Chapter 39

Mitigating the Climate Impact of Aviation: What Does Hydrogen Hold in Prospect?

Kolja Seeckt, Philip Krammer, Malte Schwarze and Dieter Scholz

Abstract This article discusses the impacts of aviation on global climate change, and shows attempts by the aviation industry to mitigate those impacts by means of alternative fuels. Special respect in this paper is given to the use of hydrogen as aviation fuel. Examples of practical and theoretical research projects on the application of hydrogen are presented and the current outlook towards an introduction of hydrogen into practice is presented. From a technological point of view, hydrogen as an aircraft fuel is feasible. However, in the current attempts by the aviation industry to improve environmental friendliness, hydrogen is not included as a measure within the foreseeable timeframe due to large financial and technical efforts.

Keywords Aircraft · Alternative fuels · Aviation · Climate change · Climate impact · Fuel cell · Hydrogen

Introduction

"Gliders use the energy of up-currents, while solar powered vehicles use the energy from the sun. Human-powered flight has also been demonstrated. Propulsive power for any other 'down to earth' flying depends on fuel. This fuel is used in the aircraft main engines." Scholz (2003)

The Meaning of Aviation for Economy and Society

International air traffic and logistics are key factors for today's global community, economy, and trade relations. The fast and safe transport of people and cargo allows

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for business and leisure flights and enables the intercontinental transport of perishable goods and express freight. Furthermore, aviation creates millions of jobs in aviation directly but also in related industries and service sectors. In detail, the Air Transport Action Group (ATAG), a coalition of several organizations and companies throughout the global air transport industry, states that 32 million jobs are generated globally by the air transport industry, of which:

- 17% are directly linked (airports, airlines, manufacturing industry)
- 20% are indirect jobs through purchases of goods and services (supply chain)
- 9% are induced jobs through spending of industry employees, and
- A remarkable 54%, i.e. 17 million jobs are created through air transport's catalytic impact on tourism (ATAG 2009)

With special respect to developing countries, "Tourism is one of the main export earners for 83% of developing countries and it is the principal export earner for one third of them. It is also a significant generator of employment: in twelve countries, employing one in five, and, in two instances (Maldives and Anguilla), employing over one half of the country's population…" (RGS-IBG 2006). Consequently, these countries are especially dependant on air traffic as well. In total (direct, indirect, induced, and catalytic), aviation's global economic impact is estimated as 7.5% of the world Gross Domestic Product (GDP) (ATAG 2009). Moreover, worldwide air traffic of passengers and cargo is still expected to continue expanding even in the light of the current world economic crisis (Embraer 2009). Annual growth rates over the next two decades are estimated at 4.9% for passenger transport and as much as 5.8% for cargo transport (Airbus 2007; Boeing 2008). This means that air traffic doubles roughly every 14 years.

The Environmental Effects and Efforts of Aviation

The global climate is warming, and there is very high confidence that human activities have been contributing to this (Penner et al. 1999). Carbon dioxide and other emissions from aircraft also add to this – especially because these emissions are produced in high altitudes. In its special report, "Aviation and the Global Atmosphere", the International Panel on Climate Change (IPCC) stated in 1999 that it is estimated that 3.5% of all anthropogenic contribution to climate change, expressed as "radiative forcing", is due to air traffic (Penner et al. 1999). Figure 39.1 shows the estimated contribution of air traffic to climate change, under different future scenarios. These scenarios range from the low-growth scenario Fc1 (2.2% annual traffic growth and broad technology improvements), to the high-growth scenario Edh with 4.7% average annual traffic growth and technology improvements mostly concentrated on nitrogen oxides emissions. All scenarios predict rising radiative forcing; however, none of these scenarios include the use of hydrogen or other alternative fuels.

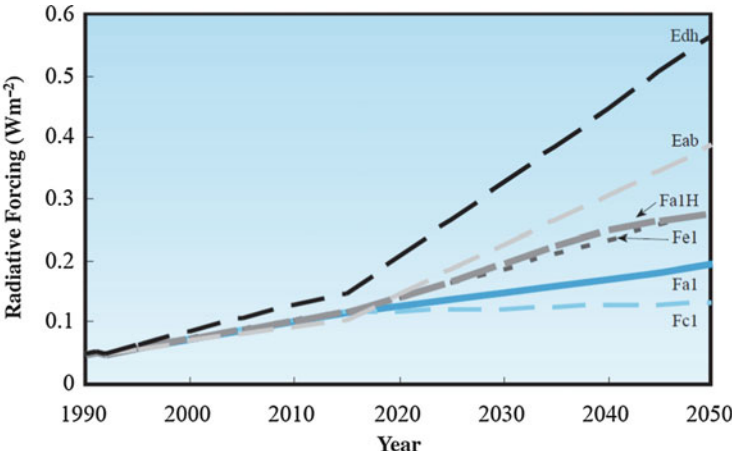

Fig. 39.1 Estimates of the globally and annually averaged total radiative forcing (without cirrus clouds) associated with aviation emissions under different scenarios to 2050 (Penner et al. 1999), with Fa1 as the reference scenario that assumes improvement in fuel efficiency and mid-range economic growth

From an industry perspective, the International Air Transport Association (IATA), the international industry trade group of airlines, states in its leaflet, “Debunking Some Persistent Myths about Air Transport and the Environment” (IATA 2009a), that air transport is responsible for only 2% of all global man-made CO_2 emissions but supports 8% of the global economic activity. On its website, IATA writes that “The best estimate of aviation’s climate change impact is about 3% of the total contribution by human activities. This may grow to 5% by 2050.” (IATA 2009b). With a full passenger load, a modern jet consumes about 3.5 l/100 km per passengers. This is only one-third the consumption of a jet in the 1950s.

However, a return trip from Frankfurt to Sydney for a family of four amounts to 10 times their annual electrical energy consumption. A compact car consumes about 1.5 l/100 km per passenger, which is still considerably less than a modern jet. On a social level, aviation is facing increasing challenges: in recent years, an increase in public awareness of climate change has been noticeable. Also, the general environmental consciousness has increased, and the public perception of aviation is becoming more critical. On a political level, the European Parliament decided in 2008 to include aviation into the emissions trading scheme of the European Union for carbon dioxide from 2012 on (European Parliament, 2009). Further environmental effects, besides global warming, that are linked to air traffic are noise, local air quality, and land use, due to an increase in the number of airports and airport growth. Regarding noise, numerous airports have introduced noise surcharges through individual sets of measures according to their specific needs (Krammer et al. 2009). Consequently, much effort is also spent on noise abatement procedures and the reduction of noise at the source, especially at the engine. Particularly logistic companies are affected by night-time operational restrictions, as their aircraft are most often operated during the night in order to deliver express freight during the office hours.

In the light of these enormous challenges, the Advisory Council for Aeronautics Research in Europe (ACARE) in 2001 set up the “Agenda for the European Aeronautics’ Ambition” referred to as “Vision 2020”. In this agenda, the two European top-level goals of “meeting society’s needs” and “winning global leadership” are addressed through a series of goals, such as:

- Reduction of the number of accidents in air transport by 80%
- Reduction of noise emissions by 50%
- Reduction of carbon dioxide emissions by 50%
- Reduction of nitrogen oxide emissions by 80% in reference to year 2000 standards (ACARE 2001)

These challenging goals put very high demands on future aircraft designs. Moreover, improvements in parameters such as fuel burn and noise, as well as fuel burn and nitrogen oxides emissions, are conflicting. Thus, the outcome can only be a compromise. However, current developments in technology do not show the potential to achieve the ACARE percentages. Furthermore, the total amount of emissions is expected to increase as the rapid growth of air traffic outpaces the achievements of new technologies to safe fuel. In order to meet future fuel demands and lower the environmental impact of transport, the consequences have to be a combination of three aspects:

- Higher fuel efficiency of current and future aircraft
- Alternatives to kerosene that are sustainable and cause a smaller carbon footprint (IATA 2009b), and
- Reducing the need to fly, e.g. by means of internet communication

Fuel: Kerosene and Its Alternatives

The world’s crude oil resources are limited. In the foreseeable future, crude oil will no longer be able to accommodate demand, as the worldwide energy consumption is permanently rising due to a growing world economy. The consequences are increasing fuel and energy prices in general and depleting resources. Thus, the time has already come to search for alternatives that can replace crude oil (BGR 2007).

Figure 39.2 shows a comparison of the energy densities of different fuels and batteries with respect to their energy-specific volume and mass on a double logarithmic scale. It becomes apparent how high the energy contents of crude oil-based fuels are. Their volumetric energy density, for example, is more than thirty times higher than the ones of batteries, which in return means that for the storage of the same energy content, batteries need more than thirty times the volume that e.g. kerosene (Jet A/Jet A-1) needs. Moreover, between kerosene and liquid hydrogen there is still a factor of about four – again in favour of kerosene. With respect to

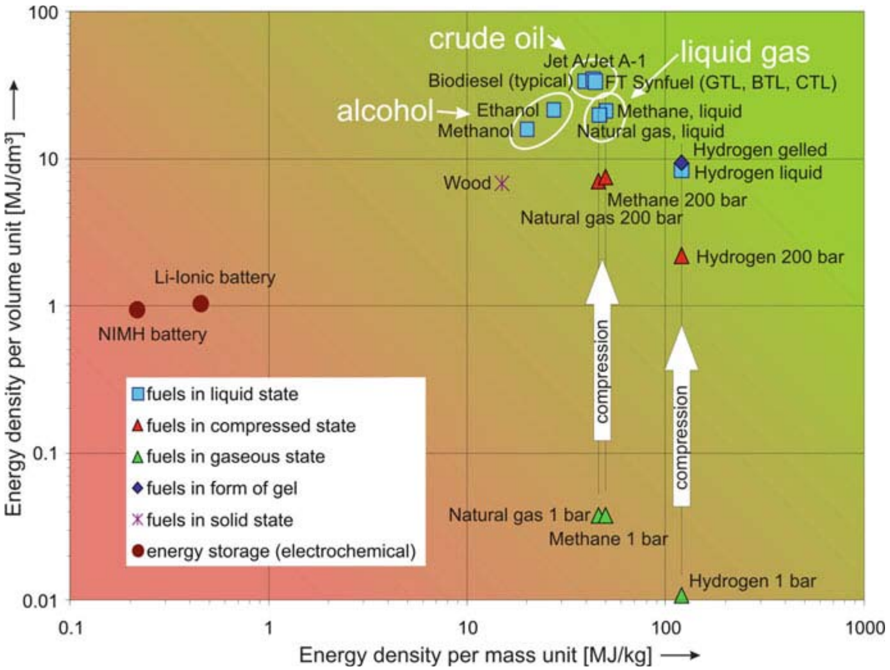

Fig. 39.2 Volumetric and gravimetric energy contents of different fuels and batteries on a double logarithmic scale (based on Sieber 2009)

mass, the factor between kerosene and liquid hydrogen is three; this time to the advantage of liquid hydrogen. This means that the same energy content has one third the mass of kerosene when stored in the form of liquid hydrogen. These numbers illustrate the very high demands posed to the alternatives that compete with current crude-oil based fuels. Energy storages in these forms become very voluminous and/or very heavy.

Hydrocarbons

Today's aviation fuel kerosene (Jet A/Jet A-1) has an energy content of 42.8 MJ/kg, and the combustion of 1 kg of kerosene requires 3.4 kg of air oxygen. Combustion products are 3.15 kg of carbon dioxide (CO_2), 1.25 kg of water vapour (H_2O), as well as further reaction by-products such as nitrogen oxides, sulphur oxides, and soot. The exact amounts of these by-products are highly subject to engine technology.

Synthetic fuels are very often produced by means of a chemical process named after its inventors, Fischer and Tropsch. Thus, they are also referred to as FT fuels. They mark an interesting alternative to conventional kerosene, as their volumetric and gravimetric energy densities lie in the same region as those of conventional kerosene.

Their handling qualities are also widely the same as those of the actual fuel. The most important synthetic fuels today are called GTL (gas-to-liquid), CTL (coal-to-liquid), and BTL (bio-to-liquid), depending on their raw material. However, only the latter one may be judged “climate-neutral”, since GTL and CTL still rely on fossil fuels.

The challenge today is to develop a fuel that is sustainable and exhibits low pollutant emissions over its whole life cycle from production to combustion (well to wing). Besides different feedstocks, there are also different production processes under investigation in several laboratories or relatively small production facilities, especially in the United States (Decker 2008). However, it will still take some time to ramp up production rates from laboratory size to industrial application. According to IATA’s Report on Alternative Fuels (IATA 2008), it does not appear possible at this time that a 100% sustainable fuel source will be available for the aviation industry.

Hydrogen

The production of hydrogen is significantly different from that of conventional kerosene or other crude oil-based fuels. In nature, hydrogen does not exist in a pure form. Consequently, hydrogen has to be separated from a feedstock first, and only parts of the invested energy for this purpose can be recovered during its use afterwards. Hence, hydrogen must not be regarded as an energy source like e.g. crude oil or wood, but must be considered an energy carrier like a battery.

Hydrogen has an energy content of 122.8 MJ/kg. The combustion of 1 kg of hydrogen produces 9 kg of water vapour and up to 90% fewer nitrogen oxides compared to the combustion of fossil fuels (NO_x, dependent on engine technology) (Funke 2009). Thus, the combustion of hydrogen generates a multiple of water vapour but significantly less NO_x than the combustion of an energy-equivalent amount of kerosene. The development of nitrogen oxides cannot be avoided completely, since the surrounding air with 78% nitrogen, which is a reactive gas, is involved in the combustion process. In total, the use of hydrogen as a future fuel for aviation offers the advantage of being an unlimited resource that, furthermore, contributes to much more environmentally friendly aircraft operation. However, today more than 90% of hydrogen is produced by reforming natural gas. The end products of the reforming process are hydrogen and carbon dioxide. Therefore, although the combustion of hydrogen generates no carbon dioxide, the reforming process itself produces a lot of this greenhouse gas. A more promising method for obtaining pure hydrogen is called electrolysis. In this process, water is split up into hydrogen and oxygen by means of electricity. Thus, if the electricity is generated from renewable energy, the production of hydrogen shows very low emissions.

With respect to safety, “Safe handling of hydrogen is no longer a problem in the industrial and commercial area” (LTH 2008). It has been used for decades in various applications such as space flight or chemical industry. Nevertheless, it is important to stress the cryogenic character of liquid hydrogen. Contact with liquid hydrogen, e.g. caused by a leakage, causes severe damage to the skin. Hydrogen has to be stored below 22 K (−251°C) to be available in liquid state (Brewer 1991).

Batteries

Figure 39.2 illustrates that batteries do not have sufficient energy densities to lend themselves as energy stores for airborne applications, although there has been significant progress in recent years. Current and foreseeable energy densities are too low to compete with kerosene. Moreover, there are still a number of unanswered questions concerning aspects such as pollutants and non-recyclable materials in their production process and disposal, as well as lifetime and charging time.

Comparison of Environmental Impacts

For an overall environmental assessment of alternative fuels, the resulting effects of industrial production have also to be taken into account. Feared effects of otherwise very promising biofuels are, for example, the conversion of cropland for food production or rainforest into cropland for the production of energy crops. This could cause deforestation and biodiversity loss as well as competition between these plants for freshwater. Concerning algae, the implications of mass production on sea flora and fauna are not yet known (Kuhlmann 2009).

Figure 39.3 compares the carbon dioxide emissions of different fuels over their whole life cycle in relation to conventional kerosene. It becomes apparent that particularly coal as a raw material for the production of different fuels leads to significantly larger carbon dioxide emissions than today's kerosene, when regarding the whole life cycle. Biofuel and liquid hydrogen produced from water and nuclear power by means of electrolysis, show significantly lower CO_2 emissions. The emission level of liquid hydrogen from water and nuclear power is even close to CO_2-neutral. However, the use of nuclear power is highly controversial.

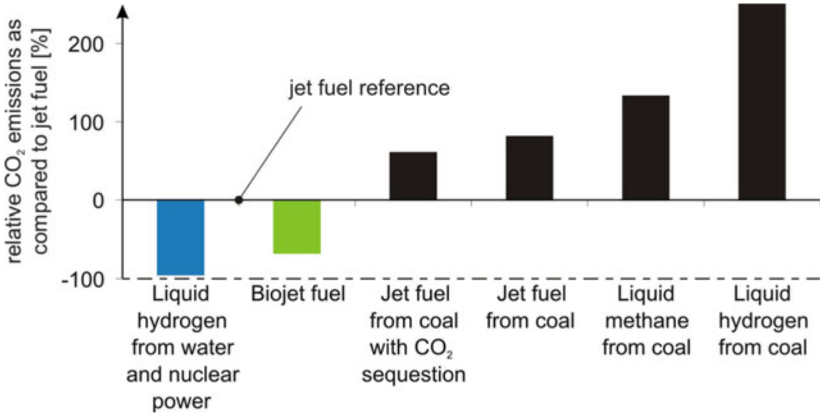

Fig. 39.3 Relative carbon dioxide emissions of different alternative fuels over their whole life cycle compared to conventional kerosene (based on IATA 2008)

Alternatives for the generation of the required electrical energy would be e.g. solar energy and wind energy.

The climate impact of condensation trails, in short contrails, which form behind aircraft under certain atmospheric conditions at altitudes greater than 8 km is not yet very well understood. The aforementioned IPCC special report stated in 1999 that “Contrails tend to warm the Earth’s surface, similar to thin high clouds” (Penner et al. 1999). More recent investigations support this tendency (Schumann 2008). Due to their significantly larger emissions of water vapour, this is especially important for hydrogen-powered aircraft, as it has effects on their climate impact and/or operational conditions if such aircraft have to stay out of the critical atmospheric conditions.

Hydrogen-Driven Aircraft

The increased environmental awareness in society has also reached aircraft manufacturers. While in the last century the aircraft design process was mainly driven by purely economic factors, which focused on low operational and ground handling costs, now there is also a priority on the environmental impacts of an aircraft. Ideally, the task is to provide society in the future with the same standards of mobility as today, but to achieve the environmental objectives in parallel. From the present technical perspective, hydrogen-powered aircraft appear to have the potential of fulfilling both requirements.

The integration of a hydrogen propulsion system into an aircraft is not a trivial matter. The large storage volume for the low-density fuel can be placed on the outside of the aircraft e.g. on top of the fuselage (see Fig. 39.4) with a significant

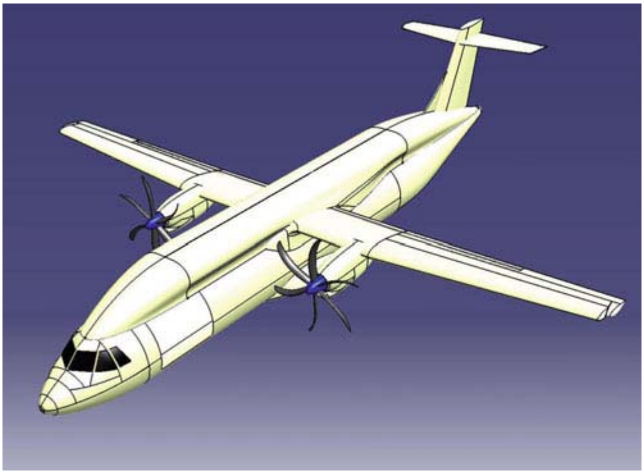

Fig. 39.4 Regional cargo aircraft with fuel stores mounted on top of the fuselage

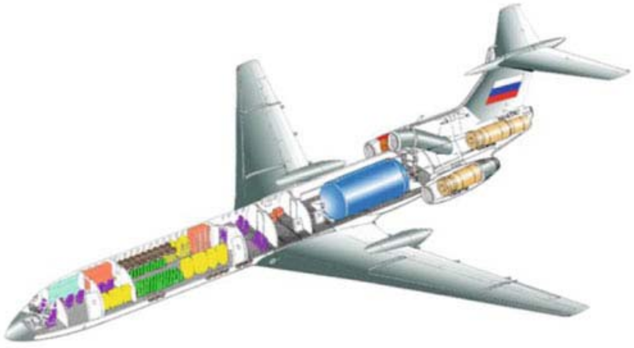

Fig. 39.5 Russian Tupolev TU-155 (Tupolev 2009)

increase in drag and fuel consumption. Alternatively, the storage volume can be placed inside the aircraft's fuselage (see Fig. 39.5), which decreases the available space for passengers or cargo.

Flying Aircraft

One approach towards hydrogen-powered demonstrator aircraft was the Russian Tupolev TU-155 (see Fig. 39.5). It first flew in 1988 as a test and demonstrator vehicle, and one of the three engines could be run on liquid hydrogen or alternatively on liquefied natural gas. In the 1990s, the idea was continued theoretically by a Russian–German research collaboration.

Theoretical Aircraft Studies

Cryoplane

From 2000 to 2002, 36 universities, research agencies and industrial partners from various nations all over Europe participated in the so-called "Cryoplane" project (see Fig. 39.6) under the leadership of Airbus. Its objective was the theoretical investigation and redesign of several hydrogen aircraft types of different size (Westenberger 2003). A real aircraft or mock-up has not been built.

Green Freighter

The Green Freighter project is a joint research project with a focus on the design and investigation of hydrogen-powered freighter aircraft. The project partners are

Fig. 39.6 Hydrogen-powered medium-range aircraft (Forschungszentrum Jülich, 2006)

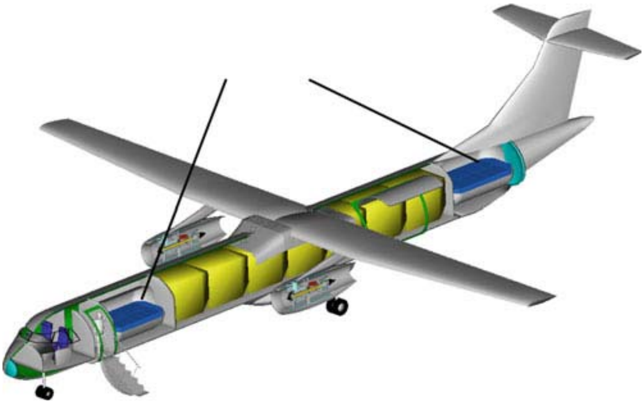

Fig. 39.7 Hydrogen-powered regional cargo aircraft with fuel tanks inside the fuselage

the Hamburg University of Applied Sciences (HAW), the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technical University of Braunschweig, Airbus, and the engineering office Bishop GmbH. As the air cargo chain includes different types and sizes of freighter aircraft, the investigations include freighter aircraft from small regional, so-called feeders, to large long-range freighters. The ATR 72 full freighter version was chosen as the regional and the Boeing B777F as the large reference aircraft (Seeckt et al. 2008; Scholz 2009a).

Figure 39.7 shows an example of a short-range aircraft that has been converted from kerosene to hydrogen as the fuel. Investigations indicate that, based on current kerosene and an energy equivalent hydrogen price, such aircraft are not economically favourable (Seeckt and Scholz 2009).

Besides the investigation of hydrogen only on conventionally shaped aircraft, the Green Freighter project also comprises unconventional aircraft configurations, namely the Blended Wing Body (BWB) configuration (see Fig. 39.8). In combination with the new aircraft layout, the aeroplanes will then be even more fuel-efficient and environmentally friendly.

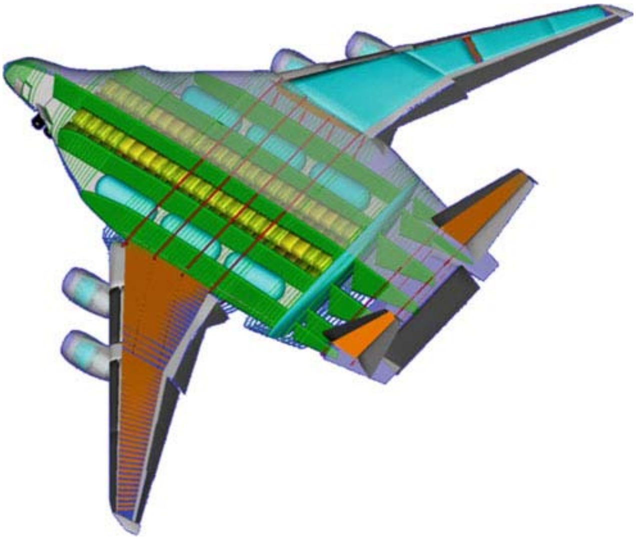

Fig. 39.8 Blended Wing Body with (hybrid) hydrogen-propulsion technology

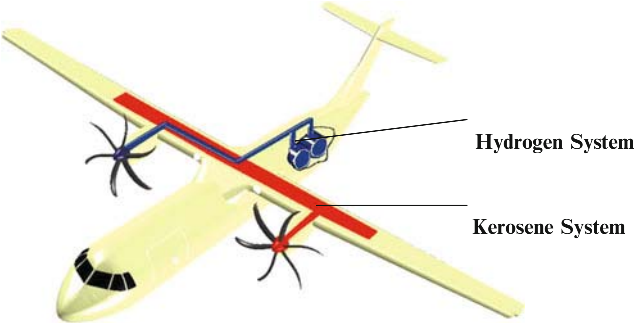

Fig. 39.9 Hybrid-powered demonstrator aircraft

Hybrid-Powered Experimental Freighter

The overall concept of a demonstrator aircraft has to be technically effective and at the same time simple in order to avoid extra spending on time and money. This leads to a hybrid propulsion concept which means that the right engine is powered by liquid hydrogen, while the left engine remains unchanged and is operated on conventional kerosene. This special architecture decreases emissions during cruise by 50% (Fig. 39.9).

As with normal aircraft, during taxi, only one engine is operated. In this architecture, the active engine is the hydrogen-powered one. The hydrogen engine is also used for the power supply of the aircraft on the parking position. The propeller is decoupled from the engine in this mode and does not rotate. Thus, ground operation without CO_2 emissions becomes possible and local air quality within the vicinity of airports is improved.

The demonstrator aircraft is set up on the basis of the regional cargo aircraft ATR 72. The turboprop concept in combination with a moderate cruise speed is well known to be generally very fuel-efficient (Snijders and Slingerland 2007), which further decreases the fuel that is needed to fly a certain reference mission.

This aircraft operates at cruising altitudes below 8 km, where the formation of contrails is very unlikely. The hydrogen engine is fed from two identical liquid hydrogen tanks, mounted in the rear of the aircraft. These tanks and the supply ducts have to be specially insulated due to the fuel's low storage temperature. In general, cargo aircraft offer a good possibility for demonstrating experience in the application of hydrogen, because psychological concerns of passengers do not need to be taken into account.

After the demonstration of reliability and safety by a liquid hydrogen-powered demonstrator aircraft, the next step could be to establish this technology in the commercial air cargo operation.

Aircraft Systems

Tasks and Impact of Aircraft Systems

Broadly speaking, an aircraft can be subdivided into three categories:

1. The airframe (the aircraft structure)
2. The power plant (the engines)
3. The aircraft systems (the equipment)

Aircraft systems comprise all the many mechanical, electrical, and electronic items, devices, and components which are installed in an aircraft for the various purposes.

Aircraft systems are needed to steer the aircraft (*flight controls*) and to handle it on the ground (*landing gear*). A *fuel system* is necessary for powered flight. Aircraft flying longer distances need *navigation* and *communication systems*; aircraft flying higher and taking passengers on board need cabin systems like *air conditioning* and *oxygen systems*. All these systems consume energy during their operation (Scholz 2003).

The engines on an aircraft produce thrust in order to overcome aerodynamic drag and to accelerate the aircraft to the desired speed. The power required to achieve this is referred to as *propulsive power*. Power that does not contribute to the propulsion of the aircraft but is nevertheless needed during flight to operate the various aircraft systems is referred to as *secondary power*.

The *consumption of secondary power* is about 5% of the total fuel consumed during the flight (Scholz 2009b). 5% is not much, but if we consider the absolute amount of fuel being burned on aircraft it definitely makes sense to consider also the impact of aircraft systems.

Energy *types of secondary power* systems are:

- Electric
- Hydraulic (special hydraulic fluid under pressure)
- Pneumatic (air under pressure)

Aircraft engines normally (i.e. during taxiing and in flight) provide all secondary power requirements onboard through electricity comes from generators attached to the aircraft engines, hydraulic power comes from engine driven hydraulic pumps, and pressurized air is taken directly from the engine compressor ("bleed air").

On the ground with engines shut off or in certain failure cases in flight, secondary power comes from an auxiliary power unit (APU). Traditionally the APU is a gas turbine providing electric and pneumatic power. Hydraulic power is produced from electric motor-driven pumps. Major airports provide secondary power to the aircraft so that there is mostly no need to run the APU once the aircraft is taken care of by the airport.

Greening of Aircraft Systems

As for the aircraft as a whole, the approach to greening of aircraft systems was and is to *improve efficiency*. Measures for improving the efficiency of aircraft systems are: better efficiency of consumers, fewer steps of energy conversions, better efficiency in power generation, improved/less/no bleed air usage, reduced system mass, reduced ram air, reduced amount of added drag. Aircraft technology is today already quite mature. For this reason, it has become difficult to achieve further savings. A recent EU research programme "Power Optimised Aircraft" (EU 2004) claims that fuel savings in aircraft systems of 5% would be achievable (Faleiro 2006), i.e. 4.75% instead of 5%, hence saving (only) 0.25% of total aircraft fuel burn. This saving potential is not much, but will have to be considered because every effort helps.

Since most of the time (during cruise) secondary power for aircraft systems comes from the engines, an important statement is: "Aircraft systems are green if the engines are green". That means, if e.g. engines run on environmentally compatible hydrogen or biofuels then automatically all power on board is also produced from these green fuels. It would be possible to achieve sustainable aircraft systems operation in this way without the need for changing aircraft systems technologies. Even old aircraft running on biofuel would have the benefit of green systems.

Another vision (Heinrich 2007) is to decouple secondary power production from the engines. In all phases of flight, secondary power would come from a *fuel cell*. The fuel cell directly converts fuel into electricity without burning the fuel. This totally different conversion principle from fuel into electrical energy has an efficiency that could save up to 20 – 30% of fuel (Heinrich 2007) in aircraft systems, hence saving about 1% of total aircraft fuel burn. The fuel cell runs on hydrogen. This means that a fuel cell could be well integrated into a hydrogen powered aircraft that already stores hydrogen in large quantities for engine operation. If no hydrogen is available on board, kerosene could be converted into hydrogen (reforming) for fuel cell operation.

If the new fuel cell technology could be *combined* with using environmentally compatible hydrogen or biofuels, than aircraft systems would be sustainably saving considerable extra amounts of energy compared with aircraft systems using today's technology.

The fuel cell has some "by-products" that make it especially interesting to integrate such a multifunctional fuel cell.

Multifunctional Fuel Cell

The application of the fuel cell in aviation is often referred to as a multifunctional fuel cell because of additional advantages that are indirectly linked to fuel efficiency.

A continuously running fuel cell produces:

- *Oxygen-depleted exhaust gas* that can be used for fuel-tank inerting (Doyle 2008), decreasing the explosion risk, and
- *Water* that can be used for
  - Flushing toilets or for tap water (after thorough purification and enrichment with minerals) (EADS Innovation 2009) and hence reducing aircraft weight of water otherwise carried in tanks
  - Passenger amenities such as water for showers
  - Cabin humidification, or
  - Water injection into the engines with the aim of increasing engine life and reducing costs and NO_X emissions (Snyder 2009)
- *Rejected heat* could be used in heat exchangers to e.g.
  - Heat up the fuel to required temperature, or
  - To heat the wing leading edge for wing anti-icing.

With electricity from a fuel cell, the aircraft could taxi on ground by an electric motor operated nose gear (autonomous taxiing) without engines running. This would improve overall fuel efficiency and would reduce emissions and noise in the airport vicinity.

In all cases where the hydrogen must be extracted from kerosene or other fuels, a reforming process is needed. There is still a great deal of research to be done on fuel reforming. Today, the mass-to-power ratio of fuel cells is still too high. Fuel cells have to show a considerable weight reduction (Turner 2006) and reduction of purchase costs before it will be feasible to integrate them into aircraft in the way discussed here. Furthermore, the introduction of the fuel cell technology on board aircraft will only be successful if maintenance costs are low. Modern health monitoring techniques will have to be applied to achieve low maintenance costs of fuel cells (Scholz 2009c).

Fuel Cell Demonstrator

For commercial wide-body aircraft, a fuel cell demonstrator was successfully demonstrated at the Berlin International Aerospace Exposition in 2008. The German Aerospace Centre (DLR) presented an Airbus A320 with an experimental 20 kW fuel cell in the rear cargo hold that replaces the Ram Air Turbine (RAT). The RAT is a little turbine that drops out if the aircraft encounters a loss of electrical power. The turbine is driven by ram air that drives an electrical generator to produce electricity for the cockpit and the primary flight controls. While the weight of fuel cell is comparable to that of RAT, the fuel cell may still supply sufficient power to extend the aircraft's flaps during a glide-approach at lower altitudes. Additionally, the fuel cell is easier to test, though it can be tested without really powering up the system (Doyle 2008).

Future Trends

Figure 39.10 shows the road map towards more environmentally friendly air traffic, as prospected by IATA. Its timeline consists of four major steps from retrofits today or in the very near future to new aircraft designs after 2020. It becomes apparent that the measures mentioned in this road map concentrate on improvements of details of current aircraft such as aerodynamics, materials and especially engines. Hydrogen is not yet listed in this outlook. This shows that from a current airline perspective, hydrogen as a fuel is not seen as a measure for improving the environmental friendliness of future air traffic.

The reason for this is not technological issues concerning the use of hydrogen. "Technologies for production, storage, and transport are available, technologically mature, and scalable" (Albrecht 2009). The main reasons are the high financial risk and technical effort of its introduction, since production and handling of hydrogen require a new airport infrastructure. Such large changes to the current airport and aircraft technology take time and are avoided. The effort to develop and introduce sustainable drop-in fuel replacements is much lower, cheaper and, therefore, more favourable for industry. Aircraft design takes decades from the preliminary studies via design, development and manufacturing until flight testing and delivery. That is why "IATA recognises that aircraft are long-lived assets and will be using kerosene or kerosene type fuels for many years to come." (IATA 2009b).

In order to justify the large efforts required to build up a hydrogen infrastructure, the exact environmental benefits of using hydrogen must first be numeralized.

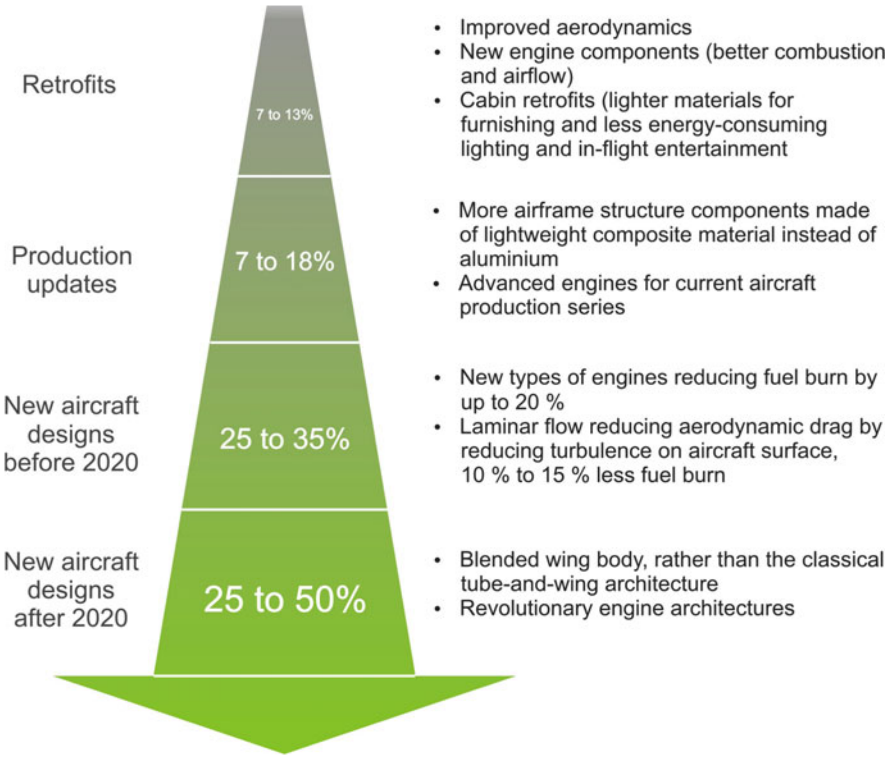

Fig. 39.10 Road map for environmental improvement (based on IATA 2009b)

Summary

Worldwide air traffic of passengers and cargo is expected to grow, and it is estimated that air traffic doubles every 14 years. The global impact of aviation amounts to 7.5% of the world Gross Domestic Product (GDP). Globally, 32 million jobs are generated by air traffic, of which a remarkable 54% are related to air transport's catalytic impact on tourism. These jobs are also found in developing countries. In summary, air traffic is very important to global business and society, and a total ban on all air travel today would have disastrous consequences on the global economy.

However, as a consumer of fossil fuel, air traffic contributes to global climate change. The emissions of aviation produced at high altitudes cause concern. Estimations of the fraction of air traffic in the total anthropogenic "radiative forcing" range from 2.2% to 4.7%. Because these numbers may still appear low in comparison to the contributions of other industries and in order to get a better idea of the influences related to flying, they have to be set against the right background of energy consumption. A return trip from Frankfurt to Sydney for a family of four, for example, amounts to 10 times their annual electric energy consumption. Furthermore, in the future, the total quantity of emissions is expected to increase due to the rapid growth of air traffic.

Future fuel demands will have to be met even though the world's crude oil and, thus, aviation's kerosene resources are limited. Therefore, in order to lower the environmental impact of aviation and to ensure the availability of future air traffic, a combination of (1) higher fuel efficiency, (2) alternatives to kerosene such as hydrogen, and (3) a reduction of the need to fly has to be found.

The examples of aircraft studies, first and foremost, the built and flown Tupolev Tu-155, show the technical feasibility of hydrogen-driven aircraft. However, the financial and technical effort to introduce hydrogen as an aviation fuel would be enormous. Consequently, the current efforts from the aviation industry to develop sustainable air traffic favour alternative drop-in replacements of conventional kerosene, due to the lower financial and technical effort and risk. Moreover, the current search for alternatives to crude oil-based kerosene also includes fuels that are based on other fossil feedstocks, such as coal or natural gas. Consequently, the timeline for the introduction of hydrogen as an aviation fuel is still unclear.

German universities have contributed to the question of introducing hydrogen as a fuel in aviation. This paper has given the examples of: hydrogen-driven regional cargo aircraft, Blended Wing Body (BWB) aircraft, and hybrid-powered demonstrator aircraft. All three projects are considering freighter aircraft because the introduction of hydrogen technology into cargo aircraft seems to be reasonably free from obstacles. Furthermore, the Hamburg University of Applied Sciences is working on the aspect of greening aircraft systems. It was recognized that the simplest way of greening aircraft systems is by using hydrogen or biofuels for the engines. In addition, the integration of the fuel cell to continuously supply power to the aircraft system during all phases of flight could result in considerable fuel savings.

Conclusion

Hydrogen as a fuel for aviation is feasible. It offers the possibility to eliminate carbon dioxide emissions and to largely reduce other emissions such as nitrogen oxides that form during combustion of hydrocarbon fuels. In order to achieve these overall environmental benefits, hydrogen has to be produced in an environmentally friendly way from renewable energy. The storage of hydrogen, even in liquid form at below −251°C, requires very large tanks and additional mass of tank and insulation.

Today, the circumstances do not justify taking the massive risk of introducing hydrogen. Before hydrogen becomes a real fuel alternative, its benefits must be pointed out clearly: its environmental friendliness and the possibility to have a sustainable energy carrier produced from renewable energies.

References

ACARE (2001) A Vision for 2020 – meeting society's needs and winning global leadership, Advisory Council for Aeronautics Research in Europe, Luxembourg, Office for Official Publications of the European Communities), ISBN: 92-894-0559-7. http://www.acare4europe.com

Airbus (2007) Global market forecast 2007–2026, Airbus Corporate Information. http://www.airbus.com/en/corporate/gmf/. Accessed 3 Mar 2009

Albrecht U (2009) Hydrogen Technology and Systems – An Overview, SWAFEA – 1st European Stakeholder Meeting Workshop III: Other Renewable Energy Sources for Aviation, Brussels, 24 April 2009

ATAG (2009) The economic and social benefits of air transport 2008, Air Transport Action Group. http://www.atag.org/. Accessed 24 Jun 2009

BGR (2007) Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2007, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover. http://www.bgr.bund.de/. Accessed 11 Mar 2009

Boeing (2008) Current market outlook 2008–2027, Boeing Corporate Information. http://www.boeing.com. Accessed 3 Mar 2009

Brewer GD (1991) Hydrogen aircraft technology. CRC Press, Boca Raton, Florida

Decker J (2008) Alternative Fuels Power Players. Flight International. Accessed 17 Jun 2008

Doyle A (2008) Fuel cell could replace ram air turbine on next Airbus narrowbody. Flight International (Article ID 224309). http://www.flightglobal.com. Accessed 21 Jun 2009

EADS Innovation (2009) Saving energy with hydrogen – Fuel cells to replace auxiliary power units for supplying electricity in aircraft. *EADS Innovation* (Aviation Articles). http://www.eads.com/. Accessed 21 Jun 2009

Embraer (2009) Market Outlook 2009–2028, Embraer Corporate Information. http://www.embraercommercialjets.com/. Accessed 3 Mar 2009

EU (2004) 'POA' – research project works to optimise aircraft power use", European Commission Research. http://ec.europa.eu/research/transport/news/article_1599_en.html. Accessed 30 Jun 2009

European Parliament (2009) Emissionshandel im Luftverkehr ab 2012, Europäisches Parlament – Informationsbüro für Deutschland. http://www.europarl.de/presse/pressemitteilungen/. Accessed 11 Mar 2009

Faleiro L (2006) Power Optimised Aircraft (POA) – a Keystone in European Research in More Electric Aircraft Equipment Systems. Aeronautics Days, Wien (Session E.6: Improving Cost Efficiency: Onboard Systems). http://www.aerodays2006.org/sessions/E_Sessions/E6/E61.pdf

Forschungszentrum Jülich (2006) HyCare, Hydrogen Energy, Chances and Risks for the Environment, Forschungszentrum Jülich, Institute of Chemistry and Dynamics of the Geosphere ICG. http://www.fz-juelich.de/icg/icg-2/datapool/page/750/cryo1.jpg. Accessed 30 Jun 2009

Funke H (2009) Status and Perspectives of Hydrogen Gas Turbine Systems in Aviation. SWAFEA – 1st European Stakeholder Meeting Workshop III: Other Renewable Energy Sources for Aviation, Brussels, 23 Apr 2009

Heinrich HJ (2007) Fuel Cell Systems for Aeronautic Applications – A Clean Way from Kerosene to Energy, Airbus Deutschland GmbH (Presentation at DGLR-Bezirksgruppe Hamburg 2007). http://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/poster_2007_05_10_Brennstoffzelle.pdf

IATA (2008) IATA 2007 Report on Alternative Fuels, IATA – International Air Transport Association (Montreal, Geneva). http://www.iata.org/whatwedo/environment/climate_change.htm. Accessed 25 Jun 2009

IATA (2009a) Some Debunking Persistent Myths about Air Transport and the Environment, IATA – International Air Transport Association. http://www.iata.org/whatwedo/environment/climate_change.htm. Accessed 25 Jun 2009

IATA (2009b) Fact Sheet: IATA Technology Roadmap for Environmental Improvement, IATA – International Air Transport Association. http://www.iata.org/pressroom/facts_figures/. Accessed 25 Jun 2009

Krammer P, Bertsch L, Werner-Spatz C (2009) Multidisciplinary Preliminary Aircraft Design with Integrated Noise Analysis Capabilites. In: *Deutsche Gesellschaft für Luft- und Raumfahrt, Tagungsband – Ausgewählte Manuskripte: Deutscher Luft- und Raumfahrtkongress* (Paper: DLRK 2009-1177, ISBN: 978-3-932182-63-4)

Kuhlmann A (2009) Luftfahrt und Klimawandel – Relevanz alternativer Kraftstoffe und des EU Emissionshandels, Bauhaus Luftfahrt e.V. München (Presentation at DGLR-Bezirksgruppe Hamburg 2009). http://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2009_06_25_BioFuel.pdf

LTH (2008) Triebwerkstechnologie – Wasserstofftechnologie, Luftfahrttechnisches Handbuch (AT 01 900-00). LTH Koordinierungsstelle, Ottobrunn, IABG

Penner JE, Lister DH, Griggs DJ et al. (eds) (1999) Aviation and the Global Atmosphere – Summary for Policy Makers, IPCC International Panel on Climate Change, Geneva, ISBN: 92-9169. http://www.ipcc.ch/ipccreports/

RGS-IBG (2006) The changing face of tourism in developing countries, Royal Geographical Society with the Institute of British Geographers. http://www.qca.org.uk/geography/innovating/. Accessed 25 Jun 2009

Scholz D (2003) Aircraft Systems. In: Davies M (ed) The Standard Handbook for Aeronautical and Astronautical Engineers. McGraw-Hill, New York

Scholz D (2009a) Forschungsprojekt GF – Grüner Fracher, Hamburg University of Applied Sciences. http://www.fzt.haw-hamburg.de/pers/Scholz/GF.html. Accessed 25 Jun 2009

Scholz D (2009b) Aircraft Systems Overview – Greening of Secondary Power Systems, SWAFEA – 1st European Stakeholder Meeting Workshop III: Other Renewable Energy Sources for Aviation, Brussels, 24 April. http://www.fzt.haw-hamburg.de/pers/Scholz/Aero/Reports_at_Aero.html

Scholz D (2009c) Forschungsprojekt – MOZART Health Monitoring of Fuel Cell Systems in Aviation, Hamburg University of Applied Sciences. http://MOZART.ProfScholz.de. Accessed 30 Jun 2009

Schumann U (2008) Globale Verkehrsemissionen in der freien Troposphäre und unteren Stratosphäre und ihre Klimawirkung. In: Metz N (publ.) Im Spannungsfeld zwischen CO_2-Einsparung und Abgasemissionsabsenkung. Expert Verlag, Renningen, pp 247–263, ISBN: 978-3-8169-2806-5

Seeckt K, Heinze W, Scholz D (2008) The Green Freighter Project – Objectives and First Results. In: CD Proceedings, ICAS 2008 – 26th International Congress of the Aeronautical Sciences, Edinburgh, UK, Optimage Ltd (Paper: ICAS 2008-4.10.3, ISBN: 0-9533991-9-2)

Seeckt K, Scholz D (2009) Jet versus prop, hydrogen versus kerosene for a regional freighter aircraft. In: Deutsche Gesellschaft für Luft- und Raumfahrt, Tagungsband – Ausgewählte Manuskripte: Deutscher Luft- und Raumfahrtkongress 2009 (Paper: DLRK 2009-1195, ISBN: 978-3-932182-63-4)

Sieber J (2009) Neue Triebwerkskonzepte und alternative Brennstoffe, Forum Ökoeffizientes Fliegen (Luftfahrtcluster Hamburg), MTU Aero Engines. http://www.mtu.de/de/technologies/engineering_news

Snijders TA, Slingerland R (2007) Design and analysis of a hydrogen fuelled turboprop airliner, 7th AIAA Aviation Technology, Integration and Operations Conference ATIO (Belfast), AIAA 2007-7752

Snyder CA (2009) Water Injection in Commercial Aircraft Investigated for Increasing Engine Life and Reducing Costs and Emissions, NASA Future Propulsion Systems Research. http://www.grc.nasa.gov/WWW/RT/2005/PB/PBA-snyder.html. Accessed 30 Jun 2009

Tupolev (2009) Cryogenic Aircraft – Development of Cryogenic Fuel Aircraft. http://www.tupolev.ru/English/Show.asp?SectionID=82. Accessed 22 Jun 2009

Turner A (2006) Fuel cell team targets certification. Flight, International (Article ID 207639). http://www.flightglobal.com. Accessed 21 Jun 2009

Westenberger A (2003) Cryoplane – Hydrogen Aircraft, H2 Expo, Hamburg, 11 Oct 2003. http://www.h2hh.de/downloads/Westenberger.pdf