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HYDROGEN AS AVIATION FUEL: A COMPARISON WITH HYDROCARBON FUELS

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Abstract—Depletion of fossil fuels and environmental considerations have led engineers and scientists to anticipate the need to develop a clean, renewable and sustainable energy system. In general, they agree that in such a system hydrogen will be used as an energy carrier.

One of the areas in which hydrogen will be replacing fossil fuels is air transportation, an area that has been under research for several decades. Hydrogen as an energy carrier for use in airplanes has some unique attributes like global availability, safety, minimum pollution and light weight, making it an ideal fuel. This paper briefly reviews hydrogen as a fuel in aviation, compares it with other aviation fuels, and discusses the possible future developments and the goals in this field. © 1997 International Association for Hydrogen Energy

1. INTRODUCTION

The aviation industry, according to the experts, is expected to grow fast in the next few decades, which will result in increasing fuel consumption in aviation. For example, the number of passengers·km, which has doubled from 1978 to 1990, from 1.10^{12} passenger·km to 2.10^{12} passengers·km, respectively, will continue to increase until the year 2075, when it is expected to stabilize at around five times the 1990 level [1, 2], viz. at 10^{13} passengers·km. Even then, the aviation sector only represents an estimated 2.5% of the worldwide energy consumption [3].

Considerations of fuel availability and of environmental concerns put liquid hydrogen (LH_2) in a very good position to replace jet fuel, when compared with other candidates for use in aircraft, viz. synthetic aviation grade kerosene (Synjet), and liquid methane (LCH_4)[4].

Alternative fuels for aviation have been studied under NASA sponsorship in the US since the energy crisis of 1973, although the history of hydrogen in the aerospace industry began in 1943, when the US Air Force studied the properties of hydrogen as an aviation fuel in an Ohio State University program, which led to the subsequent use of liquid hydrogen and liquid oxygen in the US space program [5]. The motivation for the initial studies of hydrogen as aviation fuel is found to be in the possibility that the general availability of petroleum and natural gas production will deteriorate. Therefore the renewable energy contribution to the energy demand will have to increase with time. In addition to these original motivations, we are now aware that the fragility of our environment has increased, especially because of pollution, acid rains, the greenhouse effect and ozone layer depletion. These factors make hydrogen the most ecologically acceptable aircraft fuel [6].

Another challenge in developing an aircraft using liquid hydrogen as the fuel is the utilization of fuel at cryogenic temperatures, meaning new materials for tanks and for superinsulation, safe accommodation of the cryogenic tanks, new pipes and pumps, safety systems, etc. The economic reasons are important when thinking of a new fuel for aircraft power plants. A substitute fuel must be able to compete cost-effectively with conventional fuels. It continues to be an important challenge to economically produce large quantities of liquid hydrogen. On the other hand, if the aircraft engine manufacturers delay building LH_2 fueled engines until hydrogen prices have dropped, precious time would be lost [7].

A very important question in the transition from the currently used jet fuel to the one based on hydrogen at cryogenic temperatures is the time scale, since changing the fuel means changes in almost everything in the aircraft, and it is known that the time it takes from the conception of an airplane model to its production is about 30 years [8]. This shows the importance of increasing R&D and demonstration efforts in this area. There is

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much to be done so that, in 25–50 years, LH_2 fueled subsonic aircraft, as well as supersonic and hypersonic aircraft, can fly safely over the five continents. It can also be stated that the technological level of the industrialized countries today is high enough to implement the air transportation system based on LH_2 as a fuel.

2. HISTORICAL AND TECHNOLOGICAL EVOLUTION

If we do not count Zeppelin balloons, the first aircraft that flew with hydrogen was a US Air Force B-57 twin bomber that in 1956 used liquid hydrogen pressurized with helium in one of its engines [3]. Since then, the US has had several other projects like the CL-400 airplane, the US Space Program and the Space Shuttle Program, all utilizing liquid hydrogen for propulsion [9]. Today, NASA is carving out the National Aerospace Plane Program (NASP) for an aircraft that will run at hypersonic speeds with slush hydrogen, a mixture of liquid and frozen hydrogen, that is 15–20% denser than liquid hydrogen and allows reduction in fuel storage volume and therefore in aircraft size [10]. The research being conducted will power the technology that is required for commercial hydrogen aircraft.

The potential uses of liquid hydrogen for conventional aircraft have also been studied by both the Lockheed Corporation and Boeing, and they concluded that the lower weight of the fuel required lends itself to low wing loading, high cruise altitude and higher power loading. Such an aircraft would mean a shorter runway and a lower level of noise output, and higher turbine inlet temperatures would also be possible. More efficient engines will be possible by using cold liquid hydrogen for cooling turbine blades. Also important is the fact that, due to the lower density of hydrogen, aircraft design will require greater fuselage volume to contain the fuel, and this will have a negative effect on its economy [11, 12].

In 1988, the Soviets experimented with a modified TU-154 (renamed TU-155), with one engine (out of the two) operated on hydrogen alone. Developing and testing of the plane has provided data for later developments of engines and cryogenic systems, and for developing operation techniques with the same complexity level and with the same safety standards as required by traditional airplanes [13]. Retired Pan American pilot Bill Conrad converted a four seater Grutnnab Cheetah to run on hydrogen. The power plant was a liquid hydrogen fueled I.C. engine. It became the first airplane to take-off, cruise and land on hydrogen power alone, at the Ft. Lauderdale International Airport, Florida, U.S.A., in June 1988.

During the 1989 Paris Air Show, the German partner in the European Airbus, Messerschmidt-Boelkkov-Blohm (MBB), showed an interest in developing a hydrogen-fueled twin of the Airbus A310, since the A310 has a large cargo space that allows easy placement of the liquid hydrogen tanks. Two years later, in the Hannover Air Show, the Soviet Union and Germany announced their agreement to work together on a liquid hydrogen fueled commercial aircraft prototype, similar to the A310 Airbus, or the new TU-204 Tupolev, a 200 passenger, two-engined airliner, designed to run with hydrogen with an estimated range of 500 miles. The effort brings together the Tupolev Design Bureau with the Deutsche Airbus [14, 15].

It is also worth mentioning the Samara "Trud" Project (Samara State Scientific and Production Enterprise (SSSPE) TRUD), in which an international team comprising Russian, German and US companies is studying the eventual production of an aircraft in the class of the A310 Airbus and powered by Pratt and Whitney JT9D-type engines, to be fueled by either liquefied natural gas or liquid hydrogen [16].

The two design projects for subsonic aircraft that are currently being studied in detail are the cryoplane design adopted by Russian–German Cooperative Venture on the basis of an existing Airbus A310 and that of the NASA-Langley Research Center. The first is designed for 319 passengers with the hydrogen tank on top of the fuselage, translating into little load on the wings that, incidentally, undergo a reduction in size. The NASA Project has two spherical tanks for the hydrogen, in order to minimize the surface to volume ratio and therefore the heat gain, and is designed for 400 passengers, a cruise speed of Mach 0.85 and a range of 5500 nautical miles [9, 11, 16]. The different possibilities to place the LH_2 tanks already mentioned are shown in Fig. 1, while Fig. 2 shows an artist's sketch of the proposed cryoplane.

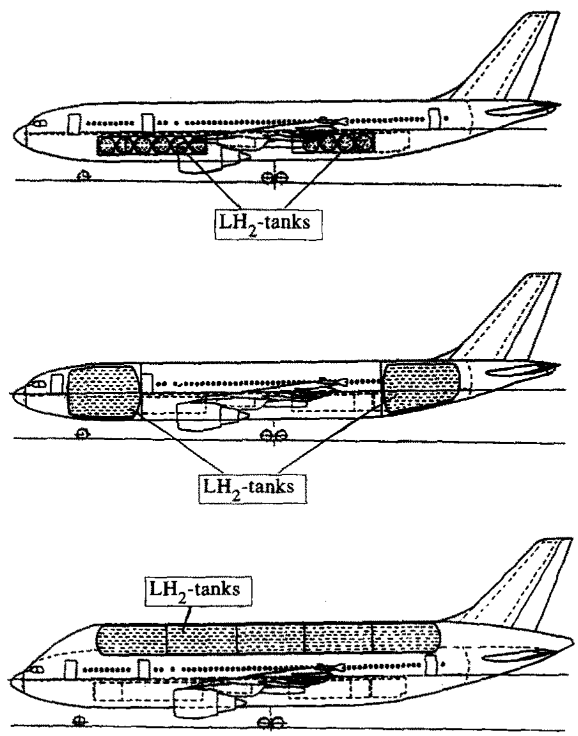

Fig. 1. Airbus consortium studies for locating liquid hydrogen storage tanks in airplanes.

Fig. 2. Artist's sketch of the cryoplane proposed by airbus consortium to fly on liquid hydrogen or liquid methane.

There are also programs for liquid hydrogen fueled supersonic/hypersonic commercial transport. Besides the NASP program already mentioned, Germany and Great Britain both have plans for a hypersonic aircraft, as do France, Russia and Japan [3, 17].

Where liquid hydrogen has no competitors is above Mach 7. All major space programs in industrial countries are already at work on aerospace engines running on the LH_2–LO_2 mixture. The US Space Shuttle Program, Ariane in Europe, ENERGIA in Russia and H-II for Japan, are examples of these programs [3].

Advantages of hydrogen

Liquid hydrogen has several advantages compared with its competitors. First, it can be produced at a given rate because its primary source is water, and as a result of combustion it only releases water vapor and a little nitrogen oxide. Hydrogen has a large energy content per unit of mass, which is very important in aviation because it allows for a greater payload. Another useful property of hydrogen as compared to hydrocarbon fuels is its flammability range, which allows it to be used in a wide range of margins, allowing lower production of NO_x. It also enables smaller engines to be used, which are quieter and require smaller wings—but a more voluminous fuselage. Table 1 presents some physicochemical properties of Synjet, methane and hydrogen, and Table 2 presents advantages and disadvantages of hydrogen as aviation fuel as compared with jet fuel. Hydrogen results in increased independence from imported petroleum, and is ecologically more acceptable. Its low toxicity and high volatility are quite important in case of spillage or leakage [15, 18, 19]. Another advantage of using liquid hydrogen as a fuel is the utilization of fuel at cryogenic temperatures. Liquid hydrogen, with a boiling point of −252.7°C, requires a highly efficient vacuum insulation to maintain the liquid temperature for several days. Improved materials with a minimum tensile strength of 170 000 lb/in^2 will be required [20]. Possible materials are Al–Li alloys and CFRP (carbon-fiber reinforced plastic) [21, 22].

A matter that will undoubtedly be the subject of much study over the next few years is the improvement of the performance of a hydrogen fueled aircraft by a technique which, to date, has only been tentatively explored. This is the concept of achieving laminar flow control using the cryogenic properties of LH_2, and which consists of taking advantage of the heat sink of LH_2 fuel to cool a fluid like gaseous nitrogen which could be used to cool the aircraft skin, so that the air flowing over the cooled surfaces will remain laminar. This can cause very significant reductions in drag. The theory is confirmed by experimentation, but more studies are necessary [18, 23].

Environmental considerations

From an environmental point of view, hydrogen-fueled aircraft are an important improvement on carbon fuels. While aviation emissions represent only a small portion of those produced by the total use of fossil fuels, their potential impact on public health and welfare can be significant, especially in areas with a high density of air traffic. For example, at the Miami International Airport, with daily numbers of operation of 1581 in 1995, taking into account the average emission rates for commercial aircraft, it is possible to estimate that the level of daily NO_x emissions would be equivalent to that produced by some 600 000 passenger vehicles, and the particulate emissions would be equivalent to 250 000 vehicles [11, 24]. Table 3 shows daily NO_x and particulates emissions

Table 1. Significant properties of aviation fuels

Property	Synjet	Methane	Hydrogen
Average formula	$C_{12.5}H_{24.4}$	CH_4	H_2
Boiling point (°C)	167–266	−161.3	−252.7
Melting point (°C)	−50	−182.0	−259.2
Density at boiling point (g/cm^3)	0.8	0.423	0.071
Lower heating value (kJ/kg) adiabatic	42 906	48 139	119 970
Flame temperature (°C)	2022	1973	2158
Heat of combustion (kJ/g)	42.8	50	120
Heat of vaporization (J/g)	360	510	446
Standard heat of formation (kJ/mol)	−208.4 (*n*-octane (g))	−74.8	0
Bond enthalpies (kJ/mol)	C–C 159.0 C=C 195.6 C≡C 811.7	C–H 414.2	H–H 435.1

Table 2. Comparison of liquid hydrogen relative to conventional fuel (jet fuel) utilization in subsonic transport

Aspect	LH_2 advantage	LH_2 disadvantage
Combustion	Higher specific energy (119 190 kJ/kg) than conventional fuel (43 60 kJ/kg). Higher fuel efficiency. Wider range of flammability. Higher flame speed. Higher combustion temperature	Four times lower energy per unit volume (see Table 4). Materials embrittlement
Aircraft configuration	Reduced gross weight (26%[a]). Reduced wing area (18%[a]). Smaller engines and noise reduction. High heat sink capacity. Cruise lift-to-drag ratio reduced by 10–18%	More voluminous fuselage. Necessity of cryogenic fuel system
Airport infrastructure		Airport hydrogen plant with following units needed: Electrolyzer, purification, liquefier, storage and distribution system
Harmful and water vapor emissions	NO missions of CO, CO_2, particles, HC, S compounds and odor. Reduced NO_x (33% or less of that produced by today's turbofan engines using combustion chambers with premixing)	About 2.5 times more H_2O

[a]For a 272 passenger and 7260 kg cargo aircraft with a range of 3400 n.mi and a cruise speed of 0.82 Mach [11].

by cars in Dade County (Greater Miami) and by aircraft at the Miami International Airport.

When hydrogen is used as a fuel, water is the only byproduct, and when it is burned with air, it also produces NO_x. We now know that regardless of the fuel, the amount of NO_x formed in gas turbines varies exponentially with flame temperature and linearly with reaction-zone dwell time. For this reason it will be necessary to work on these variables in order to produce low quantities of NO_x, at least as low as those produced with the best carbon content jet fuel [18, 21]. As hydrogen provides for a wide fuel/air ratio of operation (the flammability range of hydrogen is 14 times greater than that of kerosene), it is possible to decrease this ratio to reduce the reaction zone temperature. Since hydrogen burns quickly, it is possible to shorten combustion zone and time, both of which factors are associated with dwell time. All these technical characteristics, associated with hydrogen combustion, allow for a potential reduction in NO_x emissions, using fuel injection nozzles and alternative combustion chamber concepts, to only one-third of that produced by today's turbofan engines [25].

As for water vapor, hydrogen combustion, for the same quantity of energy, releases about 2.5 times more than Synjet and 1.5 times more than liquid methane [5, 9]. The problem with these emissions, however, is that they occur in the 8–16 km area of the troposphere (i.e. lower stratosphere), introducing new reasons for concern, since the water content of this region could be modified and therefore the radiation balance of that area of the atmosphere could be altered [2, 26]. The greenhouse effect of water vapor depends greatly on altitude. Above 6000 m, the effects per molecule of water vapor are higher than those of CO_2, due to the fact that when water condenses and forms thin ice clouds, the greenhouse effect of water vapor increases enormously. It must nevertheless be taken into account that the residence lime of CO_2 is much greater than that of H_2O [2]. Due to this short dwell time, anthropogenic water vapor is insignificant when it is compared to the atmosphere's natural water content.

Table 3. Comparison of daily NO_x and particulates emissions in Dade County (greater Miami) by cars and Miami International Airport (MIA) by aircrafts (1995)

Item	Quantity/measurement
Inspected vehicles in Dade County	1 227 069
Gas usage	804 665 000 gallons◇32 387 × 10^6 km/year
US 1983 Standards for NO_x + HC	0.8 g/km of vehicle travel
US 1983 Standards for particulates	0.1 g/km of vehicle travel
Daily landing/take-off cycles at MIA	1581
Emission factor (NO_x) for cycle	20.46 kg/cycle
Emission factor (particulate) for cycle	1.08 kg/cycle
Average daily NO_x emission for cars	70 986 kg
Average daily NO_x Emission at MIA	32 347 kg (equivalent to nearly 600 000 passenger vehicles)
Average daily particulate emission for cars	8873 kg
Average daily particulate emission for MIA	1707 kg (equivalent to nearly 250 000 passenger vehicles)

Table 4. Combustion features and products for Synjet, LCH_4 and LH_2

Item	Synjet	LCH_4	LH_2
Relation air/fuel mass	14.7	17.2	34.2
kg fuel/GJ	233	208	83.3
m^3 fuel/GJ	0.032	0.048	0.12
kg CO_2/GJ	720	550	0
kg H_2O/GJ	290	450	750
NO_x Emissions kg/GJ[a]	0.4	0.5	0.6
Precursors of O_3	NO_x, CO, HC	NO_x, CO, CH_4	NO_x
Other pollutants	SO_2, particulate, soot (C)	Particulate, soot (C)	None

[a]The NO_x emissions depend on combustion temperature and pressure, as well as on the dwell time. Hydrogen allows lowered temperatures, and so the NO_x emissions, by mean of a lean combustion process.

It may therefore be said that, if we maintain the altitude of flights in the troposphere, the greenhouse effect of water vapor is not significant [25, 27]. As a result of the studies for LH_2 and LNG, LH_2 is preferred because LNG is a depictable resource, its CO_2 emission is only 25% lower than that of Synjet, and methane is a greenhouse gas by itself.

Concluding from the above analysis of pollutants emitted by aircraft using carbon-based fuel and hydrogen, hydrogen is the most advantageous environmental option, since it does not produce CO_2, CO, SO_2, HC, soot, etc., and lowers NO_x emissions. Table 4 presents the amounts of combustion products for Synjet, LCH_4 and LH_2, while Table 5 shows the contribution of the principal greenhouse gases to the total greenhouse effect [28–30].

Safety and handling

Hydrogen is an extremely volatile fuel, which has to be handled with great care. Nevertheless, it is not unsafe. Compared with the other alternative carbon-based fuels, hydrogen is both more and less dangerous. For example, in the event of a crash, passengers who survive the impact will be far safer if the aircraft is fueled by hydrogen than any other carbon-based fuel, as it has been found that people are killed by the flames of the fire caused by the fuel and by the toxic gases that emanate in the area of the fire, which usually burns for a long time. Hydrogen is the only fuel that escapes upward, and does not form a cloud of noxious fumes. Besides having the same disadvantages of Synjet, methane stays on the ground for a long time before diffusing into the atmosphere. It can therefore stay and/or move on the surface, and a fire or an explosion could result [23].

Another important aspect of the safety of hydrogen as compared to Synjet is the placement of fuel tanks. The two carbon-based fuel tanks are normally in the wing box, whereas the hydrogen tank is to be located in the fuselage. It has been found that, in a survivable crash, the fuselage is less exposed to damage than the wings [18].

Hydrogen has a wide flammability range, and this is a disadvantage in comparison with other fuels. However, the most important thing in almost all accidental situations is the low ignition limit, the parameters being very similar in hydrogen and methane and with lower values in Synjet. The minimum ignition energy for hydrogen in air is not a determinant, since even a weak ignition source that is present in almost every accident releases more energy than necessary and thus causes ignition. Hydrogen burns with intensely hot non-luminous flames and, for this reason, it is difficult to know where the limits in a hydrogen fire are. Hydrogen, like other non-toxic gases, may produce suffocation by diluting the concentration of oxygen in the air below the levels necessary to support life.

Liquid hydrogen, along with other cryogens, has a high liquid-to-gas volume expansion ratio, so that liquid hydrogen piping should always include a pressure relief

Table 5. The principal greenhouse gases and their emissions

Item	CO_2	N_2O	CH_4	CFC-11	CFC-12
Concentration in ppmv. Preindustrial time	280	0.28	0.79	0	0
Concentration in ppmv. Present time	353	0.31	1.72	0.28×10^{-3}	0.48×10^{-3}
Residence time in years	230	160	14.4	60	120
Global warming potential (weight basis)	1	180	10	1300	3700
Global warming potential (molar basis)	1	180	3.7	4000	10 000
Contribution to total greenhouse effect (%)	50	6	18	14[a]	
Contribution to total radiative forcing 1980–1990 (%)	57	6	12	25[a]	
Current increase (%)	0.5	0.25	0.9	4[a]	

[a]All the CFCs.

Table 6. Relevant safety properties of different fuels for air transport

Property	Synjet	Methane	Hydrogen
Flammability limits in air (vol%)	0.8–6.0	5.3–15.0	4–75
Detonation in air (vol%)	1.1–3.3	6.3–13.5	13–65
Minimum ignition energy in air (mJ)	0.25	0.29	0.02
Burning velocity (ms^{-1})	43	40	265
Autoignition temperature (°C)	440	40	585
Thermal energy radiated by surroundings (%)	33–43	23–33	17–25
Theoretical explosion energy (kg TNT/m^3 gas)	44.42	7.03	2.02
Diffusion coefficient in air ($cm^2 s^{-1}$)	0.05	0.16	0.61
Buoyancy in air (m/s)	No buoyancy	0.8–6.0	1.2–9.0
Toxicity	Toxic in concentration >500 ppm	Nontoxic (asphyxia)	Nontoxic (asphyxia)

device. Besides, hydrogen, like other gases, warms up when it expands, which introduces a possible cause for ignition since hydrogen leaks from a pressurized state. On the other hand, hydrogen needs higher temperatures for ignition, has a high normal burning velocity and emits less energy when it burns, which are the properties favorable to hydrogen in the case of fire [31]. In Table 6, some relevant safety properties of hydrogen, methane and Synjet are shown.

There is already plenty of experience in LH_2 handling, but problems may arise when massive utilization of hydrogen begins. The actual world production of over 30 million tons/yr, will have to be increased several thousand times during the transition from the present energy system to the one based on hydrogen. The creation of an infrastructure for producing, distributing and refueling commercial aircraft with liquid hydrogen represents a great challenge, that, apart from management risks, involves the need for heavy investment, norms and procedural regulations and, at the same time, the preparation of precise systems of prevention, discovery and suppression of hydrogen leakage situations, as well as personnel specializing in this new sector [32–35]. In addition to emergency procedures and training, safety inspection and maintenance will be very important issues to tackle. It will also be necessary to initiate a complete change of sources in terms of commercial hydrogen supplies to replace fossil fuel energy sources presently used. It will be necessary to make the transition to production systems that use renewable energy sources or nuclear power plants. Safe handling throughout the procurement and utilization chain, from production, storage and transport to liquefaction and combustion, is a complex issue that must be addressed [26].

Economics of LH_2 aircraft

Fundamentally, the cost of travel with a LH_2 fueled aircraft will depend on the price of the fuel. In fact, when considering the direct operating cost (DOC) for LH_2 aircraft, the most influential factor is the fuel cost, representing 50% of the total DOC [21].

In any case, an adequate comparison of hydrogen and Synjet costs is necessary if we want to come to realistic results. It is important to point out that, in the case of hydrocarbon fuels, only production costs are noticed, but external costs (viz. cost for pollution abatement, prevention and climate changes) need also be taken into account. Besides, it is also necessary to consider that LH_2 price will decrease as large scale industrial facilities are installed. On the other hand, hydrogen has a greater energy efficiency, which evens out the costs. We must not forget that time is in favor of hydrogen, and besides, the actual situation could cause a quick change in the price relationship between both fuels if environmental taxes are established on C or CO_2. In Table 7 the direct operating cost (DOC) for Synjet and hydrogen is compared, with the internalization of external costs (excluding the

Table 7. Comparison of direct operating cost (DOC)[a] of synjet and LH_2 for subsonic aircraft[b]

Price of Synjet in 1995	$0.73/gallon (excluding tax) or $5.34/GJ
Projected price of Synjet in 2000	$0.72/gallon or $5.63/GJ
Price of LH_2 (Hydropower, Electrolyzers) in 1995	$10.68/GJ
Projected price of LH_2 in 2000	$10.10/GJ
DOC ratio LH_2/Synjet in 1995	1.55
Environmental damage of fossil fuels	$0.03/kwh or $1.14/GJ
Higher utilization efficiency of H_2	1.20
Effective DOC ratio LH_2/Synjet in 1995	1.43
Effective DOC ratio H2/Synjet in 2000	1.39

[a]DOC, normally expressed as cent of $/seat km or cent of $/seat n.mi. is a function of the cost for the flight crew, capital costs, insurance, maintenance, fuel and fees.

[b]LCH_4 is usually considered a temporary solution because it presents the same problems as synjet and it is a limited resource.

Table 8. Estimates of world availability and distribution of oil and natural gas at the end of 1993

Zone	Total quantities of oil (in 10^9 barrels)	% of total	Reserves remaining (R/P[b] years)	Total Quantities of NG (in $10^9\,m^3$)	% of total	Reserves remaining (R/P[b] years)
Middle East	662.94	65.70	95	44 809	30.71	219
Asia and Australia	44.80	4.44	18	13 228	9.06	57
Non OECD[a] Europe	59.10	5.86	14	56 738	38.89	55
OECD[a] Europe	16.75	1.66	8	6295	4.31	34
Africa	61.85	6.13	25	9785	6.71	49
North America	38.64	3.83	9	7300	5.00	14
South America	124.92	12.38	43	7763	5.32	70
TOTALS	100	100	–	145 918	100	–

[a]OECD: Organization for Economic Cooperation and Development.
[b]R/P: reserves/production.

cost of CO_2 effect on climate) and utilization efficiency by using average values from various sources [36–39].

Furthermore, it is inescapable that the future evolution of both fuels will bring on opposing trends: a significant rise in Synjet price (as a consequence of its depletion) and a smooth decline in hydrogen prices as market grows and technology improves. The actual estimates of petroleum and natural gas world reserves are presented in Table 8, and the probable contributions of renewable energy sources in the US to the total energy demand in the year 2030, as compared to 1990 values, are shown in Table 9. It is therefore of great importance to produce large quantities of liquid hydrogen economically, because if both fuels have similar prices, LH_2 aircraft will be used [40, 41].

Another item to consider is the need to build industrial facilities for LH_2 production, since the current world production of hydrogen, which is around 30.10^6 tons/yr [42], would not cover the daily needs of even 20 airports the size of Chicago O'Hare, which would require around 3000 tons of hydrogen a day. On this point it is perhaps enlightening to see that the Euro-Quebec project for obtaining hydrogen from hydropower will only produce 40 tons/day [43]. It is also interesting to consider that the demand for hydrogen in the year 2000 will be almost 2.5 times higher than in 1980 [44].

Table 9. Contribution in 1990 and estimate for 2030 of renewable energies in US to total energy demand

Energy	Year 1990 $\times 10^{15}$ kJ	Year 2030 $\times 10^{15}$ kJ
Hydropower	3.2	3.6
Geothermal	0.2	1.0
Biomass	3.5	12.5
Solar thermal	<0.1	2.9
Solar photovoltaics	<0.1	2.0
Wind power	<0.1	3.0
Total renewable energy	7.2	25.0
Total energy demand	85.0	145.0

CONCLUSIONS

The main concern regarding the increase of emissions into the atmosphere and the depletion of oil reserves is an immediate need, at least partly, to replace hydrocarbon fuels. LH_2 is considered a good alternative, as its use reduces the emission of pollutants, and as it is a renewable synthetic fuel.

The large scale introduction of hydrogen into aviation presents no unsolvable technical problems, but it does involve the need for the following work items:

1. A thorough study of the components of a cryogenic fuel system, mainly as regards the structural materials for tanks, pipes and insulation systems.
2. Developing monitoring systems to detect hydrogen leaks in hydrogen installations.
3. Studies on load, structure and aerodynamics, due to the large volumes necessary for hydrogen tanks.
4. More practical work on achieving laminar flow control.
5. Research on reducing NO_x emissions.
6. A more thorough understanding of ice crystal aerosols and heterogeneous reactions that enable us to follow their real significance in water vapor and greenhouse gas.

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