twin boom configuration was also examined in the Cryoplane project, and was claimed to be more promising compared to BWB (Westenberger, 2003). Cylindrical LH2 tanks are placed externally and connected to the airplane through wing structures (Figure 12).

Despite the potentials, however, no significant advantage was found for unconventional configurations over conventional ones. Meanwhile, to take the initial transformation step to a new fuel, the aircraft designers and manufacturers tend to preserve as many as possible proven technologies and features. Therefore, the first hydrogen aircraft are likely to appear similar to commercial aircraft used today.

2.2.3. Propulsion

Hydrogen fuel can be used to generate propulsion in two possible ways: (1) by combusting hydrogen, just like kerosene jet fuel, in a jet engine, and (2) by using a fuel cell to produce electricity, and drive aircraft propeller(s) through electric motor.

Hydrogen jet engine

Various studies (Haglind, Hasselrot, & Singh, 2006; Westenberger, 2003) have confirmed that conventional jet engines (Figure 13) burning hydrogen are “feasible with minimum hardware changes” (Westenberger, 2003).

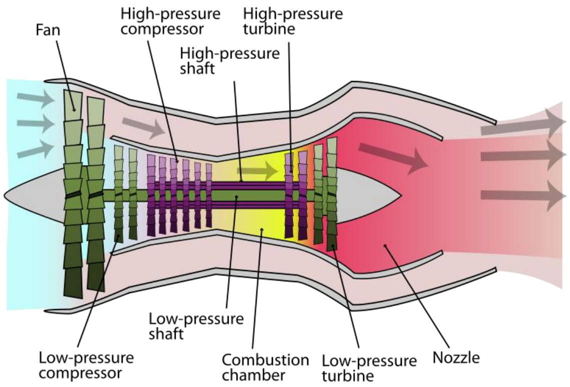


Figure 13 Schematic illustration of a turbofan jet engine (Source: Wikipedia.org/wiki/Turbofan)

The first obvious benefit of a hydrogen jet engine is a reduced fuel consumption rate. Brewer et al (G. D. Brewer et al., 1975) compared the cruise performance of Jet A and LH2 engines (Figure 14). It showed that a LH2 engine only consumes 1/3 to 1/4 of fuel by weight to produce an equal thrust as its jet fuel counterpart. Despite the fuel weight saving, energy consumption saving is less dramatic on a hydrogen jet engine. The Cryoplane Project's study on LH2 propulsion system concludes that hydrogen engine "shows a small benefit in specific energy consumption over kerosene of order up to 3%" (Westenberger, 2003). This study also found that the hydrogen engine runs cooler, with 30-50K lower turbine entering temperature (TET), which is favorable for increasing engine life. Above all, =a hydrogen jet engine is expected to run cooler, consume less kilograms of fuel, and slightly less energy, when producing the same thrust as a conventional jet fuel engine.

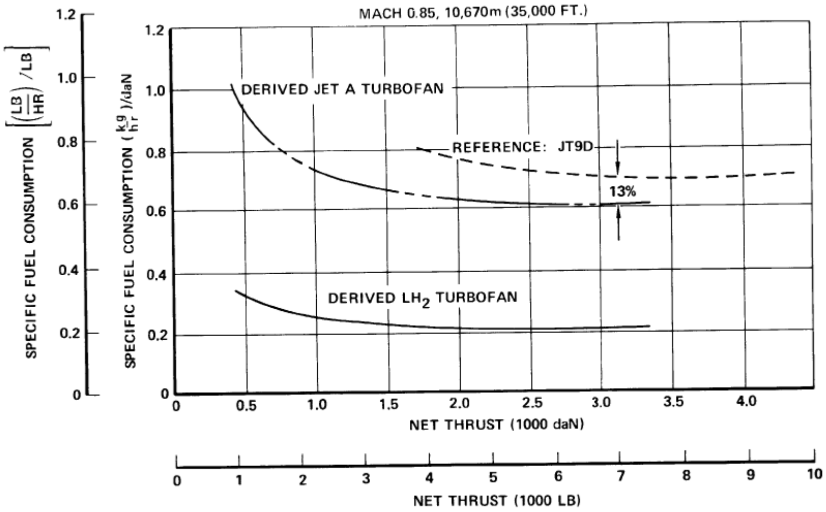


Figure 14 Jet fuel vs hydrogen engine: specific fuel consumption (G. D. Brewer et al., 1975)

Nitrogen oxides (NOx) are the only pollutants emitted by a hydrogen jet engine (Westenberger, 2003). While carbon (CO_2, hydrocarbons) and particle emissions are totally eliminated, NOx emission remains inevitable, because the major source of NOx is the reaction of nitrogen and oxygen in the atmosphere at high temperatures. Although a hydrogen engine still produces NOx, it has a good potential of reducing it because of the combusting properties of hydrogen, e.g. lean burning and low flame temperature as shown in Figure 3. Hydrogen engines are found to reduce NOx formation for the following reasons (Haglind et al., 2006):

- Hydrogen flame is operated at a lower temperature range than jet fuel.
- Hydrogen-and-air reaction happens in a high velocity (8 times faster than kerosene according to Ziemann et al. (Ziemann et al., 1998)), leaving a shorter dwelling time for the hot flame in combustion chamber.
- Hydrogen as a gaseous fuel can mix with air more completely than liquid fuel like kerosene; thus, there is smaller chance to form fuel-rich flame in local conditions, e.g. near fuel drops.

These factors only indicate a potential to reduce NOx emission by burning hydrogen. Actual emission reduction, obviously, is going to vary with specific engine implementations. One major implementation factor is the "mixedness" of hydrogen and air.

To achieve lowest NOx formation, premixing fuel with air before they enter combustion chamber is desirable. In fact, this technique is commonly used in many present utility natural gas turbines (Westenberger, 2003). Though gaseous hydrogen has a greater capacity to mix with air than liquid fuels, this favorable feature is restrained by limited fuel injection points (Haglind et al., 2006). To exploit hydrogen's low-NOx potential, premixing hydrogen with air is "undoubtedly superior" (Haglind et al., 2006). However, given high reactivity of hydrogen, the hydrogen-air premix introduces significant risk of flame flash back, which would damage the combustion system (Westenberger, 2003). In compromise, the non-premix "micro-mix" concept was developed. A micro-mix combustor consists of "a very large number (typically >1000) of very small diffusive flames uniformly distributed across the burner's main cross section", so as to "minimize geometric extension" of each combustion zone (Westenberger, 2003), and consequently achieve hydrogen-air mix completeness. Figure 15 (Dahl & Suttrop, 1998) shows test result of NOx reduction by switching fuel from kerosene (circles) to hydrogen (triangles), and implementing micro-mix (squares). An over 80% NOx reduction was achieved using the hydrogen fuel plus micro-mix technique.

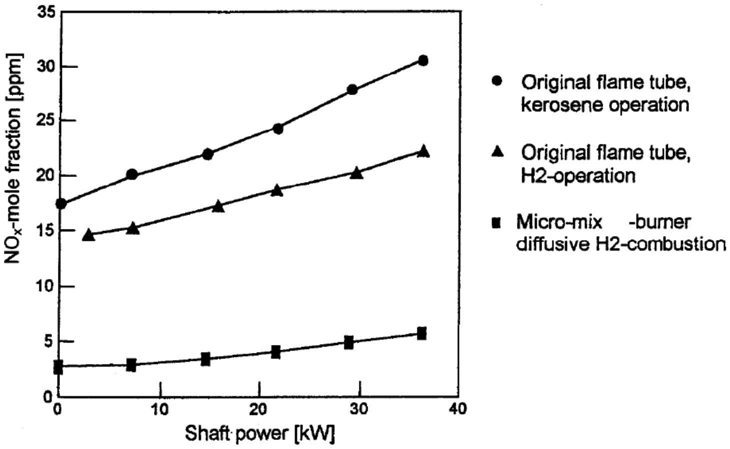


Figure 15 Reduction of NOx emission by converting a KHD T216 gas turbine to micro-mix combustion of hydrogen (Courtesy: Reference (Dahl & Suttrop, 1998))

A heat exchanger would be an additional requirement to support a LH2 jet engine, because liquid hydrogen needs to be heated up to a gaseous state before injected into the combustion chamber. The Cryoplane Project (Westenberger, 2003) studied the heat exchanger solution with the tube wrapped round engine jet pipe (Figure 16). It is shown to be a feasible design with sufficient heat transfer rate and small loss of engine thrust. They weight from 10.7 kg to 33.2 kg per engine. The Cryoplane Project concluded that "the heat exchanger can be designed to have little effect on the engine installation and therefore it is not a technical show stopper for a Cryoplane." (Westenberger, 2003).

Figure 16 Heat exchanger: tube wrapped round engine jet pipe (Westenberger, 2003)

Hydrogen fuel cell engine

Fuel cells have also been studied as an aircraft propulsion source. Fuel cells harvest the chemical energy in hydrogen fuel by converting it to electric currency rather than through combustion. A common type of fuel cell is the proton exchange membrane (PEM) fuel cell (Figure 17). Instead of having hydrogen and oxygen interacting in the form of combustion, the fuel cell splits hydrogen molecule into protons (H^+) and electrons (e-). The protons travel through the PEM to meet the oxides (O^{2-}) and form water (H_2O). The electrons are guided out to form an electrical current, which can be used to produce work, e.g. to power an electric motor that drives a propeller.

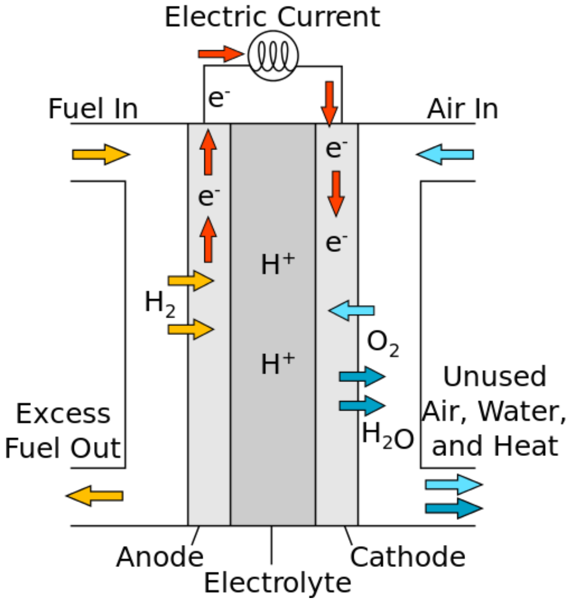


Figure 17 Diagram of a proton exchange membrane (PEM) fuel cell (Mattuci, 2015)

In 2008, Boeing test-flew a small manned airplane, the Fuel Cell Demonstrator in Spain (Figure 8). The demonstrator plane was powered by a PEM fuel cell and a Li-ion battery combined. It used both power sources when climbing and solely the PEM fuel cell when cruising. The fuel cell power plant and hydrogen fuel systems increased the airplane's basic empty weight by 40% (from 560kg to 789kg, (Lapeña-Rey et al., 2010)). Despite the weight increase, this fuel cell demonstrator showed appropriate maneuverability in the flight tests.

Fuel cell aircraft engine has a long way to go before entering commercial use. Fuel cell power plants would also depend on advancement in associated technologies, e.g. light-weight fuel cell and super conductive materials. In initial phase, fuel cell could be used to generate electricity for emergency power system and auxiliary power unit (APU).

2.2.4. LH2 fuel storage

For cost effectiveness, especially in large quantity uses, airborne hydrogen should be stored at a liquid state. Liquid hydrogen only exists at or below 20K (-253°C or -424°F). "Light-weight, durable, and insulated LH2 storage tanks (Khandelwal, Karakurt, Sekaran, Sethi, & Singh, 2013)" are desired for LH2 aircraft.

In 1970s, NASA researches selected two insulation methods (G. Brewer, 1982; G. Brewer et al., 1977): microspheres insulation system, and closed-cell foam insulation system. Both were recommended for experimental development.

The Cryoplane Project examined several types of insulation technologies, including foams, super insulation (customized fabrication), multilayer insulation, and others like powders (Westenberger, 2003). They finally selected multilayer insulation as most appropriate.

In 2013 Reference (Khandelwal et al., 2013) re-examined the LH2 aircraft tank insulation technologies, and identified the 3 most promising types of insulation as: multilayer insulation, vacuum insulation, and foam insulation.

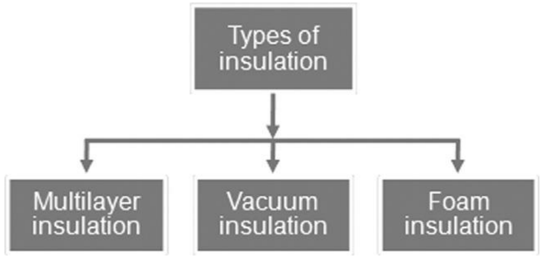


Figure 18 Types of insulation method (Khandelwal et al., 2013)

Multilayer insulation (MLI) uses a number of layers to shield heat flow. Metal foil material and thin insulation material are stacked alternately, to form the multilayer shield. Metal foils are used to reflect radiation heat, and aluminum is commonly used for this. Insulation layers can be made of glass fiber, polyester, etc. They avoid metal-to-metal contact between foils.

The vacuum insulation method uses an inner and an outer tank wall and evacuates the space in between so as to cut off thermal conduction. Venting equipment will be required to attain near-vacuum, and tank structure and material need to stand buckling due to external pressure. “The vacuum insulation technique is adopted in space applications for the storage of LH2. Several research activities have taken place for vacuum insulation and it seems to be a promising solution for a LH2 storage tank. This type of concept is well established but heavier tank walls are required, which are expensive to implement and to maintain the temperature and pressure in the vacuum.” (Khandelwal et al., 2013)

Foam insulation has a similar structure to vacuum insulation, while the space between inner and outer tank wall is filled up with insulation foam rather than evacuated. Compared to vacuum insulation, foam insulation is of lower cost and easier implementation. Besides, for vacuum insulation, loss of vacuum can cause catastrophic failure to the tank, while foam insulation has a lower chance of causing this problem.

Table 4 Cryogenic tank insulation methods

Insulation method	Advantages	Disadvantages/limits
Multilayer		- heavier weight
Vacuum	- effective insulation	- venting equipment needed - expensive - potential of catastrophic failure
Foam	- resistance to catastrophic failure - low cost - light weight	- less effective than vacuum

2.2.5. Hydrogen auxiliary power unit (APU)

In addition to the aircraft's main propulsion, the auxiliary power unit (APU) has also been studied to use hydrogen as fuel. An aircraft APU is commonly a small turbine engine that burns jet fuel. APUs do not provide propulsion, but undertakes some other important tasks such as starting the main engines, running aircraft accessories, and supplying backup electricity.

Fuel cell APUs were proposed in the early 2000s. Their benefits include: reduced APU fuel use, reduced noise, reduced emissions, fewer moving parts, improved reliability, reduced capital costs, and production of clean water for aircraft use (Daggett, Eelman, & Kristiansson, 2003). More recent analysis by the Sandia National Lab (Pratt et al., 2013) finds that "an additional (PEM) fuel cell system on a commercial airplane is technically feasible using current technology." Meanwhile, recovery and onboard use of the heat and water generated by the fuel system bring extra benefit of such a system. However, although the PEM fuel cell is more efficient than currently used gas turbine generators, it has a penalty effect to the overall performance of the aircraft, due to extra weight of the fuel cell system and hydrogen storage.

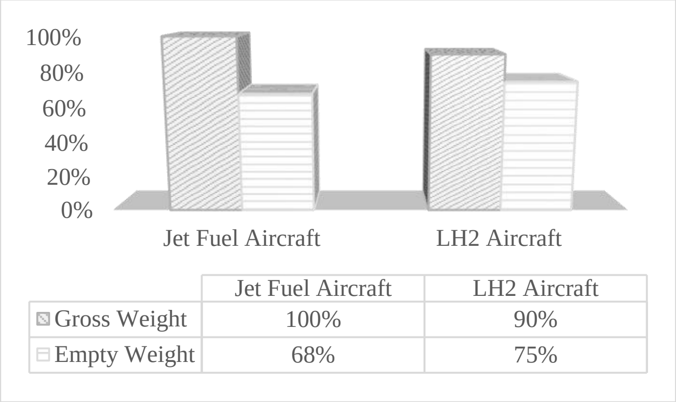
Boeing and Airbus, two major commercial aircraft manufacturers, have both conducted tests of onboard fuel cell APU systems (FuelCellToday, 2012; Morris, 2012). Although fuel cell APUs have not yet been approved for commercial use, they are likely to make the first appearance of hydrogen energy on commercial aircraft.

2.3. Aircraft performance

2.3.1. Weight: larger empty weight but less takeoff weight

Operating empty weight (OEW, aircraft weight excluding usable fuel and the payload) of LH2 aircraft is expected to increase, primarily due to cryogenic tank structures, while the maximum take-off weight (MTOW) is expected to decrease owing to the light weight of hydrogen fuel (Figure 19). The weight saving is larger for larger and longer-range aircraft, where fuel weight takes bigger portion in the aircraft's takeoff weight.

Most studies in the literature agree on this trend. The 1970s design by NASA and Lockheed estimated 27% lower MTOW and 4% lower OEW for LH2 airplane compared to jet fuel airplane designed for the same mission (G. Brewer et al., 1977). The Cryoplane Project's estimated weight change for different categories from small regional to large long-range aircraft. Due to different designs, the weight changes vary: +22% to +48% in OEW, and -15% to +5% in MTOW. The Green Freighter Project's (Seeckt et al., 2010) estimated 7% increase of OEW and 5% decrease of MTOW for hydrogen-fueled regional freighter aircraft.



	Jet Fuel Aircraft	LH2 Aircraft
▨ Gross Weight	100%	90%
▤ Empty Weight	68%	75%

Figure 19 Weight comparison: jet fuel aircraft vs. LH2 aircraft

2.3.2. Energy consumption

Existing studies have different opinions regarding the energy consumption rate of hydrogen aircraft (tank-to-wake energy consumption, i.e. not including energy consumed in producing and preparing hydrogen fuel). The Cryoplane Project estimated cryoplanes to consume 9%-34% more energy per passenger-nautical-mile compared to conventional counterparts (Westenberger, 2003). In contrast, the 1970s NASA and Lockheed studies projected hydrogen aircraft to consume 16% less fuel (G. Brewer et al., 1977). The Green Freighter Project, again, predicted a decreased energy consumption of 10% for hydrogen aircraft (Seeckt et al., 2010).

Weight and fuselage size are the two main factors affecting hydrogen aircraft's energy consumption. On one hand, the hydrogen fuel's lighter weight means less lift is needed to keep the aircraft airborne. This should lead to reduced energy consumption. However, on the other hand, the large volume needed for storing hydrogen worsens the aerodynamics of the fuselage, resulting in more drag and increased energy consumption. Weight saving and extra size may or may not dominate one another, largely depending on actual design of specific aircraft models. Given that no test data from actual prototypes are available currently, it might be more reasonable to assume that hydrogen aircraft is going to consume equal amount of energy on the same mission. In other words, we may assume hydrogen aircraft and conventional aircraft are equally efficient.

2.3.3. Safety

It is broadly agreed (G. Brewer et al., 1977; G. D. Brewer, 1991; G. D. Brewer et al., 1975; Haglind et al., 2006; Khandelwal et al., 2013; Westenberger, 2003) that aircraft using hydrogen fuel will be "at least as safe" as airliners today. Hydrogen aircraft can be even safer in some aspects:

- No fuel seeping into the ground at the airport
- A hydrogen fire is expected to produce less damage than jet a fuel fire, because of hydrogen's "rapid burning rate and low emissivity (radiant heat transfer)." (G. D. Brewer et al., 1975)
- Hydrogen fire may be more survivable for the passengers because it produces less smoke or other noxious products (G. D. Brewer et al., 1975).

- Hydrogen is chemically non-toxic, unlike jet fuel vapor which is a skin irritant and is toxic above 500ppm (G. D. Brewer et al., 1975).
- In case of fuel spill, LH2 evaporates and diffuses rapidly, limiting the existence of flammable fuel/air mixture close to the vehicle. In contrast, a spill of hydrocarbon jet fuel spill presents larger hazard since it stays for longer time and affects larger area (G. D. Brewer et al., 1975). This feature of hydrogen fuel is demonstrated in a fuel leak test performed at University of Miami (Swain, 2001),where hydrogen and gasoline fire was created on a passenger vehicle (Figure 20). It was clearly shown that the hydrogen fire rose quickly into atmosphere, while gasoline, being heavier than air, pooled beneath the car burning down the vehicle from underneath.

Figure 20 Fuel leak and fire test with hydrogen vs. gasoline fuel (Swain, 2001)

Meanwhile, liquid hydrogen fuel poses some unique risks to transportation safety.

- A flammable mixture of hydrogen requires less energy to be ignited than what is needed to ignite a jet fuel flammable mix. Thus, hydrogen fuel leak is more dangers in case of electrical discharges (G. D. Brewer et al., 1975).
- Hydrogen leak is difficult to detect.

3. A Review of Large Scale Liquid Hydrogen Supply Chain Components

A hub airport delivers fuel to aircraft at a rate of millions of gallons a day. For example, in 2012, 869 million gallons of jet fuel were sold at San Francisco International Airport (SFO) (BusinessWire, 2013). This averages to an energy flow of 1.09E+11 MJ/year, or 2.97E+08 MJ/day. To carry this amount of energy, there must be 2.38 million gallons of jet fuel, or 2478 metric tons of liquid hydrogen per day. Assuming a typical hydrogen fuel cell car consumes 1 kg hydrogen per day, the SFO airport's energy flow can support nearly 2.48 million such cars (see Table 5).

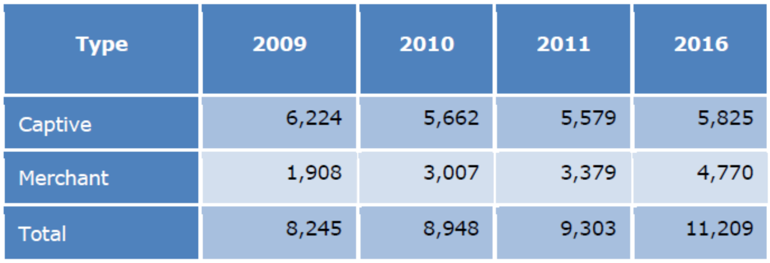
Table 5 Hydrogen demand scale comparison: San Francisco Int'l Airport (SFO) vs. road vehicles

	Amount	**Unit**
SFO 2012 annual jet fuel sale	869	million gallons
Energy flow (annual)	1.09E+11	MJ/year
Energy flow (daily)	2.97E+08	MJ/day
Equivalent H_2 fuel flow	2.48E+06	kgH2/day
Typical H_2 fuel cell vehicle daily consumption	1	kgH2/day
Airport H_2 flow scale (equivalent # road vehicles)	2.48	million

For hydrogen refueling stations planned for ground vehicles, the capacities are typically in the scale of 100-1000 kg/day (Ogden & Nicholas, 2011). In contrast, even to support only a small portion of today's aviation energy use, the hydrogen flow at a single airport would have to be at least several hundreds of metric tons. Compared to typical refueling stations for cars and trucks, airports are truly "extra-large scale stations." In order to supply fuel for the hydrogen aircraft fleet, large scale hydrogen production, delivery, storage, and pumping facilities must also be in place.

3.1. Hydrogen production

The US produces about 9 million metric tons of hydrogen per year (as of 2011) (Joseck, 2012). This amount is nearly enough to support 10 airports, assuming each airport consumes 2500 metric tons of H_2 each day (0.91 million metric tons per year). Considering the hydrogen demand from existing consumers, and the over 30 hub airports in the US, the current hydrogen production capacity is far from enough to fuel a hydrogen aviation system. New production capacity, preferably designated for aviation use, would be needed.



Type	2009	2010	2011	2016
Captive	6,224	5,662	5,579	5,825
Merchant	1,908	3,007	3,379	4,770
Total	8,245	8,948	9,303	11,209

Figure 21 U.S. Hydrogen Production by Merchant & Captive Types 2009-2016 (thousand metric tons) (Joseck, 2012)

Literature (Forsberg, 2007) describes two most suitable, low-net carbon energy sources for large-scale centralized hydrogen production: (1) nuclear energy and (2) fossil energy with carbon dioxide sequestration. Additional hydrogen production options include electrolysis with wind or solar electricity, however these technologies are currently not demonstrated for large scale hydrogen production.

Nuclear power produces heat, which is either converted to electricity for hydrogen production through electrolysis, or directly fed to hydrogen production. (Forsberg, 2007) describes 4 classes of options to utilize nuclear power:

- Traditional electrolysis: electricity + H_2O[liquid] → $H_2 + O_2$
- High-temperature electrolysis: electricity + H_2O[steam] → $H_2 + O_2$

- Hybrid cycles: electricity + heat + $H_2O \rightarrow H_2 + O_2$
- Thermochemical cycles: heat + $H_2O \rightarrow H_2 + O_2$

The electrolysis options are available in near-term, while longer-term options involve using heat in water-hydrogen conversion, which is potentially more efficient and less expensive due to avoided cost of heat-electricity conversion.

Fossil fuels can be processed through steam reforming to produce H_2 and CO_2. In order to achieve low-carbon fuel, the CO_2 byproduct must be captured and sequestrated. “There are very large economics of scale associated with steam reforming and carbon dioxide sequestration.” (Forsberg, 2007).

3.2. Hydrogen liquefaction

Hydrogen liquefaction is a multistage process. Figure 22 shows a typical liquefaction sequence for hydrogen. Room temperature (300K) pure hydrogen gas is firstly compressed to high pressure (e.g. 100 atm). This high pressure gas is cooled partially by nitrogen vapor and partially by hydrogen vapor in heat exchangers (HE_1 and HE_2) to a lower temperature, e.g. 85K. The nitrogen and hydrogen vapors are drawn from a liquid nitrogen tank and the liquid hydrogen product tank respectively. The initially-cooled hydrogen then goes through HE_3 to be further cooled by liquid nitrogen. Then the hydrogen gas reaches the 4th heat exchanger where it meets hydrogen vapor from liquid hydrogen tank again to be cooled to an even lower temperature. In the final step, gaseous hydrogen is liquefied in the Joule-Thomson valve (the “⋈” symbol in Figure 22), where Joule-Thomson expansion brings temperature down to condensation.

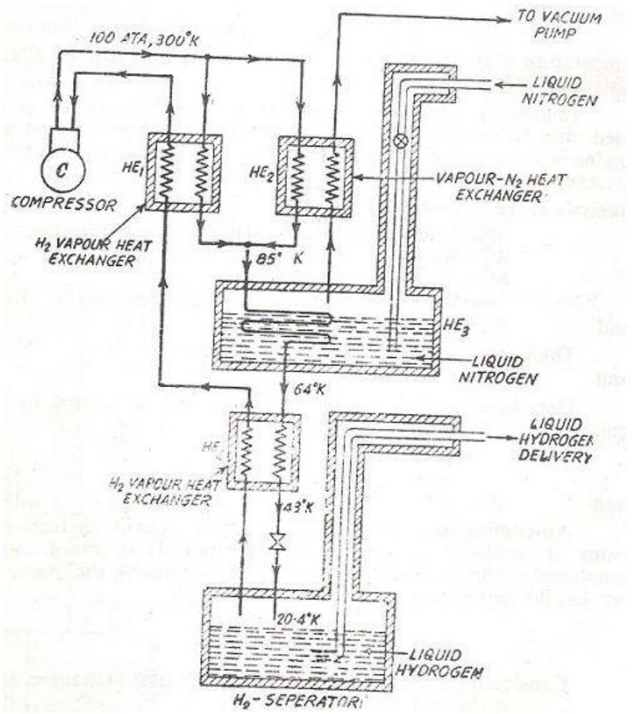
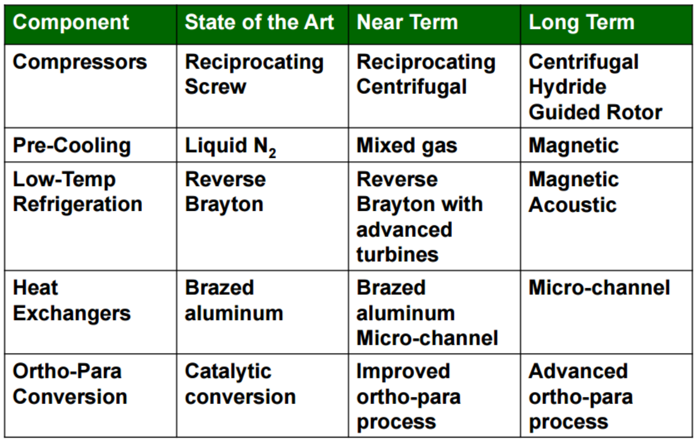


Figure 22 Hydrogen liquefaction process (Arora & Domkundwar, 1995)

Hydrogen liquefaction is an energy-intensive process. The minimum theoretical energy to liquefy hydrogen from ambient (300 K, 1.01 bar) conditions is 3.9 kWh/kg LH2 (Gardiner, 2009). In practice, actual liquefaction energy requirements are substantially higher, typically 12-15 kWh electricity per kg of LH2 (2013 status) (USDRIVE, 2013). Future large scale plants may bring the energy consumption down to 11 kWh/kgLH2 (US DOE 2020 target) (DOE, 2015). Novel liquefaction methods such as magnetic or acoustic liquefaction may require as little as 7 kWh/kgLH2 (Gardiner, 2009; USDRIVE, 2013). US DOE's ultimate goal is to bring the energy consumption down to 6kWh/kgLH2 (DOE, 2015).

Table 6 Hydrogen liquefaction components state-of-the-art and outlook by Praxair (Schwartz, 2011)



Component	State of the Art	Near Term	Long Term
Compressors	Reciprocating Screw	Reciprocating Centrifugal	Centrifugal Hydride Guided Rotor
Pre-Cooling	Liquid N_2	Mixed gas	Magnetic
Low-Temp Refrigeration	Reverse Brayton	Reverse Brayton with advanced turbines	Magnetic Acoustic
Heat Exchangers	Brazed aluminum	Brazed aluminum Micro-channel	Micro-channel
Ortho-Para Conversion	Catalytic conversion	Improved ortho-para process	Advanced ortho-para process

Currently in the US, hydrogen liquefaction is mainly motivated by hydrogen delivery needs. Over 90% of merchant hydrogen is transported in liquid form, which is the most economical means of truck transport for large market demands (>100 kg/day) and for distances greater than ~300 km. There are 10 liquefaction plants as of 2009 in North America, each varying in capacity from 5,400–32,000 kg/day (DOE, 2015).

3.3. Hydrogen delivery

Hydrogen delivery is potentially needed when hydrogen is produced off-site the airport. This type of point-to-point (central plant to airport) delivery is a typical "transmission" case as studied by (Yang & Ogden, 2007), in contrast to the "distribution" case where hydrogen is delivered from a central location to sparsely distributed dispensing points (e.g. car refueling stations).

(Yang & Ogden, 2007) compared 3 transmission mode options, (1) compressed gas H_2 truck, (2) LH2 truck, and (3) gaseous H_2 pipeline, for various hydrogen flow rate and transmission distance scenarios (Figure 23). Although it does not cover the flow rate as high thousands of metric tons per day, the trend implies pipeline to be the most suitable option for high flow rates.

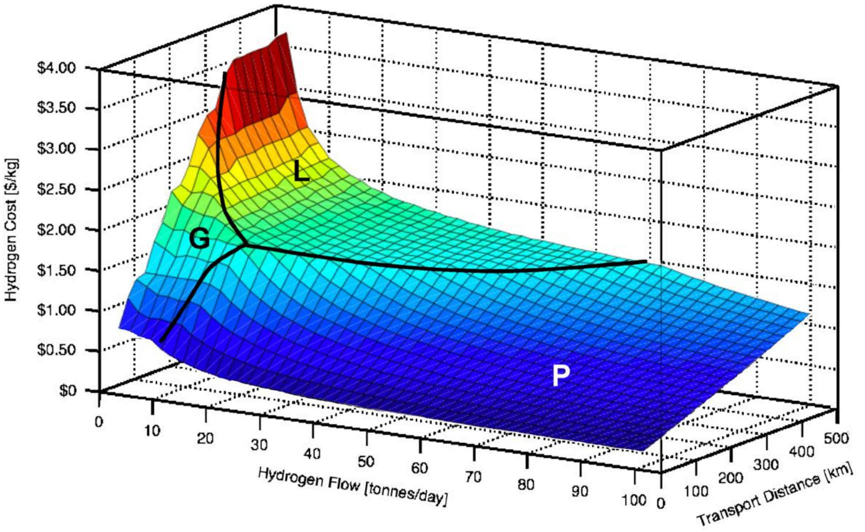


Figure 23 Minimum hydrogen transmission costs as a function of H_2 flow and transport distance (Yang & Ogden, 2007)
G = compressed gas H_2 truck, L = liquid H_2 truck, P = H_2 pipeline

3.4. Liquid hydrogen storage

In order to ensure reliable fuel supply, airports usually store fuel that can sustain at least 3 days' normal consumption. For a hydrogen airport to meet the same standard, large scale hydrogen storage must be installed.

At large scales, liquid hydrogen vessels are shown to be the most practical and low-cost form of storage, compared to compressed gas vessels and cryogenic pressure vessels (Klebanoff, 2012). NASA's decades-long space exploration experience has provided mature technologies for storing LH2 in large quantity. For example, the two LH2 storage tanks located at Kennedy Space Center's launch pads 39A and 39B each has a capacity of 850,000 gallons of LH2 (227,970 kg) (NASA, 2013b). These tanks are essentially vacuum bottles, consisting two spherical flask structures with the gap in between vacuumed. This technology is the most likely to be applied in an aviation fuel system.

3.5. Liquid hydrogen pumping

Another key component of LH2 infrastructure is its pumping. Uses of LH2 pumps include delivering LH2 into storage tanks, distributing LH2 to aircraft, refueling aircraft, and recycling unused LH2. The pumps' flow rate capacity is a key parameter of their performance.

The ACD Cryo Company (ACDCryo, 2011a) produces pumps that can pump LH2 at flow rates up to 35.8 gallons per minute (ACDCryo, 2011b, 2011c), which is equivalent to a mass flow rate of 569 kg/hr.

Lawrence Livermore National Lab (LLNL) and Linde is in their process of developing a high pressure LH2 pump system aimed for cryogenic pressure LH2 vessels. The pump aims to take low pressure LH2 (near atmospheric), and delivers it at high pressure (up to 875 bar), high density (>80 g/L), and flow rate of 100 kg/hr (Aceves et al., 2012). As of 2014, their experiments have achieved target flow rate of 100kg/hr, but only reached a delivery pressure level of 350 bar (Aceves, Berry, Espinosa-Loza, Petitpas, & Switzer, 2014).

Reference (Kajikawa & Nakamura, 2009) proposed a LH2 pump design that utilizes MgB_2 wires to replace copper winding in a traditional motor. MgB_2 can reach a superconducting state (zero resistivity to electric current) at the LH2 temperature. This character enables the MgB_2 winding pump to decrease power consumption "by about two orders of magnitude" compared to copper winding at the same operating state (Kajikawa & Nakamura, 2009).

3.6. Review summary

From the review of existing hydrogen system technologies we may find that all the major components for supporting a hydrogen aviation fuel system are technically available today. The industry has abundant experience in producing, liquefying, delivering, storing, and pumping LH2 in fairly large amounts. Many mature technologies can be readily applied in aviation fuel supply.

However, the demand for LH2 in a hydrogen aviation system still dramatically exceeds any application of hydrogen that exists today. Capacity is a major barrier in the cases of all the components. There are significant gaps in understanding and demonstrating the extra-large-scale facilities desired for LH2 aviation fuel supply.

4. Modeling Hydrogen Cost at an Airport

4.1. Methodology

4.1.1. LH2 Demand Scenarios

To estimate the amount of hydrogen needed for an airport application, we use the historical jet fuel usage at San Francisco International Airport (SFO) as a point of reference. This airport is the 7th busiest airport in terms of passenger enplanements in 2014 (ACI-NA, 2015). In 2014 it contributed 22.8 million enplanements, which makes 3.1% of all enplanements from all the 509 commercial service airports in the US (FAA, 2014). It is one of the most important hub airports on US west coast. It serves as a hub for two major domestic airlines United Airlines and Virgin America, Inc., and an international gateway for the US. Business Wire (BusinessWire, 2010, 2011, 2012, 2013, 2014) indicates that SFO's jet fuel sale grew from 810 million US gallons in 2009 to 892 million gallons in 2013 (Figure 24). Meanwhile, SFO's Air Traffic Statistics (SFO, 2015) show a passenger activity increase from 37.5 million in 2009 to 45.0 million in 2013 (Figure 24). With these data, we can derive a simplified regression model to predict fuel usage from the airport's passenger traffic, as shown in Equation 1.

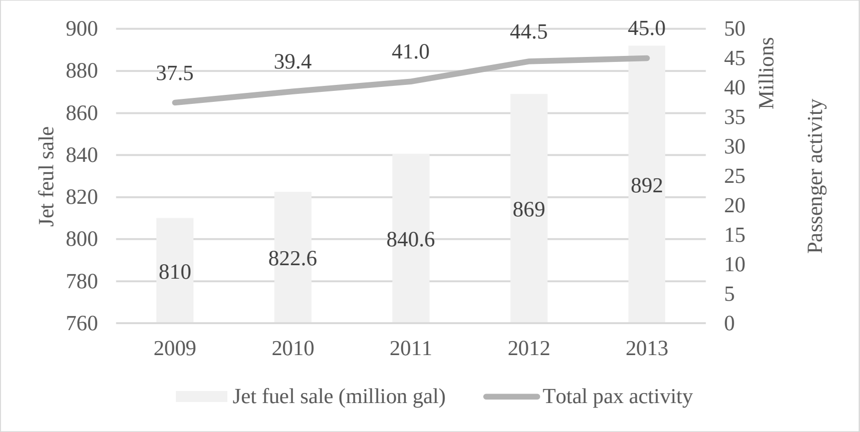


Figure 24 SFO fuel sale vs. passenger activity 2009-2013

Equation 1 Regression model to predict jet fuel usage from passenger activity

$$Fuel = 1.013 \times 10^{-5}\ Pax + 426.9$$

Fuel = annual jet fuel consumption, million gallons/year

Pax = passenger activity, passengers/year

The San Francisco Bay Area's Regional Airport Planning Committee (RAPC) forecasts SFO's annual passenger activity in 2035 to be 64.4 million passengers in its base scenario (RAPC, 2011). A low scenario forecasts 56.0 million passengers per year, and a high scenario forecasts 80.4 million passengers per year. Based on the passenger traffic forecasts, we define the respective fuel demand scenarios using Equation 1, as shown in Table 7.

Table 7 LH2 Demand Scenarios

Scenario	**Passenger activity (million/year)**	**Jet fuel demand (million gallon/year)**	**Energy consumption (million GJ/year)**	**Equivalent LH2 demand (metric ton/day)**
Low	56.0	933.9	132.8	3034.1
Base	64.4	1079	144.2	3293.8
High	80.4	1241	165.8	3788.4

The jet fuel demand is then converted to equivalent LH2 based on equal energy content. The jet fuel energy density adopts Jet A fuel specifications (energy density 35.3MJ/L) because it is the fuel type sold at SFO (FAA, 2015a). In conversion of this energy demand into equivalent LH2, we make the assumption that LH2 aircraft are of equal efficiency as jet fuel counterparts, which means both type of aircraft will consume same amount of energy when carrying out the same task. In fact, from existing studies on hydrogen aircraft we saw estimates of their fuel efficiency (measured on energy consumption per passenger distance) ranging from 9-34% poorer (Westenberger, 2003) to 16% better (G. Brewer et al., 1977). To simplify the case we choose to assume they are equally efficient. Provided that this study is aimed to assess the order of scale of a hydrogen aviation system, this assumption is justified for the purpose. In addition, the scenarios are established on a hypothetical case where in the 2035 time horizon all aircraft served at SFO are hydrogen aircraft. Although this study uses SFO as a basis for analysis, conditions such as feedstock prices, electricity prices, and land costs are based on US average, instead of local characteristics in the San Francisco area.

4.1.2. Hydrogen Production Cost Estimation Methods

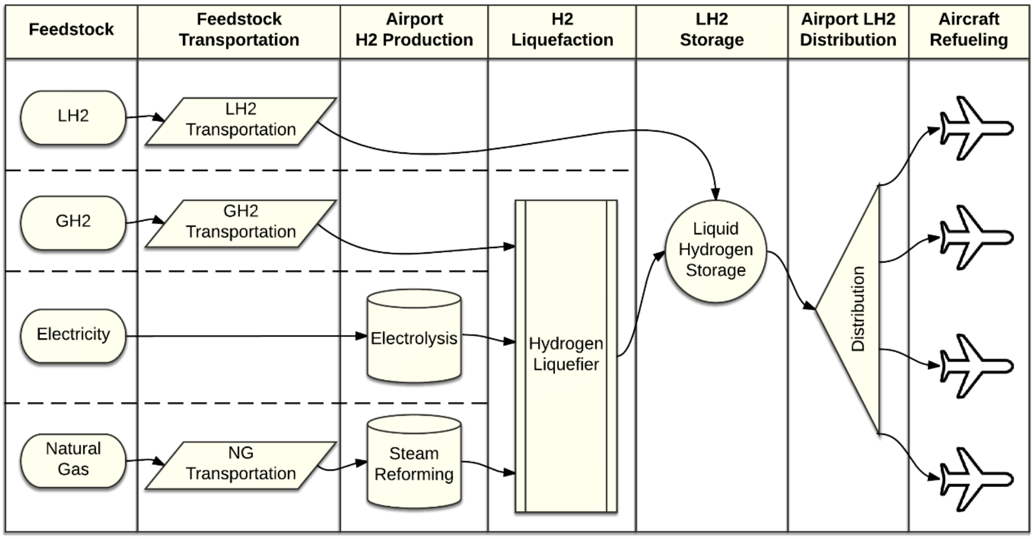


Figure 25 LH2 supplying infrastructure scheme for an airport.

Modern airports receive their fuel supply via a variety of pathways. The most common one is a pipeline directly connecting oil refinery and airport fuel storage. Other modes such as rail, truck, and/or barge are also used depending on local conditions.

Several options are available for airport LH2 supply (Figure 25). An essential design consideration is whether hydrogen is readily available at the boundary of the airport, and if it is, in what state (i.e. gas or liquid).

(1) If hydrogen is transported to the airport in liquid state, there will be no need for large scale liquefaction plant on-site the airport. A small scale hydrogen liquefaction facility is still necessary because vented hydrogen from the storage and distribution systems needs to be recycled and re-liquefied.

(2) If hydrogen is available at the airport boundary in the gaseous state, then the airport must be equipped with a liquefaction plant with enough capacity to meet the aircraft's energy demand.

(3) If no hydrogen is available at the airport boundary, hydrogen must be produced on-site. The feedstock for hydrogen production can either be electricity (for electrolysis), or natural gas (for steam methane reforming, SMR).

In this study, we analyze the cases where the airport has no readily available hydrogen supply at its boundary, and it must develop hydrogen production on its own. This condition is selected because such large scale hydrogen production as over 3000 metric tons per day truly does not exist today. By assuming everything on-site at the airport, the problem is simplified by reducing the uncertainties involving location selection, transportation mode selection, etc.

Two methods of hydrogen production are considered: (1) steam methane reforming (SMR) with carbon capture and sequestration, and (2) electrolysis using grid electricity. Both these two methods are technically available and have the potential to produce hydrogen with low or zero carbon emissions. Though there exist other technologies that are potentially suitable for central production of hydrogen, e.g. thermochemical, biochemical, and photolytic processes, they display less maturity or cost-effectiveness compared to SMR and electrolysis; therefore they are not considered in this study.

We use the US Department of Energy's Hydrogen Analysis (H2A) Central Hydrogen Production Model Version 3 (Steward, Ramsden, & Zuboy, 2012) for calculations of hydrogen production cost. The H2A Central Production Model is an integrated, spreadsheet-based model that calculates hydrogen production cost according to technical operating parameters, feedstock, utility, and capital cost specifications.

4.1.3. Hydrogen Liquefaction, Storage, and Distribution Cost Estimation Methods

After hydrogen is produced from the production procedure as described in the above section, it then proceeds to the liquefaction plant, followed by storage and distribution to aircraft terminals.

Hydrogen liquefaction, storage and distribution costs are calculated using the 'Pure LH2 Truck Terminal' subsection of H2A Delivery Components Model V2.0. This spreadsheet-based model was originally developed for a LH2 truck terminal, which consists of a central hydrogen liquefaction and storage facility, and where bulk storage of LH2 is dispensed to delivery trucks for transport to hydrogen refueling stations. Although the hydrogen flow rate at an airport is typically much higher (10^2-$10^5\times$) than a delivery truck terminal, the operating components, e.g. liquefier, storage tanks, and pumping facilities, are essentially the same. Therefore, in this study, we scale up a LH2 truck terminal to match airport demand, so as to model an airport's hydrogen processing.

Hydrogen liquefiers considered in this study have a maximum liquefaction capacity of 200,000 kg/day each (Ringer & Sozinova, 2010). When demand exceeds a single liquefier's capacity, multiple liquefiers are used in parallel to meet demands. For each liquefier, it is assumed that producing each kg of LH2 consumes 12kWh electricity, which is equivalent to 36% of energy content in that kg of LH2 product.

The IATA Guidance on Airport Fuel Storage Capacity (IATA, 2008) suggests that airports usually need to keep at least 3 days' fuel demand in storage. In practice, airports usually store more than 3 days' fuel for reliability and redundancy. In this study we choose to have 5 days' fuel storage so as to accommodate fuel supply & demand fluctuations such as hydrogen plant outage, summer fuel demand surge, and fuel quality control processes.

LH2 storage is achieved with vacuum jacketed spherical tanks, each with a maximum capacity of 3500m^3 (~248,000 kg LH2). These tanks are 19 meters in diameter. Each of these tanks can provide equivalent energy to fill maximum fuel capacity for 3.5 Boeing 747-8's, or 32 Boeing 737-900's. H2A uses Equation 2, which represents US DOT's knowledge of industry experience, to determine the capital cost of each tank. Multiple such tanks would be installed in parallel to accommodate storage needs.

Equation 2 LH2 storage tank cost

$$TankCost\ (2005US\$) = -0.168(capacity)^2 + 2064.6(capacity) + 977886$$

$* \ capacity\ in\ m^3$

The LH2 pumping cost is mainly dependent on fuel demand and refueling time requirements. In H2A, each pump unit has a maximum capacity of 250kg/hr. Multiple pump units are installed in parallel to meet higher LH2 flows.

Table 8 summaries the main parameters concerning airport hydrogen liquefaction, storage, and pumping facilities.

Table 8 Main parameters concerning airport hydrogen liquefaction, storage, and pumping facilities

Item	Amount	Reference
Liquefier capacity	200,000 kg/day	H2A default
Liquefaction electricity consumption	12 kWh/kgH2	Assumption based on industry experience
Fuel storage volume	Average daily demand ×5	IATA guidance (IATA, 2008)
Fuel tank capacity	Up to 3500 m^3	H2A default
Fuel tank cost	Equation 2	H2A default
LH2 pump capacity	250 kg/hr	H2A default

4.1.4. Feedstock and Utility Costs

The major feedstock and utility for supplying hydrogen are natural gas (NG) and electricity.

In the case of producing hydrogen through SMR, the price for industrial natural gas is set to be $4.97/MMBtu, which is the default in the H2A model. This price lies in the lower side of U.S. Energy Information Administration's (US EIA) projected industrial natural gas price for 2014-2040 (EIA, 2014) (see Figure 26).

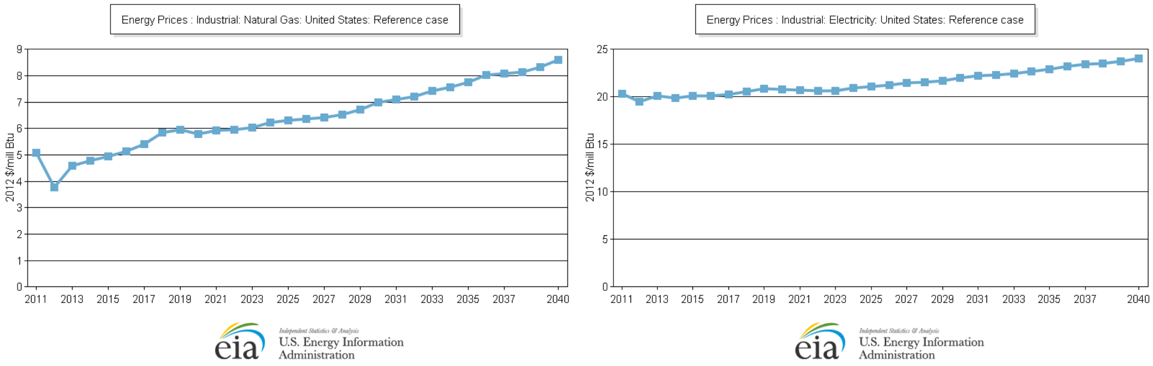


Figure 26 Industrial natural gas and electricity prices projected by US EIA.

The electricity price is assumed to be $0.06/kWh, which is equivalent to $17.6/MMBtu in 2005 US dollars, or $20.7/MMBtu in 2012 US dollars. This price agrees well with industrial electricity prices projected by US EIA (EIA, 2014) (Figure 26).

Feedstock and utility requirements (Steward et al., 2012) for producing H_2 are listed below:

- SMR method requires 0.165MMBtu of NG and 0.569kWh electricity for each kg of H_2 product
- Electrolysis requires no NG but 44.7kWh electricity for each kg of H_2 product

4.2. Cost Modeling Results

4.2.1. LH2 Cost Dispensed to Aircraft

The LH2 cost dispensed to the aircraft includes: (1) feedstock and utility cost to produce hydrogen (from SMR or electrolysis); (2) cost for building and operating the hydrogen production plant; (3) cost for building and operating the hydrogen liquefaction plant; (4) cost for building and operating the LH2 storage facilities; and (5) cost for pumping LH2 to move around the system (e.g. between liquefier and storage, and from storage to dispensing sites). Estimation results are listed in Table 9.

Table 9 Dispensed LH2 Costs in Different Demand Scenarios (USD₂₀₀₅/kgLH2)

Scenario	**Cost (dispensed to aircraft)**	
	From SMR	From electrolysis
Low traffic	$3.05	$4.74
Base traffic	$3.03	$4.74
High traffic	$3.04	$4.75

4.2.2. Hydrogen Production Cost Breakdown

Production from SMR

H2 production from SMR costs about $1.21 per kg H_2 produced. Figure 27 shows breakdown of this cost. Feedstock cost ($0.84/kgH2) makes the largest contribution (~70%) to SMR production cost. Following feedstock cost are capital cost and utility cost, each contributing about 10% to total SMR production cost. Carbon sequestration adds another $0.1/kgH2. O&M cost makes the rest about 1% of total SMR production cost.

The SMR production pathway does not demonstrate significant economies of scale in the scale range studied. Feedstock, utility, and carbon sequestration remain proportional to production volume. The capital cost shows a slight reduction of $0.01/kgH2 when upscaling from base to high traffic scenario.

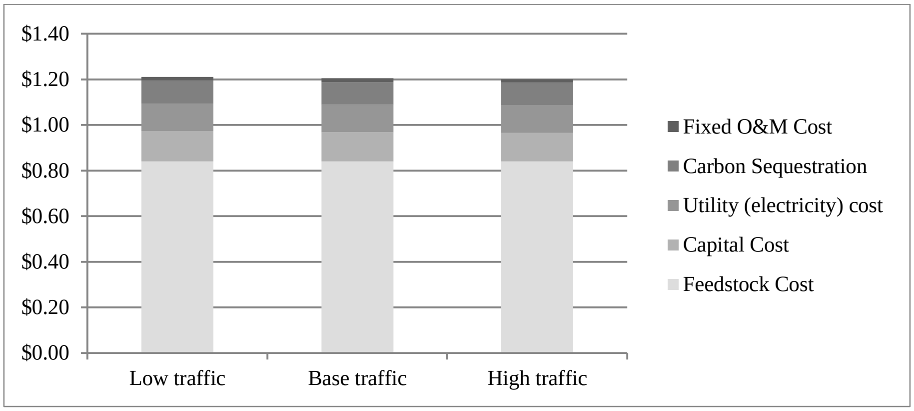


Figure 27 Levelized cost of H_2 production from SMR (USD_{2005}/kgLH2).

Production from Electrolysis

Producing H_2 from electrolysis costs are higher. Each kg of H_2 costs \$2.90. Electricity makes the largest contribution (96%) to the total cost. The rest are capital cost and operation & management cost. (Figure 28)

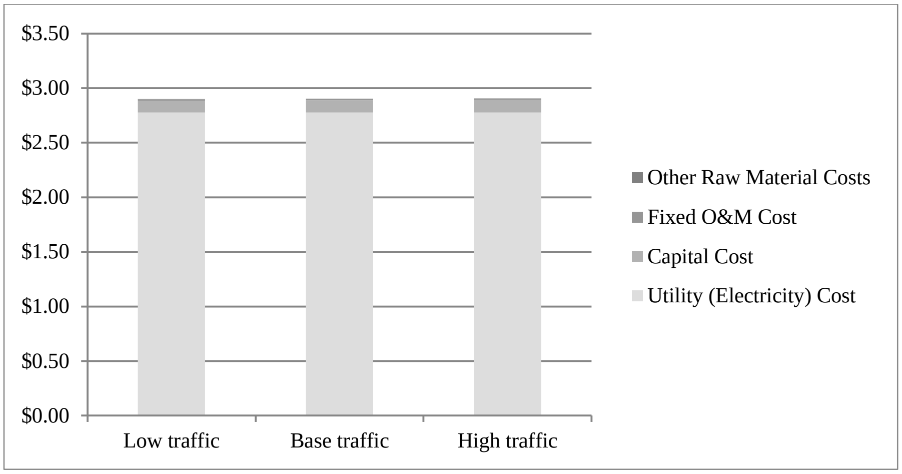


Figure 28 Levelized cost of H_2 production from electrolysis (USD_{2005}/kgLH2).

4.2.3. Hydrogen Processing Cost Breakdown

After being produced, the hydrogen goes through liquefaction, storage, and distribution before being delivered to airplanes. These procedures add extra costs to the LH2 fuel on top of producing H_2 from either SMR or electrolysis.

The added costs in post-production processes are about \$1.83/kgLH2 (USD 2005) across scenarios (Figure 29). No obvious economies of scale are obtained in the hydrogen processing. Among all facilities, the liquefier is responsible for the majority of post-production costs, accounting for 74%. Following liquefiers are LH2 pump and storage.

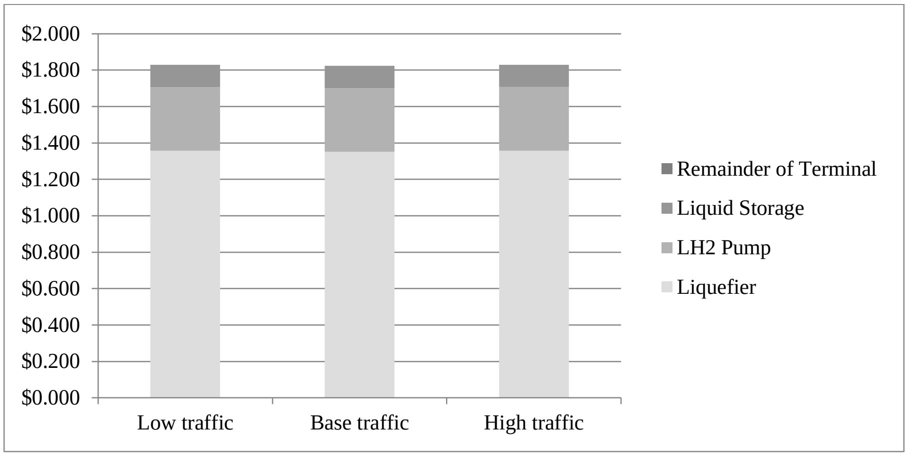


Figure 29 Levelized hydrogen processing costs (USD_{2005}/kgLH2).

Liquefier cost can be further broken down as in Figure 30. Capital investment and energy expense (electricity in this case) are each responsible for about half of the total cost. It is also noticeable that this breakdown shows little change across demand scenarios, indicating lack of economies of scales in the application of hydrogen liquefiers.

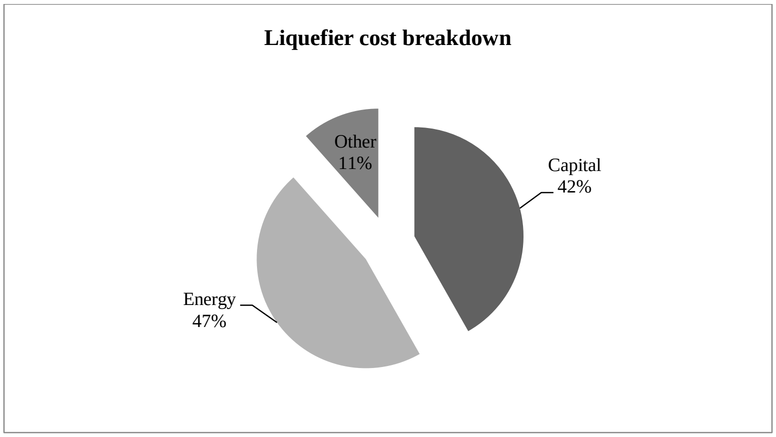


Figure 30 Liquefier cost breakdown.

4.2.4. Other Impacts

Power Demand

Supplying an airport with LH2 fuel consumes a huge amount of electricity power, especially when producing hydrogen with electrolysis. To understand the electricity demands from the hydrogen airport, the amount of electric energy is excerpted from the H2A model, which calculates annual kWh of electricity requirements based on demanded hydrogen. The annual total energy is then divided by the number of ours in a year to obtain an average electric power demand (assuming the hydrogen plant operates 24/7). Figure 31 shows the electric power demand from the LH2 fuel supply system (hydrogen production and processing combined) for one single airport. For reference, capacities of world's largest power plant, Three Gorges Dam, world's largest nuclear power plant, Kashiwazaki-Kariwa, and California's own nuclear power plant, Diablo Canyon, are plotted on the same diagram. This large electricity demand of would require dramatic changes in the power grid. Building mega power plants designated for airports may be a reasonable option, given the large electricity demand and relatively stable and predictable energy demands from air traffic.

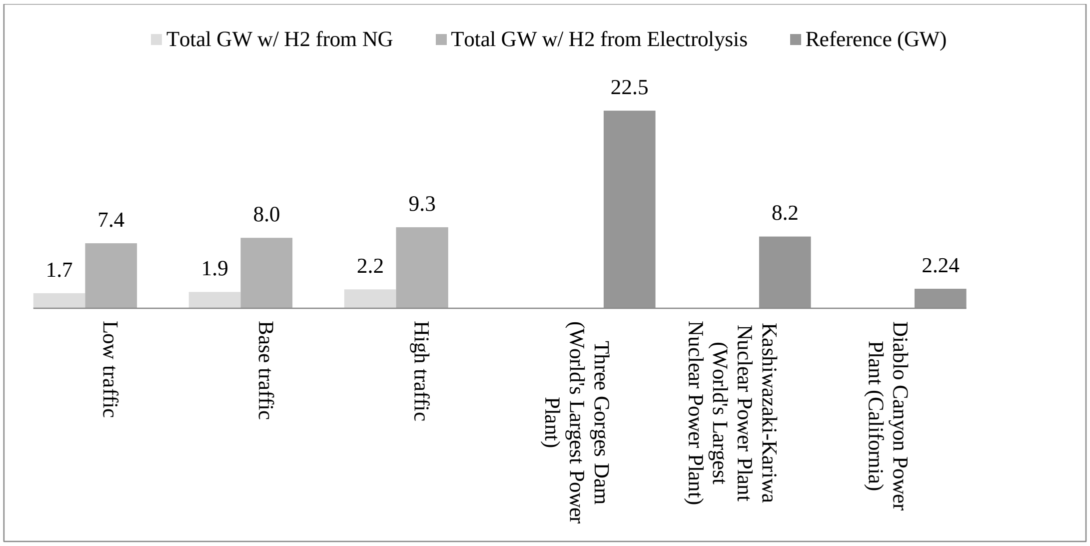


Figure 31 LH2 fuel supply electric power requirement (GW).

Land Area

Another challenged faced with a hydrogen airport is the land area needed for deploying the hydrogen facilities. An estimate for the land requirement is shown in this section.

The H2A Central Production Model does not offer land area calculation for the central production plant. Therefore only the electrolysis production scenario is analyzed here. The electrolyzers are assumed to occupy 75 m^2 per MW energy output rate, following the experience from Schlumberger SBC Energy Institute (Schlumberger, 2014). The liquefier land area requirement is calculated by the H2A Delivery Model, which assumes 25000 m^2 for a 30 tonne/day liquefier unit, and then scales with a 0.6 factor (Ringer & Sozinova, 2010). The storage tanks (19 m in diameter) are assumed to be located in a hexagonal cellular arrangement, and kept a 15 m clearance distance between one another.

Figure 32 shows land area requirements to facilitate the airport with LH2 fuel production, liquefaction, and storage. Only the electrolysis production method is analyzed here. Electrolyzer land area is calculated based on the assumption that each MW hydrogen energy flow requires 75m^2 land area (Decourt, Lajoie, Debarre, & Soupa, 2014). Liquefier and storage facility area is given by the H2A model. Land area used for electricity production is not included.

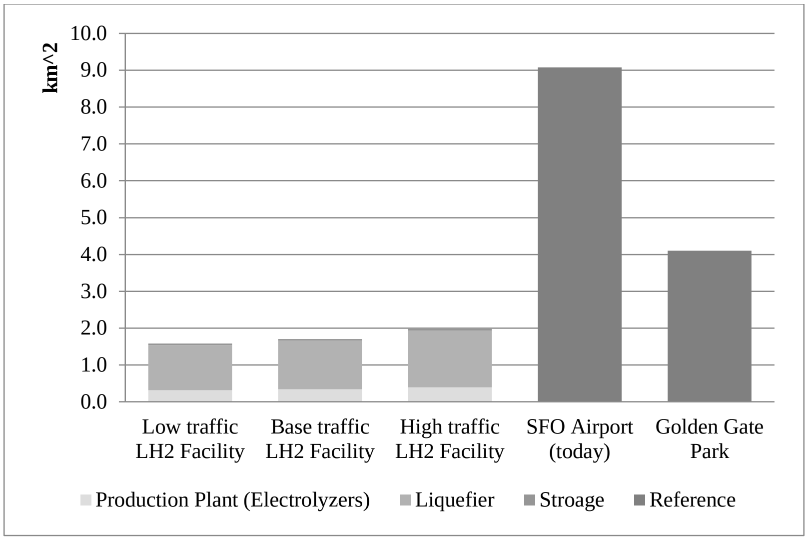


Figure 32 LH2 fuel facility land area requirements.

The land area requirement presents an obvious challenge to developing a hydrogen powered aviation system. At San Francisco International Airport (SFO), for example, hydrogen fuel facilities would require an equivalent of 19% of the total area occupied by the airport itself today (including terminals, runways, ground services, and ground transportations; Figure 32), in the base traffic scenario. When traffic volume goes higher, even more land is needed. Considering the fact that SFO opened in 1927 on only 150 acres (0.6 km^2) of land ("Mills Field Memories," 2007), and has grown to over 9 km^2 in the last about 90 years, we may anticipate that it would continue expanding in area as its traffic grows, regardless of whether hydrogen fuel systems are introduced. Therefore, the hydrogen facilities may only be a part of airports' future expansions, but still remain a significant portion.

Land areas adjacent to the major airports are usually urban or suburban lands, which are difficult or expensive to convert for airport infrastructure uses. For seaside airports like SFO, it could be possible to obtain land by reclaiming from the sea. From a system-wide view, however, land issues must be resolved for each node (airport) in the network so as to enable the whole system to function with LH2 fuel.

Instead of locating all hydrogen production and processing facilities on-site at the airport, one other option is to transport LH2 from a distance away where it is produced and prepared off-site, similar to how jet fuel is supplied for modern airports today. This approach would introduce increased cost in transporting LH2 by truck, rail, or pipelines. Another alternative is producing gaseous hydrogen off-site and piping it to the airport, but keeping the liquefier, storage and pumping system at the airport. This approach may save transporting cost by avoiding expensive insulated pipelines/trains/trucks required to move cryogenic LH2. To understand costs of these alternative supply pathways, further research will be needed.

Figure 33 SFO airport land occupation versus land area required for its LH2 facilities

4.3. Discussion

Comparing hydrogen fuel costs in the base, low, and high traffic scenarios, it can be found that both hydrogen production and processing costs show little sensitivity to scale. This lack of economies of scale has to do with the limitations of the H2A models. In the H2A model, which is primarily designed for modeling ground transportation infrastructure, hydrogen facilities have capacities that are significantly smaller than the energy demand of a large airport. For example, the liquefiers are limited to 200 metric tons/unit/day, thus 16 units must be placed in parallel to meet the energy demand (in the base traffic scenario); the LH_2 storage tanks are limited to 3500 m^3 each, thus 64 such tanks are needed at the airport. These limitations of the H2A model reflects the absence of such extra-large-scale devices for handling hydrogen in the real world. Current commercial applications, including large centralized reformers at refineries, and even future light duty vehicles fuel supply designs don't required centralized liquefaction and storage facilities on the scale of airports. Even modern space projects do not demand such a large and concentrated amount of hydrogen as hydrogen aviation. More research is needed on the scale-up of hydrogen facilities.

Therefore, an important indication from the hydrogen cost modeling is that the major barrier for mass produced inexpensive hydrogen fuel is the lack of large-scale hydrogen handling technologies. Although a hydrogen plant of several tons per day capacity can fully sustain a number of car refueling stations, facilities with several order of magnitudes larger capacities should be envisioned if hydrogen is to be used in aviation.

5. Environmental Impacts of Hydrogen Fueled Aviation

5.1. How aviation impacts environment

Aviation is contributing about 5% (Lee et al., 2009) of the global anthropogenic radiative forcing (RF) effect (2005 data). Though airliners' efficiency is improving over time, the world's air traffic is growing at a 5% annual rate (2000-2007 average) and this pace is expected to continue in the upcoming years (Lee et al., 2009). Aircraft manufacturers predict that the global civil fleet may nearly double from ~20,500 aircraft in 2006 to ~40,500 aircraft in 2026 (Airbus, 2007). Air traffic growth may partly offset the benefits gained from more efficient new aircrafts.

It is commonly agreed that aviation affects climate in three major ways (Wuebbles et al., 2006):

(1) Direct emission of GHG, including CO_2 and water vapor
(2) Indirect impacts from emissions of NOx, which interact with ozone, methane and other GHG (indirect impact on climate)
(3) Contrails, cirrus, aviation-induced cloudiness (AIC)

The most unique character of aviation is that these emissions occur not only near the earth surface, but also at high altitudes, usually 30K-40K ft (~9-12km), lying in the upper troposphere and lower stratosphere (UTLS) region, where emissions "have increased effectiveness to cause chemical and aerosol effects relevant to climate forcing." (Lee et al., 2009).

Table 10 Contributing factors to climate change from aviation

		CO_2	Water vapor	NOx	Contrail	Cirrus clouds
Impact mechanism		GHG	GHG	Increases O_3, depletes CH_4	RF effect	RF effect
Emission index		3.15 $kgCO_2$/kg jet fuel	1.26 kgH2O/kg jet fuel	Variable	Variable	Not well understood
Climate impact vs altitude	Tropopause	Indifferent	Build up concentration, RF effect	Largest ozone increase due to a/c NOx	Most likely to form	Most likely to form
	Troposphere		Negligible due to rapid removal via precipitation		Negligible	Negligible
Overall contribution to climate change		★★★	★☆☆	★★☆	★★★?	★★★?
Level of scientific understanding		★★★	★☆☆	★☆☆	★★☆	☆☆☆

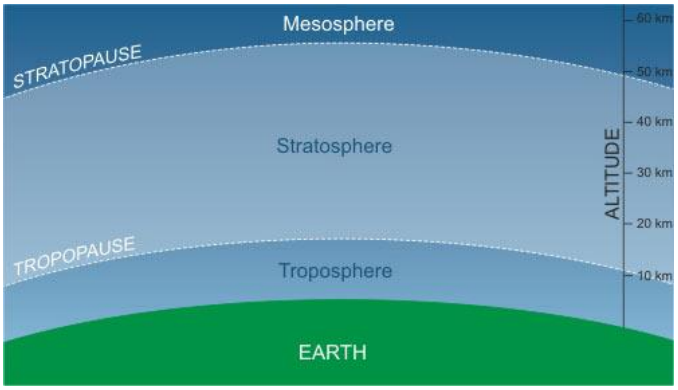


Figure 34 Atmospheric layers: troposphere, stratosphere and mesosphere

5.1.1. CO_2

CO_2 is a main product of the combustion of hydrocarbon fuel. Jet fuel's CO_2 emission index is 3.15 $kgCO_2$/kg fuel (J.E.Penner, D.H.Lister, D.J.Griggs, D.J.Dokken, & M.McFarland, 1999). An IPCC report in 1999 (J.E.Penner et al., 1999) reports the amount of CO_2 emitted by aircraft in 1992 to be 510 million metric tons, which is contributes 2% to all anthropogenic CO_2 emission and 13% to all transportation CO_2 emission of that year. In 2013 these stats are updated to 705 million metric tons CO_2 emission, accounting for 2% of all anthropogenic CO_2 emissions, and 12% of all transportation CO_2 emissions (ATAG, 2014).

The environmental effects of CO_2 is broadly believed to be indifferent across altitudes of emission source, due to CO_2's long lifetime, which enables it to uniformly distribute across the globe. This means CO_2 emitted from an aircraft have the same climate impact as same amount of CO_2 emitted from a ground source.

5.1.2. Water vapor

Water is another product of the combustion of hydrocarbon fuel. Jet fuel's H_2O emission index is 1.26 kgH_2O/kg fuel (J.E.Penner et al., 1999). Water vapor is a greenhouse gas. In the troposphere, water vapor is usually rapidly removed in the form of precipitation within 1-2 weeks, thus its greenhouse effect is negligible in low altitudes. In upper troposphere and lower stratosphere, however, water vapor can build up to concentrations large enough to warm the earth's surface. The overall greenhouse effect of water vapor, though, is smaller than that of other aircraft emissions like CO_2 and NOx.

5.1.3. NOx

Oxides of nitrogen, or NOx, is formed by the reaction of nitrogen and oxygen at high temperatures in the combustion process. NOx affects climate indirectly, by assisting formation of ozone (O_3) and depleting methane (CH_4), both of which are greenhouse gases. Increases in the concentration of NOx from aircraft generally will increase the rate of ozone production by speeding the oxidation of CO and CH_4 (J.E.Penner et al., 1999). The NOx emissions from subsonic aircraft in 1992 were estimated to have increased ozone concentrations at cruise altitudes in northern mid-latitudes by up to 6%, and decreased methane concentration by 2%, compared to an atmosphere without aircraft emissions. The emission rate of NOx varies with aircraft engine and its operation status.

Unlike CO_2, the climate impact of NOx emission is more location-sensitive, both laterally and vertically. Laterally, because ozone has a shorter residual time in the atmosphere, its greenhouse effects are more regional instead of global. Vertically, aircraft NOx emissions are more effective at producing ozone in the upper troposphere than near the surface. Additionally, increase of ozone concentration in the upper troposphere is more effective in increasing radiative forcing than at lower attitudes. The largest increase in ozone concentration induced by aircraft emissions is found to occur near the tropopause (J.E.Penner et al., 1999).

5.1.4. Contrails, cirrus clouds, and AIC

Contrails are line-shaped clouds formed through condensation of water vapor emitted by aircraft. Contrails' radiative forcing effect depends on their optical properties and global cover. The optical properties are mainly determined by aircraft's particle emissions (as condensation nuclei) and ambient atmospheric conditions. Cirrus clouds, beyond those identified as line-shaped contrails, are also found to develop after the formation of persistent contrails.

Contrails and AIC play an important role in global warming effects, but unfortunately, the science of their detailed effects is not well understood (Figure 35). The IPCC AR4 provided an estimate for persistent linear contrail RF of 10 mW/m^2. This figure is very uncertain mainly due to two significant uncertainties: (1) Contrail coverage, and (2) Optical depth (transparency) of contrails.

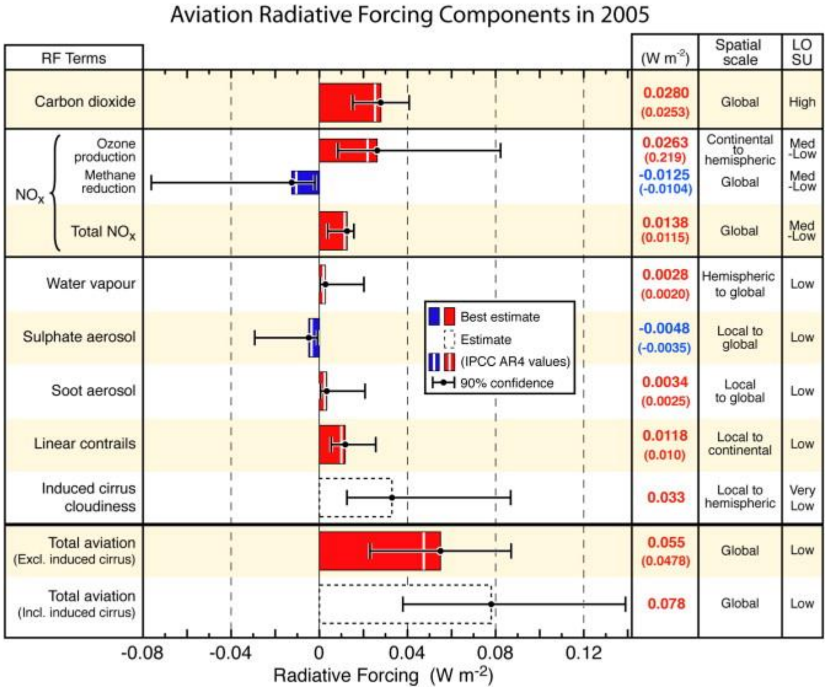


Figure 35 Radiative forcing effects from aviation in 2005 (IPCC AR4)

5.2. Environmental impacts of hydrogen aviation

5.2.1. Water

The emission index of H_2O hydrogen fuel is 9 $kgH_2O/kgLH_2$, or 3.21 kgH_2O per kg jet fuel equivalent. In comparison, the emission index of conventional jet fuel is1.26 kgH_2O/kg. This higher H_2O emission index indicates a 2.55 times increase in global H_2O emission, when the conventional fleet is replaced with hydrogen fueled fleet (Marquart, Sausen, Ponater, & Grewe, 2001). As part of the Cryoplane Project, a hypothetical global hydrogen aviation scenario is depicted (Figure 36) by Marquart et al. (Marquart et al., 2001) showing the distribution of water emission given ~280 Tg jet fuel equivalent energy consumption. It can be clearly seen that the H_2O emissions show higher concentration on main flight routes such as North America and Europe, and on main cruise altitudes between 10 and 12 km (33,000-40,000 ft).

The direct impact of water vapor, though, is nearly negligible despite the more than doubled H_2O emission, since “the aircraft-induced water vapor change is several orders of magnitude smaller than the background water vapor.” (Marquart et al., 2001) . The maximum change by a global cryoplane fleet is only 0.41% compared to natural atmospheric water vapor.

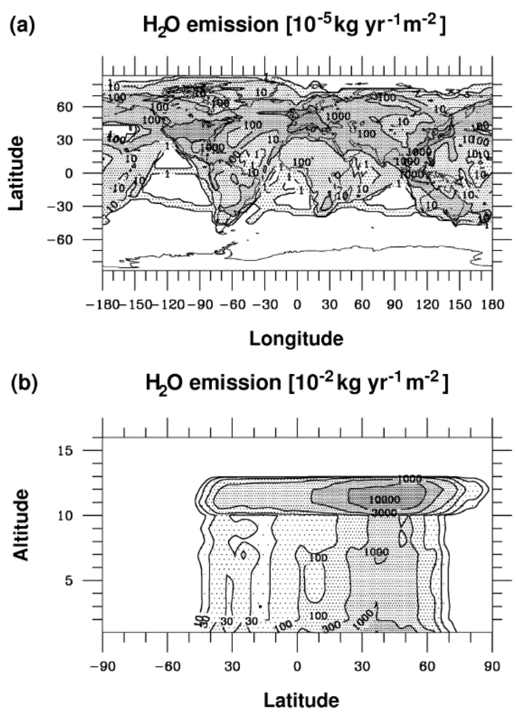


Figure 36 (a) Vertically and (b) horizontally integrated annual mean H_2O emissions of the cryoplane fleet in 2015. Only emissions below 13 km are considered. (Marquart et al., 2001)

Gauss et al. (Gauss, Isaksen, Wong, & Wang, 2003) estimated that increased radiative forcing (RF) due to subsonic cryoplane water emission to be 5.8-6.5mW/m^2 (assuming subsonic kerosene fleet complete replaced by cryoplanes). This number is very uncertain, but it is highly likely that the global RF due to increased water emission is on the order of 10mW/m^2, less than the ~30mW/m^2 RF by aviation CO_2 (Figure 35) which can be avoided by replacing fossil fuel with hydrogen.

Pohl (H.-W. Pohl, 1995) studied the greenhouse effect of various aviation fuel candidates, and found that the greenhouse effect of hydrogen fuel is negligible under 10 km (33,000 ft) altitude, and is smaller than kerosene below 12 km (39,000 ft) altitude. This indicates the negative effects induced by additional water emission can be mitigated by managing the cruise altitude of hydrogen aircraft, although this must be balanced with the fuel efficiency loss due to increased drag at lower altitudes. In addition, certain other air traffic management strategies could help mitigate the impact of water emission from aviation, for example, lowering flight altitude and routing farther from the poles, where tropopause is lower.

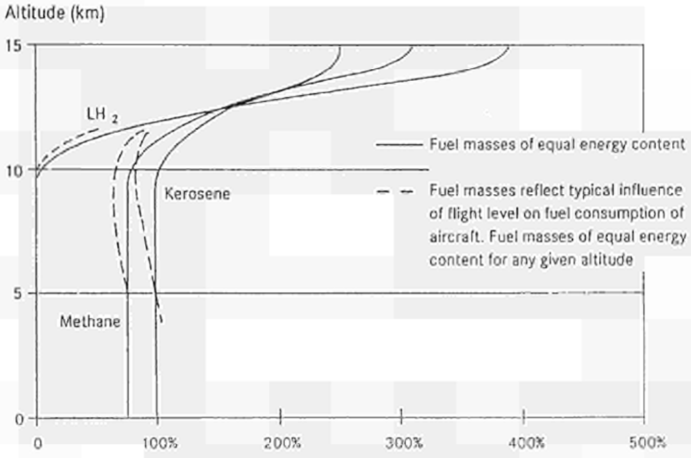


Fig. 10.14 Greenhouse effect of various fuels.

Figure 37 Greenhouse effect of various aviation fuels (H.-W. Pohl, 1995)

5.2.2. NOx

NOx is not a combustion product of the fuel, but a byproduct of nitrogen reacting with oxygen at high temperatures in the combustion chambers. Actual NOx emission strongly depend on specific engine designs and operating conditions. According to past experience from experiments (Dahl & Suttrop, 1998; Marquart et al., 2001), it is possible to reduce mean NOx emission index by 60%-90% by operating LH2 aircraft engines instead of conventional engines.

As a result of significant NOx reduction, formation of O_3 and depletion of CH4 are both decreased. Analysis from Marquart (Marquart et al., 2001) suggests that O_3-induced RF will decrease linearly with NOx reduction, from 0.054 Wm^{-2} in the conventional air fleet scenario to 0.005-0.021Wm^{-2} in the hydrogen fleet scenario. CH_4-induced RF, which is negative because CH_4 (a GHG) is depleted by NOx, will change from −0.036 Wm^{-2} for the conventional fleet, to −0.004 to −0.014 Wm^{-2} for the cryoplane fleet.

5.2.3. Contrails

The impacts of contrails can be roughly broken down into 2 factors: (1) global contrail coverage, and (2) optical properties of contrail. The global contrail coverage is commonly expected to increase due to introduction of hydrogen airplane fleet. However, the contrails produced from LH2 combustion are likely to be of smaller optical thickness and faster sedimentation of contrail particles, resulting in smaller radiative forcing. Marquart et al. (Marquart et al., 2001) argues that cryoplanes' contrails "probably consist of less but larger particles in comparison to the contrails of conventional aircraft because of the higher specific H_2O emission combined with a negligible emission of particles."

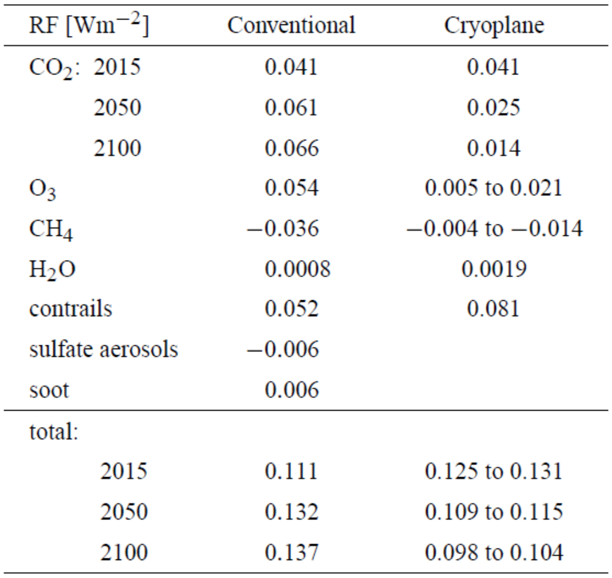
Table 11 Research findings about the impact of contrails from aviation

Reference	Global mean contrail coverage & RF due to contrails		Increase due to hydrogen aviation
	Conventional aviation	H2 aviation	
(Marquart et al., 2001)	0.235% 0.052 W/m^2	0.366% 0.081 W/m^2	56% 56%
(Fahey et al., 1999; Gierens, Sausen, & Schumann, 1999)	0.27% 0.060 W/m^2	0.47% 0.100 W/m^2	74% 67%

5.2.4. Total environmental effect

With both significantly increased H_2O and reduced NOx emissions, hydrogen aviation has a mixed and complex effect on environment. Additionally, many aspects of the environmental impacts are not well understood scientifically.

Table 12 Contributions to RF for the conventional and the cryoplane scenarios for 2015, 2050 and 2100 (Marquart et al., 2001)



RF [Wm^{-2}]		Conventional	Cryoplane
CO_2:	2015	0.041	0.041
	2050	0.061	0.025
	2100	0.066	0.014
O_3		0.054	0.005 to 0.021
CH_4		−0.036	−0.004 to −0.014
H_2O		0.0008	0.0019
contrails		0.052	0.081
sulfate aerosols		−0.006	
soot		0.006	
total:			
	2015	0.111	0.125 to 0.131
	2050	0.132	0.109 to 0.115
	2100	0.137	0.098 to 0.104

* CO_2 RF exists due to existing CO_2 emission before global air fleet is switched to hydrogen.

(Marquart et al., 2001) concludes their study with Table 12. They assumes a instantaneous global fleet renew to hydrogen fleet in 2015, and finds that the total RF of the hydrogen air fleet is larger than conventional fleet at the beginning, due to pre-existing atmospheric CO_2 and increased contrail formation, but then drops lower than conventional fleet in the following future. Despite the NOx reduction and contrail coverage increase, the total RF of conventional and hydrogen air fleet are in the same order of magnitude. Hence the authors concludes "that current knowledge is not sufficient to decide whether a substitution of the conventional fleet by a fleet of cryoplanes is of environmental benefit."

6. Comparison with Other Alternatives: Biofuel and Liquefied Natural Gas

6.1. Aviation Biofuel

Biofuel is currently under the most serious consideration by the aviation industry among all types of alternative aviation fuels. The industry expects the alternative aviation fuel to be "drop-in", which means it must meet the same level of performance and safety specifications as conventional jet fuel, and be fully compatible with existing aircraft and ground facilities. For this reason, bio-derived liquid fuel is a more viable option in the short term, compared to fuels of different nature like hydrogen and liquid natural gas.

3 types of biofuel have been certified by American Society for Testing and Materials International (ASTM International) for worldwide commercial aviation use. One additional type (alcohol to jet fuel) is currently in testing procedures, and is expected to obtain certification in the near future. (See Table 13 below.)

Table 13 Summary of available aviation biofuels

Biofuel type	Acronym	Certified in	Sample feedstock	Blend limit
Fischer-Tropsch synthetic paraffinic kerosene	FT SPK	2009	Coal, natural gas, or biomass	50%
Hydroprocessed esters and fatty acids synthetic paraffinic kerosene, or hydroprocessed renewable jet fuel	HEFA SPK, or HRJ	July 2011	Plant oils, animal fats, or waste grease	50%
Synthesized iso-paraffinic	SIP	June 2014	Sugars	10%
Alcohol to jet fuel	ATJ SPK	Not yet	Alcohol	N/A

The Fischer-Tropsch (FT) method takes a variety of carbonaceous feedstocks, e.g. coal, natural gas, and/or biomass, to produce a series of liquid fuel including jet fuel. Regardless of what feedstock is used, the jet fuel produced from FT method all have similar characteristics since they are required by standards to meet the same specifications (ASTM-International, 2014). Feedstock choice only influences production cost, life-cycle GHG emission, and production potential (J. I. Hileman et al., 2009). FT SPK is characterized by: near-zero sulfur, high thermal stability, reduced lubricity, near-zero aromatic content (J. I. Hileman et al., 2009)

Table 14 FT SPK properties (Lobo, Hagen, & Whitefield, 2011)

Fuel	Density (kg/L, @15 ℃)	Specific energy (MJ/kg)	EI CO_2 (gCO_2/kg fuel burned)	H/C ratio	Aromatic content (vol %)
Jet A-1	0.797	43.3	3155	1.92	18.5
50% FT/50% Jet A-1	0.776	43.6	3127	2.04	9.25
100% FT	0.755	44.1	3100	2.17	<0.2

Hydroprocessed esters and fatty acids, or HEFA, is also known as hydroprocessed renewable jet fuel (HRJ). It can be produced from plant oils, animal fats, or waste grease. The process "first uses hydrotreatment to deoxygenate the oil and then uses hydroisomerization to create normal and isoparaffinic hydrocarbons that fill the distillation range of Jet A." (J. I. Hileman et al., 2009) Because HEFA is produced to meet the same specifications in terms of carbon chain lengths as FT SPK, it has similar characteristics as FT SPK.

The biofuels are slightly less carbon intensive than conventional jet fuel in the fuel burning phase (tank-to-wake, or TTW), as shown in Table 10. However, the overall impact of biofuels must also include emissions related to production and preparation of the fuel (well-to-tank, or WTT). In a life-cycle well-to-wake (WTW) point of view, different aviation biofuels can vary dramatically depending on multiple factors including: feedstock, conversion technology, the availability of carbon capture and sequestration, and indirect land use changes (J. Hileman et al., 2008).

Stratton (Russell William Stratton, 2010) carried out a comprehensive life cycle assessment for FT and HEFA jet fuels, and their results are shown in Figure 38 and Figure 39. It is clear that the emissions of the aviation biofuels can vary from near-zero life-cycle GHG, up to 8 times life-cycle impact compared to conventional jet fuel. Therefore in comparing aviation biofuel with other alternative fuels, specifying feedstock and production method of that biofuel is extremely important. Although there exist many different estimates on biofuel's life-cycle emissions, in this study the Stratton study is adopted for primary reference.

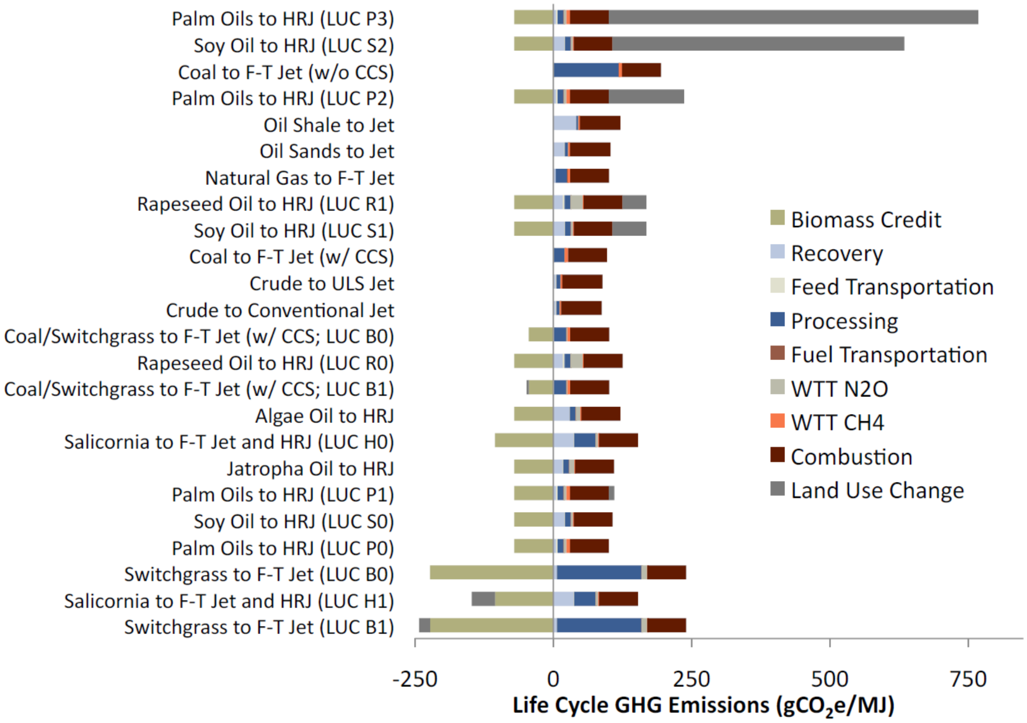


Figure 38 Life cycle GHG emissions for various alternative jet pathways (Russell William Stratton, 2010)

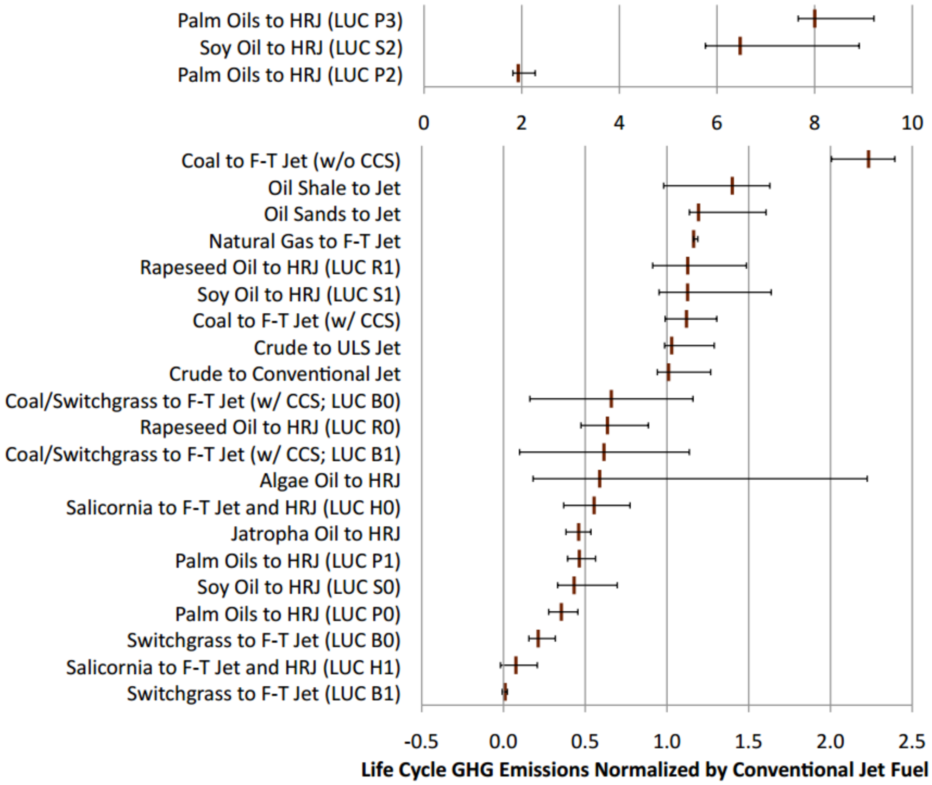


Figure 39 Life cycle GHG emissions for various alternative jet fuel pathways, normalized by conventional jet fuel (Russell William Stratton, 2010)

Aviation biofuels have shown potential of large PM reductions. Lobo et al. (Lobo et al., 2011) carried out engine tests and found that 50% blend FT fuel could reduce PM emission by 39±7% compared to Jet A-1 fuel, measured on a per fuel mass basis. This PM reduction is measured under 100% thrust output of the CFM56-7B engine; when thrust is reduced, the 50% FT fuel shows even more PM reduction compared to Jet A-1. The study explains PM emission reduction by the fuel's aromatic content and H/C ratio. 50% blend FT fuel has lower aromatic content (9.25% vol, compared to 18.5% for Jet A-1) and higher H/C ratio (2.04, compared to 1.92 for Jet A-1). 100% FT fuel, although currently not certified for commercial use, has even lower aromatic content and higher H/C ratio, and consequently larger PM reduction potential.

6.2. Liquefied Natural Gas (LNG) Aviation Fuel

LNG was studied for an alternative aviation fuel in the 1970s and 1980s. In late 1980s the USSR successfully test flew a TU-155 airplane with 1 of its 3 engines running on LNG (Sosounov, 1990). LNG is identified by NASA as a technology "appropriate to aircraft operation in the N+4 2040 timeframe" (Bradley & Droney, 2012). NASA found that higher heating value of LNG reduces the weight of fuel burned, but because of heavier aircraft systems, more energy is used for a given flight. LNG fueled aircraft have the potential for significant emissions advantages and LNG enhances the integration of fuel cells into the aircraft propulsion and power system.

6.3. Aviation Alternative Fuels Comparison: Methodology

6.3.1. Flight mission

In order to cross-compare the performance of different fuel pathways, we select a typical long-haul flight mission, from Los Angeles to Hong Kong, which is 11679 km (6036 nmi) in distance, and takes about 13 hours flight time. Different phases in the flight (e.g. takeoff, climb, cruise, descent, and landing) are not take into account; instead, all the compared metrics reflect the average performance through the entire mission.

6.3.2. Aircraft

5 types of aircraft are selected for comparison: (1) conventional jet, (2) more efficient jet, (3) bio jet, (4) LNG jet, and (5) LH2 jet.

The “conventional jet” is represented by Boeing 747-400, a widely used model for long-haul flights worldwide. The “efficient jet” is represented by Boeing 747-8, the latest model in the B747 series with improved efficiency. Fuel consumption rate for “conventional jet” (B747-400) and “efficient jet” (B747-8) are obtained from the manufacturer’s published performance summaries (Boeing, 2010a, 2010b).

“Bio jet” is essentially the same as “efficient jet”, but runs on 100% biofuel and consumes equal amount of energy per seat-km as “efficient jet”.

“LNG jet” and “LH2 jet” are hypothetical aircraft based on “efficient jet”. LNG jet is assumed to consume 10% more energy compared to “efficient jet”, mainly due to its increased volume to accommodate LNG fuel. LH2 also requires larger aircraft fuselage volume, but its weight saving is significant. While there are contradictory conclusions regarding LH2 aircraft’s fuel efficiency (G. Brewer et al., 1977; Westenberger, 2003), we assumed they consume equal amount of energy as “efficient jet”. Figure 40 summaries the fuel consumption rate, in terms of energy per seat-distance, of the 5 types of aircraft in our scope.

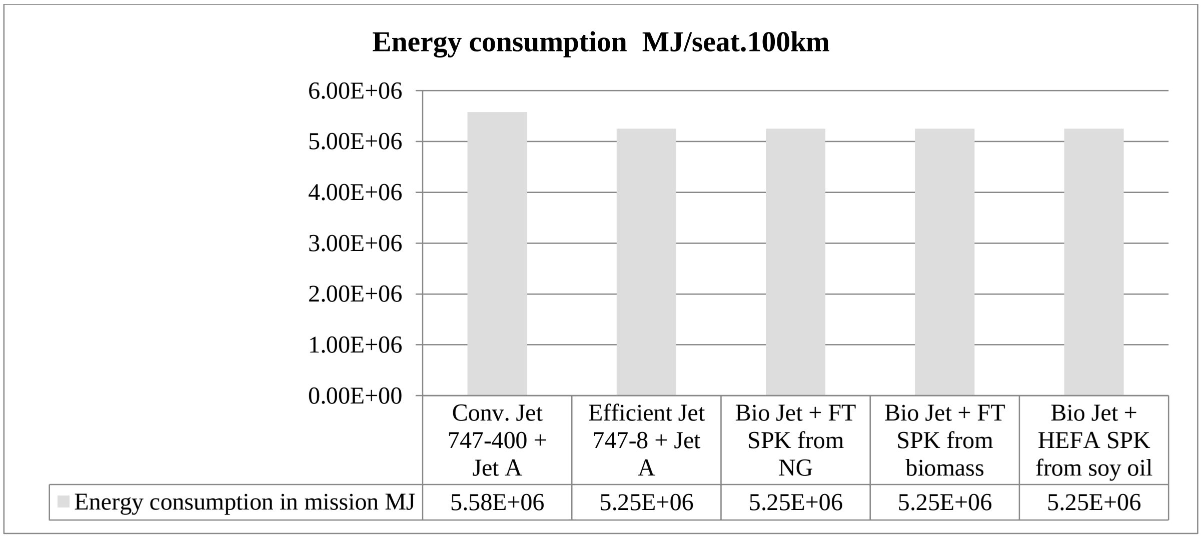


Figure 40 Aircraft energy consumption rate assumptions

6.3.3. Fuels

8 types of fuels are considered in this comparison: (1) jet fuel, (2) FT SPK from natural gas, (3) FT SPK from biomass, (4) HEFA SPK from soy oil, (5) HEFA SPK from algae oil, (6) LNG, (7) LH2 from SMR, and (8) LH2 from electrolysis

Table 15 Properties of aviation fuel candidates

	Jet A	SPK (FT or HEFA)	LNG	LH2
Nominal composition	$CH_{1.93}$	$CH_{2.17}$	CH_4	H_2
Heat of combustion (MJ/kg)	42.8	44.2	50.0	120
Liquid density (kg/L)	0.811	0.755	0.423	0.071
Energy density (MJ/L)	34.71	33.37	21.15	8.52
Boiling point at 1 atm (K)	440-539	468-570	112	20.27
Freezing point (K)	233	208-223	91	14.4

Table 16 lists some key properties of the fuels. While the biofuels have similar properties as jet fuel, LNG and LH2 are dramatically different. Both LNG and LH2 have much higher energy content per unit mass, but their low densities offset this advantage and lead to significantly lower energy content per unit volume than jet fuel and biofuel. Figure 41 shows a comparison of fuel volume and mass requirements for the respective aircraft (as described in the Aircraft section above) to carry out the mission described in the Flight mission section.

Additionally, while jet fuel and biofuel are in their liquid state at normal atmospheric temperatures, boiling points of LNG and LH2 are both well below any temperature that is likely to occur in the atmosphere, which means they both must be maintained in a cryogenic state when in service.

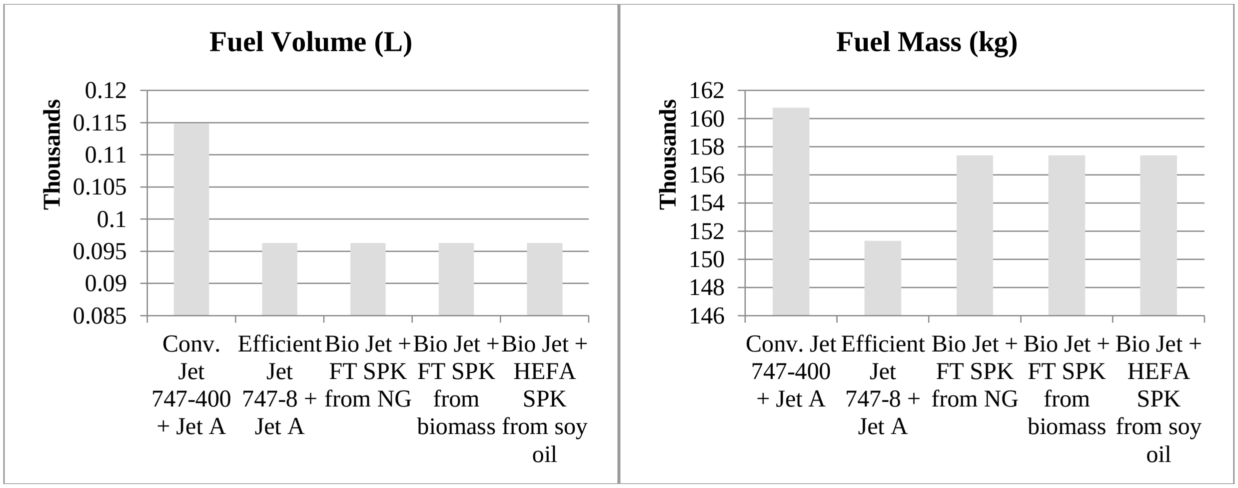


Figure 41 Fuel volume and mass requirements for the same mission

Table 16 lists the emission intensity and cost of the candidate fuels. Pre-2013 jet fuel price is selected despite the recent dramatic drop of jet fuel price, since this price level maintained stable for about 5 year before 2014, and jet fuel price is expected to rise in the long run. FT SPK from NG and biomass are chosen to represent high and low life cycle GHG emission FT SPKs; HEFA SPK from soy oil and algae oil are representatives of high and low life cycle GHG emission HEFA. Since few data is available regarding the cost of aviation biofuels, it is assumed that all SPKs are \$1.01/L, as suggested by (Pearlson, Wollersheim, & Hileman, 2013). Emission intensity of SMR and electrolysis hydrogen are obtained from the GREET .net 2014 database (ANL, 2014), and their costs are obtained from modeling results from the Modeling Hydrogen Cost at an Airport section of this study.

Table 16 Emission intensity and cost of candidate fuels

	WTT GHG emission (gCO_2e/MJ)	**TTW GHG emission (gCO_2e/MJ)**	**Cost ($0.01USD_{2012}/MJ$)**
Jet A	19.274 [a]	74.2 [c]	2.18 ($23/MMBtu) [e]
FT SPK from NG	33.352 [a]	70.4 [b]	3.03 [g]
FT SPK from biomass	-56.609 [a]	70.4 [b]	3.03 [g]
HEFA SPK from soy oil	32.465 [a]	70.4 [b]	3.03 ($1.01/L) [f]
HEFA SPK from algae oil	-19.7 [b]	70.4 [b]	10.29 ($13/gallon) [i]
LNG	23.016 [a]	55.7 [c]	1.80 ($2.45/dge) [h]
LH2 from SMR	153.421 [a]	0	2.97
LH2 from electrolysis	6.531 [a,d]	0	4.64

Notes: a. GREET.net 2014 model by Argonne National Laboratory (ANL, 2014)
b. from PARTNER Project study (Russell W. Stratton, Wong, & Hileman, 2010)
c. Emission Factors for Greenhouse Gas Inventories by US EPA (EPA, 2014)
d. Electrolysis electricity is from nuclear high temperature gas-cooled reactor (HTGR) plant
e. US EIA Annual Energy Outlook 2014 (EIA, 2014)
f. Pearlson study (Pearlson et al., 2013)
g. Assumed equal as soy oil HEFA SPK
h. From STEPS NG truck study (Jaffe et al., 2015);
i. From STEPS algae biofuel study, unpublished work

6.4. Aviation Alternative Fuels Comparison: Results

6.4.1. Well-to-wake GHG emissions

Given the flight mission, aircraft, and fuels described in Aviation Alternative Fuels Comparison: Methodology, a comparison of the life cycle GHG emission across the alternative fuel candidates is shown in Figure 42. Details of the comparison data are attached in Appendix II.

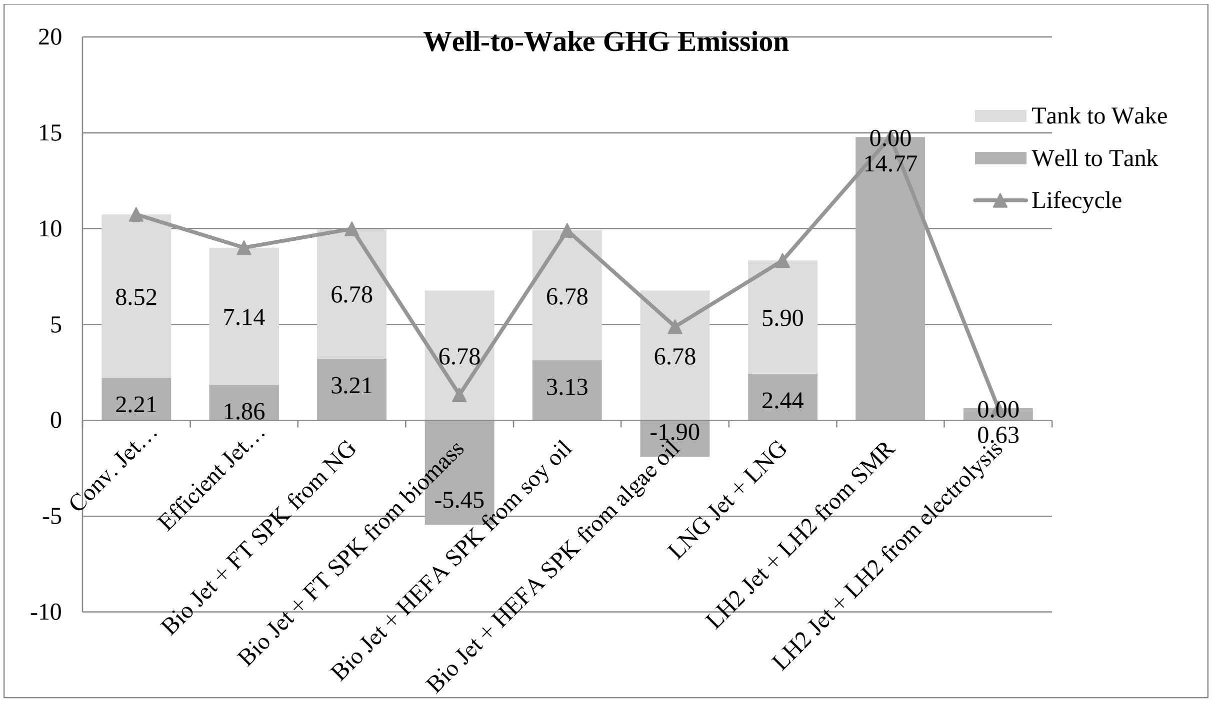


Figure 42 Well-to-wake GHG emission (CO_2e/seat.km)

From the GHG emission comparison we can find:

(1) Aircraft fuel efficiency enhancement is an effective measure to reduce emissions from aviation
(2) Aviation biofuel may or may not result in GHG reduction. While both technologies (FT and HEFA) have the potential to reduce GHG, the key factor is feedstock selection. FT SPK from NG, and HEFA SPK from soy oil both failed to reduce GHG compared to the efficient jet aircraft. FT SPK from biomass and HEFA SPK from algae, however, are able to capture the benefit of negative carbon emission in their well-to-tank phase, therefore lead to significant GHG savings.
(3) LNG fuel has a larger upstream (well-to-tank) GHG emission compared to jet fuel, however, its life cycle profile still shows a slight advantage over jet fuel.
(4) LNG fuel achieves less GHG saving than the best biofuels.
(5) If LH2 fuel is produced from natural gas with SMR, its lifecycle GHG intensity is higher than that of conventional jet fuel.
(6) When using LH2 as aviation fuel, GHG saving can only be achieved by producing hydrogen from low carbon energy sources. Nuclear power combined with electrolysis is one valid option for achieving low-carbon LH2 fuel for aviation

6.4.2. GHG abatement cost

The above section shows that biofuel, LNG, and LH2 all have the potential of GHG abatement. This section shows how such GHG abatement costs compare with each other. In order to conduct this comparison, we make the following assumptions:

1. Purchase costs for “conventional” and “efficient jet” are prices listed for Boeing 747-400 and 747-8 on the manufacturer’s website (Boeing, 2013).
2. LNG and LH2 aircraft are assumed to cost $450 million, about 20% higher than “efficient jet”.
3. All aircraft are purchased through a 10-year payment plan, at an interest rate of 10%.
4. All aircraft have a service life of 25 years.
5. All aircraft travel 2 million statute miles annually.
6. Aircraft purchase payments and fuel payments are discounted to present value via a 4% discount rate.
7. The benefit of “efficient jet” is relative to “conventional jet”. Benefits of bio jet, LNG jet, and LH2 jet are relative to “efficient jet”.
8. Aircraft operating (except for fuel) and maintenance costs are assumed to be equal across all aircraft, thus it is not included in the comparison.

Table 17 Aircraft lifetime cost and GHG comparison

	Conventional Jet	Efficient Jet	Bio Jet + FT SPK from biomass	Bio Jet + HEFA SPK from algae oil	LNG	LH2 from electrolysis
Aircraft						
Purchase cost (million $)	298	367.8	367.8	367.8	450	450
Annual payment ($)	48,498,128	59,857,756	59,857,756	59,857,756	73,235,428	73,235,428
Fuel						
Annual Energy Use (MJ)	1.54E+09	1.45E+09	1.45E+09	1.45E+09	1.59E+09	1.45E+09
Specific energy cost (cent/MJ)	2.18	2.18	3.03	10.29	1.80	4.64
Annual fuel cost ($)	33,500,223	31,528,522	43,807,795	148,956,839	28,725,225	67,183,121
Present values						
10 years’ aircraft payment	393,363,259	485,500,022	485,500,022	485,500,022	594,004,921	594,004,921
25 years’ fuel payment	523,343,156	492,541,091	684,368,876	2,327,015,647	448,747,764	1,049,540,089
Total lifetime cost PV	916,706,415	978,041,114	1,169,868,898	2,812,515,669	1,042,752,685	1,643,545,011
% of base jet	100%	107%	128%	307%	114%	179%
% of efficient jet	94%	100%	120%	288%	107%	168%
Abatement costs		*(vs. conv. jet)*	*(vs. efficient jet)*	*(vs. efficient jet)*	*(vs. efficient jet)*	*(vs. efficient jet)*
Extra cost ($)	-	61,334,699	191,827,784	1,834,474,555	64,711,572	665,503,897
Extra cost ($) per seat.100km	-	0.163	0.510	4.882	0.172	1.771
GHG emission kgCO_2eq/seat.100km	10.74	9.00	1.33	4.88	8.34	0.63
GHG abatement kgCO_2eq/seat.100km	0	1.74	7.67	4.12	0.66	8.37
Abatement cost $/ton$CO_2$eq		94.06	66.53	1,185.24	259.69	211.54

Table 17 shows the calculated results. Figure 43 and Figure 44 shows the lifetime cost and GHG abatement cost of the respective fuel options.

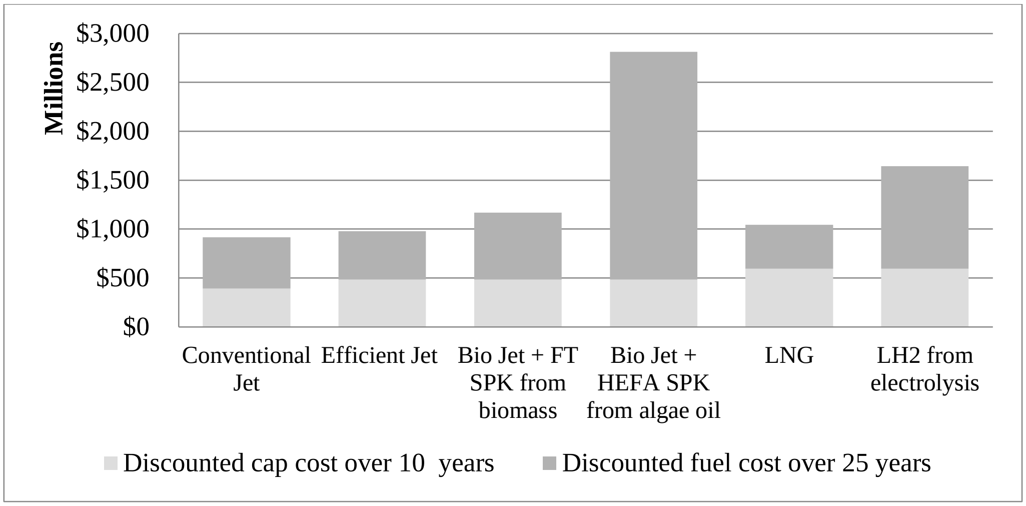


Figure 43 Lifetime cost of the compared aircraft & fuel options

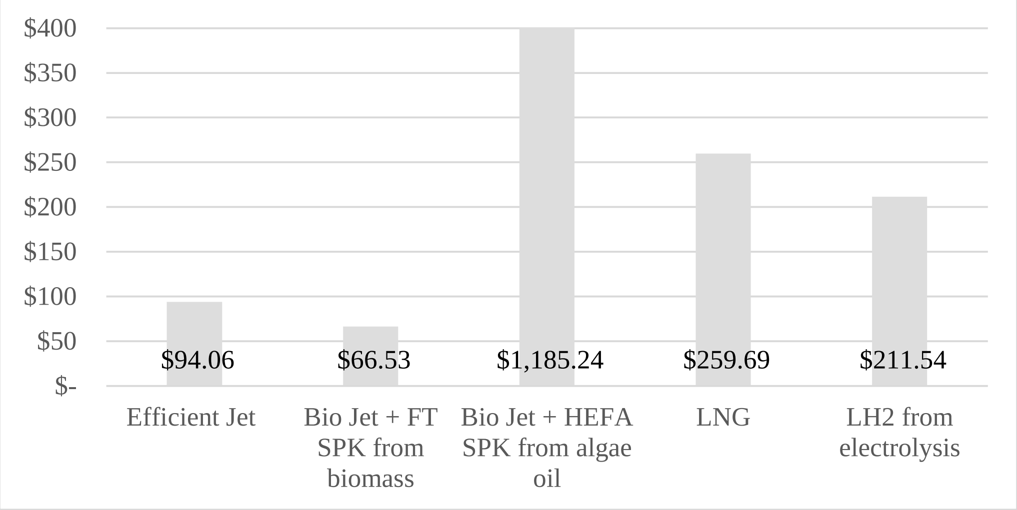


Figure 44 GHG abatement cost of the compared aircraft & fuel options

From the comparison we can see that switching from conventional to more efficient aircraft is a relatively low-cost option for reducing environmental impacts from aviation. The GHG abatement cost is estimated to be $94 per metric ton of CO_2-equivalent.

The cost of biofuel aircraft varies dramatically with the cost of biofuels. The biomass FT SPK is assumed to be rather cheap ($1.01/L or $3.81/gallon) and environmentally friendly, therefore it yields an attractive GHG abatement cost, $66.53 per metric ton of CO_2-equivalent. Despite the environmental gains, the total cost of operating an aircraft on biomass FT SPK is about 20% higher than operating the same aircraft on conventional jet fuel. In the algae oil HEFA SPK case, the extreme high cost of the fuel makes both aircraft operation and GHG abatement extremely costly.

LNG and LH2 fuel options both achieve a GHG abatement cost in the ~\$200/tonCO_2eq order. The lifetime fuel cost of an LH2 aircraft is more than twice as high as LNG aircraft, but the GHG saving is also significant. On a cost per GHG abatement basis, LH2 shows more advantage with \$211.54/tonCO_2eq abatement, compared to \$259.69/tonCO_2eq abatement for LNG.

7. Conclusions

This thesis is a preliminary investigation into the technical feasibility and cost effectiveness of a hydrogen-fueled aviation system.

A review on hydrogen aircraft reveals that although there are limited activities in actual designs of hydrogen fueled aircraft, the existing efforts from 1950s to today have demonstrated that designing and manufacturing hydrogen-powered aircraft is technically feasible given aero technologies available today. Aircraft configurations designated for hydrogen aircraft have been proposed and studied. Among the proposals, conventional tube-and-wing configurations are the most preferred. Hydrogen jet engines and hydrogen fuel cell engines are the two major options for hydrogen-fueled propulsion for aircraft. Onboard LH2 storage is a major change on hydrogen aircraft. Depending on aircraft size and range, the LH2 storage may be placed above, fore, aft the passenger cabin, or combinations of the three. The storage tanks must be insulated, with multilayer insulation, vacuum insulation, or foam insulation. In addition to aircraft propulsion, hydrogen is also proposed to be used in aircraft auxiliary power units. Fuel cell APUs are found feasible and are under test on commercial airplanes. Hydrogen aircraft are likely to be heavier than conventional aircraft when fuel is not included, but be lighter at maximum takeoff weight. The energy consumption rate of hydrogen aircraft is not well understood, because it benefits from the light fuel weight but has a penalty form extra volume occupied by LH2 fuel. Hydrogen aircraft are at least as safe as conventional aircraft, and they have the potential to provide extra safety in certain aspects.

From the review of exiting hydrogen system technologies we may find that all the major components for supporting a hydrogen aviation fuel system is technically available today. The industry has abundant experience in producing, liquefying, delivering, storing, and pumping LH2 in fairly large amounts. Many mature technologies can be readily applied in aviation fuel supply. However, the demand for LH2 in a hydrogen aviation system still dramatically exceeds any application of hydrogen that exist today. Capacity is a major barrier in the cases of all the components. There exists a significant gap in understanding and demonstrating the extra-large-scale facilities desired for LH2 aviation fuel supply.

In order to understand the cost to supply hydrogen fuel for aviation, an airport hydrogen supply system is modelled in this study. Modeling results reveal that with hydrogen technologies available today, LH2 fuel can be supplied to the aircraft at \$3.03 (produced from SMR) to \$4.75 (produced from electrolysis) per kg (\$=USD 2005). At such large scales as ~3000 metric tons per day, feedstock and energy costs (natural gas and electricity) are responsible for the major part of LH2 fuel cost (over 70%). In addition, supplying hydrogen at an airport creates huge challenges to local electric power supply and land use, because the hydrogen facility associated with an airport can easily demand several gigawatts of electric power and square kilometers of land.

Hydrogen aviation will totally eliminate CO_2 emission at the mobile sources (tank-to-wake). The NOx emissions will be 60%-90% lower than conventional aviation due to combusting characteristics of hydrogen. The water vapor emission will increase by a factor of 2.55, introducing higher probability of contrails and cirrus clouds. The impacts of contrails and cirrus clouds are unclear.

In comparison with other aviation alternative fuels, e.g. biofuel and LNG, LH2 is costly but offers significant emission saving potentials. Hydrogen flights have higher life cycle environmental impact than traditional aviation if the hydrogen fuel if produced from natural gas. When hydrogen is produced from nuclear generated electricity, it shows significant reduction in GHG compared to conventional fuel. The comparison also reveals that enhancing aircraft fuel efficiency and adapting aviation biofuel are likely to be the most effective measures for reducing environment impacts of aviation. In the long term, hydrogen shows advantage over LNG in terms of GHG abutment costs.

ACKNOWLEDGEMENTS

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Firstly I would like to express my sincere gratitude to my advisors Dr. Joan Ogden and Dr. Lewis Fulton for the continuous support of my Master's study and related research, for their kindness, patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis.

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Last but not the least, I would like to thank my parents for supporting me spiritually throughout my research, my writing of this thesis, and my life in general.

APPENDIX

Appendix I. Literature on hydrogen aircraft, 1955-2013

Year	Author	Title	Affiliation	Country /region
2013	Khandelwal	Hydrogen powered aircraft: The future of air transport	Cranfield University	EU
2011	Khandelwal	Implication of Different Fuel Injector Configurations for Hydrogen Fuelled Micromix Combustors	Cranfield University	EU
2011	Murthy	Hydrogen as a Fuel for Gas Turbine Engines with Novel Micromix Type Combustors	Cranfield University	EU
2010	Turgut	Partial substitution of hydrogen for conventional fuel in an aircraft by utilizing unused cargo compartment space	Anadolu University	Turkey
2009	Nojoumi	Greenhouse gas emissions assessment of hydrogen and kerosene-fueled aircraft propulsion	University of Ontario Institute of Technology	CANA DA
2009	Millis	Hydrogen Fuel System Design Trades for High-Altitude Long-Endurance Remotely-Operated Aircraft	NASA	USA
2008	Westenberger	LH2 as alternative fuel for aeronautics - study on aircraft concepts	Cryoplane	EU
2006	Haglind	Potential of reducing the environmental impact of aviation by using hydrogen	Swedish Defence Research Agency	EU
2006	Mital	Review of Current State of the Art and Key Design Issues With Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications	NASA	USA
2006	Juste	Hydrogen injection as additional fuel in gas turbine combustor. Evaluation of effects	Technical University of Madrid	EU
2005	Svensson	Potential of reducing the environmental impact of civil subsonic aviation by using liquid hydrogen	Cranfield University	EU
2005	Marek	Low emission hydrogen combustors for gas turbines using lean direct injection	NASA	USA
2004	Svensson	Reduced environmental impact by lowering cruise altitude for liquid hydrogen fuelled aircraft		EU
2004	Haberbusch	Thermally optimized zero boil-off densified cryogen storage system for space		USA
2003	Westenberger	Hydrogen fuelled aircraft-system analysis. Final technical report	Cryoplane	EU
2003	Zuttel	Materials for hydrogen storage	University of Fribourg	EU
2002	Guynn	Evaluation of an Aircraft Concept With Over-Wing, Hydrogen-Fueled Engines for Reduced Noise and Emissions	NASA	USA
2002	Colozza	Hydrogen storage for aircraft applications overview	NASA	USA
2002	Westenberger	Task technical report	Cryoplane	EU
2002	Schefer	Combustion of hydrogen-enriched methane in a lean premixed swirl-stabilized burner	Sandia NL	USA
2001	Klug	CRYOPLANE: hydrogen fuelled aircraft - status and challenges	Cryoplane	EU
2001	Dahl	Combustion chamber and emissions, the micromix hydrogen combustor technology	Cryoplane	EU

2000	Sefain	Hydrogen aircraft concepts and ground support	Cranfield University	EU
1998	Dahl	Engine control and low-NOx combustion for hydrogen fuelled aircraft gas turbines		EU
1998	Ziemann	Potential use of hydrogen in air propulsion	Euro-Quebec Hydro-Hydrogen Pilot Project	EU
1998	Ziemann	Low-NOx combustors for hydrogen fueled aero engine	Airbus	EU
1997	Contreras	Hydrogen as aviation fuel: A comparison with hydrocarbon fuels	UNED Ciudad Universitaria	EU
1991	Brewer	Hydrogen aircraft technology		USA
1991	Price	Liquid hydrogen-alternative aviation fuel		USA
1979	Payzer	Hydrogen fueled high bypass turbofans in subsonic aircraft		
1978	Sloop	Liquid hydrogen as a propulsion fuel, 1945-1959	NASA	USA
1955	Silverstein	Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft	NASA	USA
1997	Pohl	Hydrogen in future civil aviation	Airbus	EU
2006	Daggett	Alternative fuels and their potential impact on aviation	Boeing	USA
2007	Trevisani	Advanced energy recovery systems from liquid hydrogen	University of Bologna	EU
2008	Valenti	Proposal of an innovative, high-efficiency, large-scale hydrogen liquefier	Politecnico di Milano	EU
2005	Koroneos	Advantages of the use of hydrogen fuel as compared to kerosene	Aristotle University of Thessaloniki	EU
2006	Maniaci	Operational Performance Prediction of a Hydrogen-Fueled Commercial Transport	Pennsylvania State University	USA
2006	Ponater	Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment	DLR Oberpfaffenhofen	EU
2005	Dornheim	Fuel-Cell Flier: Global Observer to stay aloft 7–10 days at 65,000 ft. using liquid hydrogen		USA
2006	Sullivan	Engineering analysis studies for preliminary design of lightweight cryogenic hydrogen tanks in UAV applications	NASA	USA
2006	Himansu	Hybrid solid oxide fuel cell/gas turbine system design for high altitude long endurance aerospace missions	NASA	USA
2003	Kohout	Fuel cell propulsion systems for an all-electric personal air vehicle	NASA	USA
1996	Klug	Cryoplane-quantitative comparison of contribution to anthropogenic greenhouse effect of liquid hydrogen aircraft versus conventional kerosene aircraft	Cryoplane	EU
2004	Svensson	Effects of using hydrogen on aero gas turbine pollutant emissions, performance and design	Swedish Defense Research Agency	EU
2005	Marquart	An upgraded estimate of the radiative forcing of cryoplane contrails	Heidelberg University	EU
2005	Svensson	Potential of reducing the environmental impact of civil subsonic aviation by using liquid hydrogen	Swedish Defense Research Agency	EU
2001	Klug	Mid/Longterm Planning – Preparation for Transition, Task Technical Report 1.1-4, CRYOPLANE Project	Cryoplane	EU
2001	Sefain	Definition of facilities requiring change for LH2 operations, Task Final Report 7.6-2, CRYOPLANE Project	Cryoplane	EU

2002	Bracha	Infrastructure for production, storing and distribution at airports, Task Technical Report 7.5-1, CRYOPLANE Project	Cryoplane	EU
2001	Schmidtchen	Aircraft specific safety aspects, Task Final Report 5.3-1, CRYOPLANE Project	Cryoplane	EU
2001	Hoyt	Design Concepts for LH2 Airport Facilities		
2002	Kronberger	Hydrogen production processes Based upon renewable energy, Task 7.3, CRYOPLANE Project	Cryoplane	EU
2001	Schnieder	Global energy resources and hydrogen supply costs, Task Final Report 8.4-1, CRYOPLANE Project	Cryoplane	EU
1997	Klug	CRYOPLANE - Liquid Hydrogen Propulsion for Aircraft	Cryoplane	EU
2001	Oelkers	Aircraft configuration - short/medium range aircraft, Task Final Report 2.3.4, CRYOPLANE Project	Cryoplane	EU
2000	Oelkers	Design requirements for short/medium range commercial transports, Task Technical Report 2.2-6R, CRYOPLANE project	Cryoplane	EU
1978	Reshotko	Drag Reduction by Cooling in Hydrogen Fueled Aircraft		
1962	Esgar	Cryogenic Propellant Tank Structures		
1955	Reynolds	Aircraft-Fuel-Tank Design for Liquid Hydrogen	National Advisory Committee for Aeronautics	USA
1997	Minakawa	Development of a hydrogen-fueled micro gas turbine with a lean premixed combustor	Tokyo Metropolitan Institute of Technology	JAPAN
1996	Maughan	Reducing gas turbine emissions through hydrogen-enhanced, steam-injected combustion	General Electric	USA
2002	Allidieres	WP3 - Systems and Components, Task Final Report 3.1, CRYOPLANE Project	Cryoplane	EU
2001	Bagheri	Design and testing of a two-dimensional combustor segment for hydrogen operation on the basis of the IAE V2500 aircraft engine	FH Aachen	EU
1979	Baerst	Preliminary studies of a turbofan engine and fuel system for use with liquid hydrogen	AiResearch Manufacturing Company	USA
2002	Boggia	Some unconventional aero gas turbines using hydrogen fuel	Cranfield University	EU
2001	Boggia	Unconventional cycles for aero gas turbine engines burning hydrogen	Cranfield University	EU
2001	Boggia	Four Unconventional Aero Gas Turbine Engines Burning Hydrogen-Cryoplane Project	Cranfield University	EU
1982	Brewer	The prospects for liquid hydrogen fueled aircraft		USA
1979	Brewer	Characteristics of liquid hydrogen-fueled aircraft.		USA
1979	Conrad	Turbine engine altitude chamber and flight testing with liquid hydrogen	NASA	USA
2005	Corchero	An Approach to the use of hydrogen for commercial aircraft engines	Technical University of Madrid	EU
2002	Dahl	Auxiliary Power Unit (APU). Task Technical Report 4.7, CRYOPLANE Project	Cryoplane	EU

2001	Dahl	Combustion Chamber and Emissions, Review of Proposed Hydrogen Combustors, Benefits and Drawbacks, Task Technical Report 4.4-4, CRYOPLANE Project	Cryoplane	EU
2001	Dahl	Combustion Chamber and Emissions, Estimated NOx Reduction Potential of Hydrogen Fuelled Aircraft Engines	Cryoplane	EU
2003	Gauss	Impact of H2O emissions from cryoplanes and kerosene aircraft on the atmosphere	University of Oslo	EU
1993	Klug	The Cryoplane Project, Aircraft Using Cryogenic Fuel and their Impact on the Atmosphere	Cryoplane	EU
2001	Marquart	Estimate of the climate impact of cryoplanes	German Aerospace Center	EU
1974	Pratt	Hydrogen as a Turbojet Engine Fuel - Technological, Economical and Environmental Impact		
2001	Sarigiannis	D22 Emissions inventory and comparative assessment of emissions from alternatives in hydrogen production from renewables	Cryoplane	EU
2002	Sausen	Global Effect of Gaseous Emissions and Contrails	Cryoplane	EU
1990	Sosounov	Experimental Turbofan Using Liquid Hydrogen and Liquid Natural Gas as Fuel		USSR
2005	Svensson	Design of Hydrogen-fuelled Aero Gas Turbines for Low Environmental Impact	Cranfield University	EU
2003	Brand	Potential use of hydrogen in air propulsion	Pratt & Whitney Canada	CANADA
2003	Shih	Numerical studies of a single hydrogen/air gas turbine fuel nozzle	NASA	USA
1957	Mulholland	Flight investigation of a liquid-hydrogen fuel system	NACA	USA
1969	Fenn	Flight operation of a pump-fed, liquid-hydrogen fuel system		
1991	Akyurtlu	Evaluation of On-Board Hydrogen Storage Methods for High-Speed Aircraft	Hampton University	USA
1977	Brewer	Study of Fuel Systems for LH2 Fueled Subsonic Transport Aircraft	Lockheed	USA
1976	Brewer	LH2 Airport Requirements Study	NASA	USA
1978	Mikolowsky	The potential of Liquid Hydrogen as a Military Aircraft Fuel	USAF	USA
1997	Schmidtchen	Hydrogen aircraft and airport safety		EU
1995	Pohl	Hydrogen and other alternative fuel for air and ground transportation		EU
2001	Sanchez	Ground Operations and Airport Facilites for a Liquid Hydrogen Fuelled Aircraft - Cryoplane	Cranfield University	EU
1997	Sorralump	Liquid Hydrogen in Aviation	Cranfield University	EU
1964	Mulready	Liquid Hydrogen Engines		
1991	Suttrop	Low NOx-Potential of Hydrogen-Fuelled Gas Turbine Engines		
1992	Dahl	Modification of the fuel system of a turboshaft engine from kerosene to hydrogen		EU
1990	Victor	Liquid hydrogen aircraft and the greenhouse effects	International Institute for Applied Systems Analysis	EU

1990	Winter	Hydrogen in high-speed air transportation	German Aerospace Center	EU
1994	Kocer	Consideration of liquid hydrogen for commercial aircraft	University of Miami	USA
1994	Tupolev	Utilization of liquid hydrogen or liquid natural gas as an aviation fuel		RUSSIA
1988	Dini	Hydrogen-fueled engines for low and high supersonic airplanes		
1996	Zittel	Molecular hydrogen and water vapor emissions in a global hydrogen energy economy		
1978	Lichte	Layout and Design of Aircraft Using LH2 Fuel		
2001	Koroneos	Life Cycle Analysis of Kerosens, Cryoplane - Liquid Hydrogen Fuelled Aircraft - System Analysis		EU
2004	Koroneos	Life cycle assessment of hydrogen fuel production processes		EU
2006	Moffitt	Design and performance validation of a fuel cell unmanned aerial vehicle		USA
2005	Steffen	Solid oxide fuel cell/gas turbine hybrid cycle technology for auxiliary aerospace power	NASA	USA
2005	Freeh	Off-design performance analysis of a solid-oxide fuel cell/gas turbine hybrid for auxiliary aerospace power	NASA	USA
2002	Strom	First simulations of cryoplane contrails	DLR Oberpfaffenhofen	EU
2000	Jackson	Engine Performance Changes	Cryoplane	EU
2000	Jones	Current Aircraft Ground Support Requirements, Task Technical Report 7.6-1, CRYOPLANE Project	Cryoplane	EU
2001	Huttig	Global transition scenarios. Task final report 8.5-1, CRYOPLANE Project	Cryoplane	EU
2001	Klug	Preliminary data for NOx-emissions of kerosene and hydrogen engines. Task Technical Report 1.1-6, CRYOPLANE Project	Cryoplane	EU
1979	Brewer	A plan for active development of LH2 for use in aircraft		USA
1975	Escher	Hydrogen: makesense fuel for an American supersonic transport		USA
1975	Brewer	Study of the application of hydrogen fuel to long-range subsonic transport aircraft		USA
1976	Brewer	Study of LH2 fueled subsonic passenger transport aircraft		USA
1983	Brewer	An assessment of the safety of hydrogenfueled aircraft		USA
2001	Corchero	Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE). Task 4.2: minimum engine change configurations		EU
1989	Sosounov	Some Aspects of Hydrogen and Other Alternative Fuels for Application in Air-Breathing Engines		USSR
1982	Brewer	Is LH2 high cost option for aircraft fuels?		USA
1981	Brewer	Assessment of Crash Fire Hazard of LH2-fueled aircraft		USA
1989	Olifirov	Fuel Feed and Control Systems of Civil Egnines Using Cryogenic Fuel		
1998	Birkenstock	Hydrogen Aircraft Fuel Research Plan		
1998	Ziemann	Key Elements of a Hydrogen Aircraft Fuel System & Powerplant		EU
1974	Brewer	Advanced Supersonic Technology Concept Study - Hydrogen Fueled Configurations	NASA	USA
1975	Brewer	Minimum Energy, Liquid Hydrogen Supersonic Cruise Vehicle Study	NASA	USA
1978	Brewer	Hydrogen usage in air transportation	Lockheed	USA
1990	Winter	Hydrogen Technologies for Future Aircraft		

1994	Kocer	Liquid hydrogen powered commercial aircraft		
1976	Boeing	An Exploratory Study To Determine the Integrated Technological Air Transportation System Ground Requirements of Liquid-Hydrogen-Fueled Subsonic, Long-Haul Civil Air Transports	Boeing	
1982	Brewer	The relative crash safety of LH2-fueled aircraft		USA
1998	Dini	Modification of the fuel control system of a gas turbine engine from kerosene to hydrogen	Università di Pisa	EU
1987	Alder	Hydrogen in air transportation. Feasibility study for Zurich airport, Switzerland	Swiss Federal Institute of Reactor Research	EU
1987	Marchetti	The future of hydrogen—an analysis at world level with a special look at air transport	International Institute for Applied Systems Analysis	EU
2005	Kellogg	Fuel Cells for Micro Air Vehicles		USA
2004	Ofoma	Design of a Fuel Cell Powered UAV for Environmental Research	California State University	USA
2005	Soban	Design of a UAV to Optimize Use of Fuel Cell Propulsion Technology	Georgia Institute of Technology	USA
2005	AeroVironment	AeroVironment Flies World’s First Liquid Hydrogen Powered UAV		USA
2004	Freeh	Development of a Solid-Oxide Fuel Cell/Gas Turbine Hybrid System Model for Aerospace Applications		
2003	Daggett	Fuel Cell APU for Commerical Aircraft	Boeing	USA
2004	Kemm	Operation and Performance Limitations for Solid Oxide Fuel Cells and Gas Turbines in a Hybrid System	Lund Institute of Technology	EU
1974	Johnson	The Economics of Liquid Hydrogen Supply for Air Transportation		
1976	Tsaros	A study of the conversion of coal to hydrogen, methane, and liquid fuels for aircraft	NASA	USA
1977	Witcofski	The thermal efficiency and cost of producing hydrogen and other synthetic aircraft fuels from coal	NASA	USA
1979	Edeskuty	Safety of Liquid Hydrogen in Air Transportation		
1979	Theisen	Laminar flow stabilization by surface cooling on hydrogen fueled aircraft	Lockheed	USA
1977	Momenthy	Fuel subsystems for LH2 aircraft: R & D requirements	Boeing	USA
1981	Brewer	Meeting AHEG for Hydrogen in Air Transportation		USA
1982	Braun	Cost Estimate of the Electrolysis for LH2 Supply at Zurich Airport		EU
1982	Alder	Liquid Hydrogen (LH2) in Civil Aviation		
1982	Braun	AHEG on Hydrogen in Air Transportation		EU
1984	Youngblood	Design of Long-endurance Unmanned Airplanes Incorporating Solar and Fuel Cell Propulsion	NASA	USA
1993	Hansel	Safety Considerations in the Design of Hydrogen-powered vehicles	Air Products	USA
2004	Mavris	Technology Assessment of a Fuel Cell Auxiliary Power System for Naval Aviation		
2003	Friend	Fuel cell demonstrator airplane	Boeing	USA
1978	Korycinski	Air terminals and liquid hydrogen commercial air transports	NASA	USA
2010	Janic	Is liquid hydrogen a solution for mitigating air pollution by airports?	Delft University of Technology	EU

1976	Brewer	Aviation usage of liquid hydrogen fuel—prospects and problems	Lockheed	USA
1978	Korycinski	Some early perspectives on ground requirements of liquid hydrogen air transports	NASA	USA
2009	Coenen	A proposal to convert air transport to clean hydrogen (CATCH)		USA
2008	Janic	The potential of liquid hydrogen for the future ‘‘carbon-neutral air transport system’’.		

Appendix II. Emission comparison details across aviation alternative fuel options

Parameter	unit	Conv. Jet 747-400 + Jet A	Efficient Jet 747-8 + Jet A	Bio Jet + FT SPK from NG	Bio Jet + FT SPK from biomass	Bio Jet + HEFA SPK from soy oil	Bio Jet + HEFA SPK from algae oil	LNG Jet + LNG	LH2 Jet + LH2 from SMR	LH2 Jet + LH2 from electrolysis
Speed	km/h	913	917	917	917	917	917	917	917	917
Duration	hr	12.79	12.74	12.74	12.74	12.74	12.74	12.74	12.74	12.74
Seats	seat	416	467	467	467	467	467	467	467	467
Fuel consump. rate [Volume]	L/seat.100km	3.26	2.75							
Fuel consump. rate [mass]	kg/seat.100km	2.684	2.250							
Energy consumption in mission	MJ	5.58E+06	5.25E+06	5.25E+06	5.25E+06	5.25E+06	5.25E+06	5.78E+06	5.25E+06	5.25E+06
Fuel consump. rate [Energy]	MJ/seat.100km	114.86	96.29	96.29	96.29	96.29	96.29	105.92	96.29	96.29
Fuel Volume	L	1.61E+05	1.51E+05	1.57E+05	1.57E+05	1.57E+05	1.57E+05	2.73E+05	6.16E+05	6.16E+05
Fuel Mass	kg	1.30E+05	1.23E+05	1.19E+05	1.19E+05	1.19E+05	1.19E+05	1.16E+05	4.38E+04	4.38E+04
Emissions										
Upstream WTT CO2eq. Entire flight	kg	107554.85	101224.57	175160.42	-297303.19	170502.01	-103461.87	132964.78	805747.36	34299.97
Tailpipe TTW CO2eq. Entire flight	kg	414058.85	389688.86	369731.75	369731.75	369731.75	369731.75	321782.16	0.00	0.00
Up-stream CO2eq per seat.100km	kg/seat.100km	2.21	1.86	3.21	-5.45	3.13	-1.90	2.44	14.77	0.63
Tailpipe TTW CO2eq per seat.100km	kg/seat.100km	8.52	7.14	6.78	6.78	6.78	6.78	5.90	0.00	0.00
Lifecycle CO2eq per seat.100km	kg/seat.100km	10.74	9.00	9.99	1.33	9.91	4.88	8.34	14.77	0.63

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