# Working Paper

## Liquid Hydrogen Aircraft and the Greenhouse Effect

*David G. Victor*

WP-90-02
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# LIQUID HYDROGEN AIRCRAFT AND THE GREENHOUSE EFFECT

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## Preface

Road transport is presently by far the most important form of travel and goods transport. Air transport, however, is growing worldwide more rapidly than any other long-distance mode. Although it presently represents a small share in the total passenger-kilometers traveled and total tons of freight transported globally, sustained growth of air operations and possible further increases in commercial air transport well into the next century, could shift the emphasis of adverse environmental effects of transport systems from road to air. Often such an environmental assessment deals with local and regional air pollution and ecology. There is, however, also the possibility of longer-term global warming as a consequence of increased atmospheric concentration of so-called greenhouse gases released by aircraft.

Efficiency improvement and conservation would certainly help mitigate some of the adverse effects of increasing energy consumption in general and vehicle fuels in particular. There is also the possibility of a shift toward fuels with inherently lower levels of greenhouse gas emissions. Some energy carriers such as electricity and hydrogen do not emit any greenhouse gases in end-use, provided that they are produced by energy sources and technologies that themselves do not emit any greenhouse gases such as nuclear and solar energy. Aircraft powered by liquid hydrogen are such a technology. Combustion of hydrogen in air results in water vapor and nitrogen oxides.

David Victor demonstrates that such advanced air transport could play an important role in greenhouse gas reduction policy. Since the current fleets of conventional, kerosene fueled aircraft cannot be replaced overnight, David also incorporates various scenarios of fleet replacement regimes and efficiency improvements of both hydrogen and conventional transport in his analysis. He demonstrates that the overall carbon dioxide emission profile is very sensitive with respect to the assumed rates of change of the fleet structure and efficiency of aircraft.

The paper identifies an important policy dimension concerning the reduction of carbon dioxide emissions in the transport sector: Vigorous growth of air transport in the future could lead to continued increase in carbon dioxide emissions even under conditions of rapid replacement of conventional by liquid hydrogen aircraft. Other possible effects of hydrogen fueled aircraft, not analyzed in the paper, might aggravate the overall loading of the atmosphere as the result of further growth of air transport. For instance, higher water vapor concentrations along the flight routes, directly or indirectly through the formation of contrail cirrous clouds, could lead to enhanced "greenhouse" heating.

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Abstract

A simple model of the world air market is used to test the role that liquid hydrogen ($LH_2$) aircraft might play in reducing carbon dioxide ($CO_2$) emissions from this sector of the economy. I assume that $LH_2$ aircraft can penetrate up to 70% of the market and will do so along a logistic diffusion curve with $\Delta t = 40$ yrs. Using two scenarios--high and low demand--I find that although $LH_2$ aircraft and the $LH_2$ supply system can be configured to release no $CO_2$, the remaining conventional aircraft in the market continue to play a large role in the total sector $CO_2$ emissions. The model is very sensitive to the balance between the $LH_2$ substitution effect, market growth, and efficiency growth. Liquid hydrogen aircraft can help reduce $CO_2$ emissions, but reducing $CO_2$ emissions below current levels will also require constraints on growth in the entire air market.

## Introduction

Recently, scientific and political attention has focused on the theory of global warming due to the emission of "greenhouse" gases such as $CO_2$, $CH_4$, $N_2O$, and chlorofluorcarbons (CFCs). Numerous studies have outlined the relative effects of these gases,[1] and it is widely believed that reductions in some or all of these would be a central component of an effective greenhouse policy. Through the framework of the Montreal Protocol, 80 nations have agreed to limit the emission of CFCs;[2] and at national levels, policies are emerging to cut emissions of $CO_2$,[3] the most abundant and largest contributor to the anthropogenic greenhouse effect.[4]

$CO_2$ reductions are possible through a number of pathways: 1) energy conservation can reduce the amount of energy required thereby reducing $CO_2$ produced as a byproduct of energy consumption.[5] 2) Energy consumers can switch to less $CO_2$-intensive fuels such as natural gas (methane).[6] And 3) shifts to "zero-$CO_2$" technologies like solar, nuclear, and hydroelectric might allow energy consumption without $CO_2$ emissions.[7]

In the air transportation market, liquid hydrogen-fueled ($LH_2$) aircraft may be one such "zero-$CO_2$" technology. The aircraft themselves emit only water vapor and nitrogen oxides, and if "zero-$CO_2$" technologies are used in the production of liquid hydrogen, these aircraft might play an important role in a greenhouse gas reduction policy. To test this hypothesis, I have developed a model of the aircraft market and used it to project to the year 2075 with liquid hydrogen aircraft penetrating the market starting in 2000. The structure of the model is summarized in figure 1, and the four classes of included variables are discussed below.

Market penetration

Numerous studies on the diffusion of new technologies into the marketplace have noticed that market share follows logistic curve trends similar to the niche competition between species.[8] For this analysis, it is assumed (somewhat arbitrarily) that liquid hydrogen aircraft are introduced in the year 2000 and will ultimately penetrate up to 70% of the air transport market with the main diffusion taking place over 40 years ($\Delta t$ = 40 yrs). The remaining 30% will likely consist of short-range flights (ill-suited for liquid hydrogen technology) and flights to and from airports which are infrequently used (where liquid hydrogen distribution and storage facilities would be highly cost ineffective). It is difficult to imagine that versatile petroleum-based liquid fuels will entirely disappear from the market. However, there are many reasons why synthetic fuels (e.g. Synjet) may become widely used for remaining conventional jet aircraft, but these may not affect $CO_2$ calculations, though in many cases synthetic fuels release more $CO_2$ per unit of energy, depending on the process used to manufacture the fuel.

Figure 2 summarizes the scenario diffusion of liquid hydrogen aircraft the market[9] and figure 3 shows the changing market shares for conventional jet aircraft and liquid hydrogen aircraft.

Market growth

Concern about the greenhouse effect, energy security, and other energy-related issues has focused attention on the role conservation might play in the future. However, it is not clear how extensively conservation measures might be followed, so two scenarios are used. The high-demand scenario (figure 4) assumes that the air market will follow past growth trends from the present to the year 2075.[10] Since 1970, growth has been about 7% per year; since 1980 the average growth rate has been about 6% per year.[11] In general, growth rates in the air transport market have been decreasing since 1945 so a lower number like 5% might be the most reasonable assumption for a high demand case, though it is possible growth may be higher. For this scenario, it is assumed that 50% of the liquid hydrogen aircraft are supersonic; much of the air market growth would result from the availability of economical, high speed transportation. Although many problems such as ozone depletion from supersonic aircraft exhaust remain unresolved,[12] this growth scenario with 1/2 the $LH_2$ ton-km supersonic simply represents a likely upper bound on energy use in the future air market.

Higher energy prices, better alternatives to air transport, regulatory programs to limit energy use, and noise or environmental concerns might all yield lower growth in the air market. A low demand scenario (figure 5) assumes 5% per year growth to the year 2000 then, as part of broad conservation effort, growth is gradually reduced to zero. By 2075, the air market stabilizes at about five times 1989 levels. For this low demand scenario it is assumed that essentially all the aircraft will be subsonic.

Putting these scenarios in perspective, figure 6 shows the ton-km per capita for both the high and low demand cases. Population statistics from World Bank forecasts predict gradually decreasing growth rates from the current 1.7% per year to an average of 0.26% per year for the period 2050 to 2075. Population reaches 10.17 billion in 2075.[13] Note that other forecasts such as those by the United Nations predict more vigorous population growth, at least through 2025.[14]

The results of other air market forecasts are superimposed on figures 4, 5, and 6. Fitting a long wave scenario to past air transport volume, Nakicenovic and Grübler suggest that penetration of conventional jet aircraft into the intercity transport market will peak in about 2010.[15] They argue that conventional jet aircraft market shares will then gradually decrease when new transport systems--probably liquid hydrogen or natural gas aircraft--penetrate the market. Both the high and low demand scenarios exceed Nakicenovic and Grübler's forecast for conventional aircraft. However, Nakicenovic and Grübler have noted that in the past, diffusion of jet aircraft into the transportation market led to a ten-fold increase in travel.[16] Such a 40 year pulse for liquid hydrogen aircraft starting in 2000 is consistent with the high demand forecast which relies, in part, the introduction of practical supersonic aircraft for market growth. Supersonic transport might offer the same revolution in transportation that the jet aircraft did thirty years ago.

Boeing estimates on market growth are also shown and are quite similar to my scenarios although they only extend to 2005. Boeing predicts 5.3% growth per year from 1986 to 2000 then 4.9% from 2000 to 2005.[17]

## Efficiency

Some information on liquid hydrogen aircraft efficiency is available from a Soviet test in April, 1988.[18] Although the Soviet aircraft was configured as a test aircraft and performance details remain incomplete,[19] their flight indicates that liquid hydrogen technologies can work in existing production aircraft.[20] However, for this analysis I have relied on a series of more detailed feasibility studies for $LH_2$ aircraft at the Zurich airport (Zurich study)[21] which combined representatives from all branches of the air transportation industry. These data are probably as reliable as currently possible.[22]

According to the Zurich study, a "conservative" estimate is that production hydrogen aircraft will have higher empty weight than their conventional jet counterparts but roughly comparable weight is saved by the high energy density of hydrogen fuel. Thus operating weights of long-range (10,200 km) hydrogen and conventional aircraft will likely be about the same; therefore, energy requirements will be similar.

However, this probably represents a worst case for hydrogen aircraft since many of the associated technologies have not been fully explored in production aircraft to the same extent as conventional jet technologies. An "ideal" case for liquid $H_2$ aircraft would be 70% more efficient than new conventional aircraft; an "advanced" case--between the "conservative" and "ideal" case--would be 50% more efficient than conventional jet aircraft.[23] Better fuel systems, lightweight hydrogen storage tanks, engines, and aircraft designed to optimize liquid hydrogen advantages may all contribute to lower weights, less drag, and better fuel economy. I will use an "advanced" liquid hydrogen aircraft with an efficiency of about 100 ton-km/MBTU when it first appears on the market in 2000.[24]

Although individual hydrogen aircraft may only be 50% more efficient than <u>new</u> conventional jet aircraft, statistics on existing aircraft efficiency indicate the conventional jet <u>fleet</u> is substantially less efficient than new aircraft. New aircraft may reach efficiencies of 65 ton-km/MBTU (at the current 67% load factor), but fleet averages for OECD countries in 1985 were 33 ton-km/MBTU.[25] US average figures were about the same, and world figures were about 10% lower.[26] It is unclear how to test this data since highly reliable sources on fuel consumption and aircraft use are not available; this is especially true for world data. However, the US/OECD figures are probably as reliable as currently available and are used for this analysis.

Clearly projecting efficiency improvements is complex and includes many factors such as economic growth and fuel prices that are nearly impossible to include in a long-range forecast. Since 1970 the average growth in efficiency has been about 5% per year but in the early 1980s that rate dropped to about 2.5% per year. For this forecast, I have assumed that efficiency will continue to improve at 2.5% per year while the most inefficient aircraft are substituted out of the fleet. In 1995 the rate will start to decline such that by 2005 the efficiency improvement for conventional aircraft is 1% per year where it will stay until 2075 (figure 7). This schedule of efficiency growth will put the fleet of conventional jet aircraft at nearly half the efficiency (48 ton-km/MBTU) of liquid hydrogen aircraft in 2000.

I am assuming that these long term efficiency increases will likely come from two areas: first, investments in information systems will increase aircraft utilization from current levels of 67%.[27] Second, advances in composite materials, engines, flight management systems, and coordinated air traffic control will all lead to lower fuel use per flight. However, beyond the efficiency differences at the time of introduction, liquid hydrogen aircraft will not become progressively more or less efficient than conventional aircraft since these efficiency increases equally apply to both aircraft technologies.

Computing the efficiency of supersonic liquid hydrogen aircraft for the high demand scenario is quite difficult. Supersonic technology--mostly the domain of the military--has not been tested in production civilian air transport since the introduction of the Concorde. Consequently, there is not a clear indicator of the efficiency losses that are incurred with supersonic aircraft which are also designed with fuel economy in mind. NASA research on supersonic passenger aircraft suggests that conventional fueled supersonic passenger aircraft may be consistently half as efficient as subsonic aircraft.[28] I have assumed the same proportion will prevail for liquid hydrogen aircraft. However, this may understate the eventual relative efficiency of supersonic liquid hydrogen aircraft: although a huge drag penalty exists for supersonic flight, liquid hydrogen cooling of flight surfaces may offer unparalleled advantages in drag reduction at supersonic speeds.[29] As with subsonic $LH_2$ and conventional aircraft, efficiency of supersonic $LH_2$ aircraft is assumed to increase 1% per year. Note that with these assumptions, supersonic $LH_2$ aircraft are slightly more efficient than subsonic conventional aircraft; as mentioned before, this study probably assumes the best cast for liquid hydrogen aircraft relative to conventional jet aircraft.

## Liquid hydrogen production

The combination of market growth and efficiency yields projections for $LH_2$ demand which is then fulfilled using one or both of two $LH_2$ production technologies. First, hydrogen can be produced from water by electrolysis and then liquified. Based on data reported in the Zurich study, it is assumed that the electrolysis process is about 68% efficient which is consistent with "membrel" ionexchange electrolytic cells under development.[30] An additional 25% energy input is required to cool the hydrogen gas to $19^{o}K$. The entire process requires about 61.5 kwh per kilogram of liquid hydrogen produced: overall, the process is about 54% efficient.[31] Based on the "advanced" case, a liquid hydrogen airplane with 36 ton (400 passengers plus baggage) payload will require about 22 tons of liquid hydrogen for a 10,200km flight.[32]

6% of all electricity delivered from power plants to a liquid hydrogen plant is assumed lost in transmission which is consistent with current experience.[33] The ultimate demand for electricity (64.7 kwh per kg of $LH_2$) is met by one of three generation technologies: oil, natural gas (NG), or nuclear.

For oil and gas, electricity generation efficiencies are widely distributed due to different technologies and management practices, but an average figure of 37% for oil[34] and 50% for gas[35] is realistic for generation capacity built at the margin to supply electrolysis plants.[36] It is assumed that the entire electrolysis process--from electricity generation to liquefaction--will increase in efficiency by .5% per year from 1989 levels to 2000 then 1% per year until 2075. These improvements are due to increases in three areas: generation and transmission efficiency, electrolysis technology, and cryogenic technology. Nakicenovic has noted that efficiency changes in general are highly dependent upon pricing or other incentives,[37] so my assumption of gradual efficiency changes is only valid if such long-term incentives exist in the future. In 2075, the whole process is 2.3 times as efficient as today which represents a best case for efficiency improvements since electricity generation/transmission (at least for natural gas) is currently close to the theoretical (second law) efficiency. Therefore, this scenario for efficiency improvements relies heavily upon increases in electrolysis and liquefaction technologies.[38]

In terms of $CO_2$ emitted, natural gas is even more efficient than oil since the latter releases about 40% more $CO_2$ per unit of energy produced.[39] Nuclear power is assumed not to release any $CO_2$.

A second means of $LH_2$ production is steam reforming of natural gas:

$$CH_4 + 2H_2O \xrightarrow{\text{Energy}} CO_2 + 4H_2$$

Marchetti has suggested running the process with nuclear heat and discharging the high purity $CO_2$ back into oil wells or vacant natural gas deposits; as with nuclear electricity generation and electrolysis, the process would not release $CO_2$. Reforming would also be more efficient since efficiency losses from electricity generation would be avoided.[40]

$CO_2$ from steam reforming may also be vented to the atmosphere if recharging it into the ground is not feasible (e.g. if oil/gas fields are not nearby), but doing so would not appreciably alter the scenarios for steam reforming. The high energy density (energy per molecule) of $H_2$ allows very little $CO_2$ production per unit of combustible $H_2$ energy produced.

There are, of course, many technologies such as solar power which do not release $CO_2$, all of which are subsumed under the category "nuclear/renewable." For other reasons--environment, economics, risk, etc.--some of these may be more favorable than others, but in terms of $CO_2$ emitted they are all the same.

In calculating $CO_2$ from conventional jet aircraft there is an assumed 7% loss from refining operations (needed to produce jet fuel).[41] $CO_2$ emissions due to transport of fuel are not included; also, $CO_2$ emissions due to industrial activity required to build aircraft, airports, hydrogen plants, etc. are also omitted. Consequently, the model will underestimate total $CO_2$ emissions by several percent; however, many of these errors will exist systematically and probably not affect the comparison of different scenarios.

## Results

The two scenarios--high and low demand--are summarized in table I, and results from the two scenarios are shown in figures 8 and 9. Percentage changes in $CO_2$ are compared with $CO_2$ emissions from air transport in the base year 2000. A number of national policies aimed at reducing $CO_2$ emissions use a base year system for setting target emission levels. Furthermore, international efforts to control greenhouse gas emissions may follow the pattern of the Montreal Protocol on ozone-depleting substances which set emission levels as percentages of base year (1986) emissions.[42] Thus base year analyses may be the most useful means of assessing different scenarios and their contribution to greenhouse warming.

In an effort to put $CO_2$ emissions from air transport in perspective with other fossil fuel uses, absolute values for $CO_2$ emissions due to my different scenarios are reported in table II. In 1980, $CO_2$ emissions due to all fossil fuel uses was about 5200 trillion g of carbon per year,[43] so emissions due to air transport are relatively small (but, remarkably, not that small under the high demand scenario). However, $CO_2$ reduction schemes may require somewhat proportional cuts in all sectors, so the curves (figures 8 and 9) should be a guide to the role of liquid hydrogen aircraft in achieving such proportional cuts (or growth limits) in $CO_2$ emissions from the world air market.

In general, differences in $CO_2$ emissions between the two scenarios are from two areas. First, the low demand scenario is more efficient because all aircraft are subsonic; although efficiency increases over time are the same for both scenarios, supersonic aircraft are assumed consistently half as efficient as subsonic aircraft. Second, the low demand scenario simply entails fewer ton-km performed.

The high demand scenario leads to exponential $CO_2$ increases, even when liquid hydrogen is produced without any $CO_2$ byproduct (nuclear/renewable curve). A strong substitution effect is evident in 2010 to 2050: the nuclear/renewable (i.e. no $CO_2$) curve is nearly flat since substitution to zero-$CO_2$ technologies is about equal to $CO_2$ growth from remaining conventional aircraft. Note that this exponential trend would still be evident if efficiency grew at the recent trend of 2.5% per year rather than the 1% per year that I have assumed. For the high demand scenario, market growth is substantially more vigorous than efficiency growth.

If the assumption that liquid hydrogen aircraft can only penetrate 70% of the market is correct, $CO_2$ emissions from air transport with nuclear/renewable $LH_2$ production will climb to five times base levels simply because the entire market--including non-$LH_2$ operations--is increasing. The figures are much higher for non-nuclear $LH_2$ production.

In such an expanding market, reducing $CO_2$ emissions to base levels would require at least 94% penetration and complete use of non-$CO_2$ technologies for liquid hydrogen production. With such a scenario, $CO_2$ from air transport would return to base levels in 2062, but by 2075 emissions from the remaining 6% conventional ton-km would rise again to about 1.3 times base levels.

The low demand scenario demonstrates the critical role that growth restraints in combination with efficiency improvements can play in greenhouse gas reductions. $CO_2$ emissions from the air transport sector return to base year levels by 2040 if nuclear/renewable technologies are used to produce liquid hydrogen. Increases of 100% to 200% are evident around 2035 if other technologies are used to produce liquid hydrogen, but thereafter emissions steadily decline. Efficiency improvements overtake market growth in about 2040 and produce these declines. Note that the "no $LH_2$" curve which represents the $CO_2$ increases that would result if no liquid hydrogen aircraft were used has a slightly different shape from the NG and oil curves. This is because NG and oil incorporate two efficiency increases--one in the aircraft and one in the electrolysis--whereas the "no $LH_2$" curve includes only aircraft efficiency improvements. Once efficiency improvements dominate the $CO_2$ emission patterns, the $LH_2$ curves decline faster than the "no $LH_2$" curve. These trends are not visible when market growth dominates $CO_2$ emission patterns (high demand case).

Ausubel et al. have argued that an emerging "methane economy" is increasingly reliant upon natural gas energy sources.[44] Such an economy would likely include liquified natural gas (LNG) aircraft. Indeed, the Soviet liquid hydrogen flight was a first step in the development of a LNG aircraft which was later tested in January, 1989.[45] For comparison, a curve representing LNG airplanes is also included. Since $LH_2$ and LNG technologies are similar, it is assumed that LNG aircraft will have the same efficiency[46] and market penetration as liquid hydrogen aircraft but the higher boiling point of natural gas requires only a 4 KWH/kg energy input for liquefaction (liquid hydrogen required 12.5 KWH/kg).[47] Energy for liquefaction comes from a natural gas-fired electric power plant with the efficiency assumptions outlined earlier. The efficiency of the entire liquefaction process is assumed to increase 0.8% per year.[48] Note that the LNG curves offer a median case between nuclear/renewable $LH_2$ and oil-based electrolytic production of $LH_2$. LNG emissions are lower than those of conventional jet aircraft ("no $LH_2$" curve). In sum, LNG aircraft can contribute to $CO_2$ reduction efforts since $CO_2$ emissions are lower than conventional jet aircraft based on the efficiency assumptions in this analysis. Furthermore, using LNG aircraft is a better option in terms of $CO_2$ emissions than using $LH_2$ aircraft if it is believed that the nuclear/renewable option will not be usable at some point in the future.

The relationship between the no $LH_2$ curve and the others curves reflects my best estimates for system efficiencies. Clearly if the relative efficiencies of liquid hydrogen aircraft and conventional aircraft change over time, the relationship between these curves will change as well. For example, a modest campaign to reduce the age of the conventional jet aircraft fleet might increase the efficiency of the fleet by 15% or 20% which would make conventional jet aircraft (i.e. no switching to $LH_2$ or LNG) a much more appealing option.

## Conclusions

Without 100% penetration of non-$CO_2$ technologies--which is unlikely--there are no technological "fixes" for the greenhouse effect, at least not in a rapidly growing transportation sector. Liquid hydrogen aircraft can play an important role in a campaign to reduce greenhouse gas emissions, but the model suggests that restricting market growth is equally important.

Efficiency improvements are also important. For scenarios with essentially unrestricted market growth (high demand), realistic efficiency improvements are overwhelmed by growth and $CO_2$ emissions grow exponentially. But if demand is controlled at or below the rate of efficiency improvements (low demand scenario) there is ample room for technological fixes--like liquid hydrogen aircraft--to play a significant role in reducing greenhouse gas emissions. Although difficult to administer, this research suggests that a policy of setting target market growth at or below fleet efficiency improvements may be the basis for a sane greenhouse policy. Rather than unrestricted economic growth, policies might be tuned towards an efficiency-driven process. New technologies such as the introduction of liquid $H_2$ aircraft could then be used to shift the emission curves down, depending on degree of market penetration. This approach may be helpful for policy makers interested in mitigating greenhouse gas emissions, decreasing energy consumption for economic or security reasons, or reducing other emission-dependent effects such as acid rain or urban pollution. Please note, however, that emissions other than $CO_2$ from liquid hydrogen aircraft are not examined in this paper: there may be serious environmental effects from, for example, the release of nitrogen oxides and/or hydrogen in the upper atmosphere. The case in favor of liquid hydrogen aircraft may be different if these emissions are included in addition to $CO_2$.

Finally, a scheme to reduce $CO_2$ emissions with liquid $H_2$ aircraft may be heavily dependent upon nuclear reactors. Solar and hydroelectric production of $LH_2$ are being explored (both are "zero $CO_2$ technologies), but for areas poor in hydro and solar resources, transport of $LH_2$ from hydro/solar production sites may be an unattractive option when compared with local production of $LH_2$ using nuclear power. However, many serious social and engineering issues that pertain to nuclear power remain to be resolved. In sum, the capacity to produce $LH_2$ without (or with minimal) $CO_2$ releases may be limited in many areas of the world.[49]

## Notes

1. e.g. R.E. Dickinson and R.J. Cicerone, 1986. "Future Global Warming from Atmospheric Trace Gases," Nature 319:109-115.

2. In May, 1989 the signatories met and agreed, in principle, to ban the production of CFCs. Currently the Montreal Protocol calls for a 50% reduction from 1986 production by 2000 with a 10 year delay for developing countries. See C.R. Whitney, 1989. "80 nations favor ban to help ozone," New York Times, May 13, p.A9.

3. e.g. the Netherlands has introduced a policy to cut $CO_2$ by 20% to 30% by the year 2010. However, funding issues related to the policy have led to the downfall of the present cabinet. Dr. Jös Bruggink, 1989 "Sustainable Development and Energy Policy in the Netherlands," presented at International Institute for Applied Systems Analysis, Laxenburg, Austria; 19 June.

4. The relative contributions of greenhouse gases, their trends, atmospheric processes and effects are reviewed in B. Bolin, B.R. Doos, and J. Jaeger, eds., 1986. The Greenhouse effect, Climatic Change, and Ecosystems: Synthesis of Present Knowledge (Chichester: Wiley).

5. e.g. A.B. Lovins, L.H. Lovins, F. Krause, and W. Bach, 1982. Least Cost Energy: Solving the $CO_2$ Problem (Cambridge, MA: Brick House Publishing).

6. e.g. W.M. Burnett and S.D. Ban, 1989. "Changing Prospects for Natural Gas in the United States," Science 244:305-310. Oil and coal emit about 40% and 80% (respectively) more $CO_2$ per unit of energy than natural gas.

7. e.g. D. Rose, M. Miller, and C. Agnew, 1983. "Global Energy Futures and $CO_2$ Induced Climate Change," MIT Energy Laboratory 83-015, Massachusetts Institute of Technology, Cambridge, MA.

8. J.C. Fisher and R.H. Pry, 1971. "A simple substitution model of technological change," Technol Forec & Soc Chg 3:75-88. For an application of this diffusion principle to automobile technologies see N. Nakicenovic, 1986. "The Automobile Road to Technological Change," Technol Forec & Soc Chg 29:309-340.

9. The curve is from an equation of the form:

$$\text{market fraction} = \frac{K}{1 + \exp(-b(t-t_o))}$$

where K is .7 (70%) and b is a constant set by the rate of diffusion (b=0.1099 for this model). $\Delta t$, the time it takes from penetration of 10% of the market (when K is 1) to 90% of the market is 40 years.

10. The air market is measured in revenue ton-km performed.

11. IATA, 1988. World Air Transport Statistics, 1987 and earlier issues of World Air Transport Statistics.

12. A byproduct of high aircraft engine temperatures is the emission of nitrogen oxides which catalytically destroy ozone. For a summary of issues surrounding stratospheric flight and ozone depletion see M.B. McElroy, 1976. "Man's Impact on the Global Environment: some recent problems in atmospheric pollution," in Atomic Processes and Applications pp.73-107 (Amsterdam: North-Holland). See, especially, the chart on page 97.

13. K.C. Zackariah and M.T. Vu, 1988. World Population Projections: 1987-88 edition (Baltimore: Johns Hopkins press for the World Bank).

14. United Nations, 1988. "UN population estimates and projections, revised 1988," (chart). Projections only through 2025 when world population is estimated to by 9.5 billion.

15. N. Nakicenovic and A. Grübler, 1989. "World Volume of Air Transport," chart; International Institute for Applied Systems Analysis, Laxenburg, Austria.

16. N. Nakicenovic and A. Grübler, 1989, personal communication.

17. Boeing corporation, 1988. Current Market Outlook (Seattle). To avoid accounting differences, we have used our 1986 data from IATA and projected into the future with the Boeing growth figures. Therefore, the points marked "Boeing" only reflect Boeing growth estimates.

18. Associated Press, "Soviets claim world first with completed test flight of plane using liquid hydrogen fuel," 16 April 1988.

19. The aircraft was a TU-155, the designation given to a cryogenic version of the TU-154. The center engine was fueled by liquid hydrogen and believed to be an NK-88, an older version not installed in new production TU-154 aircraft. Jane's All the World's Aircraft: 1989 (London: Jane's), p.271. Due to the engine differences and the fact that half the rear cabin was occupied by liquid hydrogen tanks, it is difficult to extend useful information on production efficiency from the test.

20. However, the airplane was extensively modified to accommodate the liquid hydrogen fuel system, and only one of the three engines ran on liquid hydrogen.

21. H.P. Alder, 1986. Hydrogen in Air Transportation Feasibility study for Zurich airport, Switzerland, EIR-Bericht Nr. 600, p.7.

22. Reliable data also exist from studies that explore conversion of Airbus A-300 aircraft to $LH_2$ fuel use. However, these are not directly applicable to my study since the aircraft would be short range (European continent only) and would be conversions of existing aircraft designs. Many of the advantages of $LH_2$ could not be used without completely new designs. For more information see, for example, "Pilotprojekt Airbus mit

Wasserstoffantrieb," MBB Unternehmensgruppe Transport und Verkehrsflugzeuge report March 1989 (Tel: Germany 155-060/89).

23. H.P. Alder, 1986. Hydrogen in Air Transportation Feasibility study for Zurich airport, Switzerland, EIR-Bericht Nr. 600, p.7.

24. According to the Zurich study, the efficiency for a fully loaded "advanced" aircraft is 149 ton-km per MBTU; the figure is 100 ton-km/MBTU when corrected for a load factor of 67% which is the current rate for all commercial flight operations.

25. Calculated from Energy balances of OECD countries (for fuel consumption) and IATA and UN statistics (for ton-km).

26. Computed from Shell Energy Demand (fuel data) and an estimate of world aircraft use based on IATA data (for ton-km).

27. Aircraft utilization for all commercial operations of ICAO airlines as reported in IATA, 1988. World Air Transport Statistics, 1987.

28. F.E. McLean, 1985. Supersonic Cruise Technology (Washington: NASA), p.168. Available from the Supt. of Documents, NASA SP-472.

29. Liquid hydrogen must be warmed from 19°K to operating temperatures with heat exchanges using ambient heat. One theory is that the heat exchangers could also serve to influence the aerodynamics of the aircraft.

30. The term "efficiency" as used here is simply the ratio of energy out of the system (i.e. from burning the $LH_2$ in a calorimeter) to the total energy inputs.

31. Other studies use similar efficiencies: an overall efficiency of 55.3% was used in a German study on the possibility of $LH_2$ production in Canada. This does not include the energy required to transport the $LH_2$

to Germany for final consumption (efficiency drops to 44.6% when maritime transport is included). See "A Study for the Generation, Inter-Continental Transport, and Use of Hydrogen as a Source of Clean Energy, on the Basis of Large-scale and Cheap Hydro-Electricity," Hydrogen Pilot Project--Canada, translation of German final report issued June, 1987.

32. H.P. Alder, 1986. Hydrogen in Air Transportation: Feasibility Study for Zurich-Airport, Switzerland, EIR-Bericht Nr. 600. p.7.

33. Computed from OECD statistics in OECD, 1989. Energy Balances of OECD Countries (Paris: OECD).

34. Computed from OECD statistics on oil energy input and electricity output from oil generation equipment in OECD countries. OECD, 1989. Energy balances of OECD countries (Paris: OECD).

35. A reasonable value based on the range of possible efficiencies for current and near-term gas-fired power plants as outlined in T.H. Lee, 1987. "Combined Cycle Systems: Technology and Implications," in T.H. Lee et al., eds. The Methane Age (Dordrecht: Kluwer Academic), a IIASA publication.

36. The United Nations uses a lower figure (20%, converted into coal equivalents) as an average for all power plants, but new power plants built at the margin to produce electricity for electrolysis will be able to achieve higher efficiencies. UN data from United Nations, 1986. 1984 Energy Statistics Yearbook, p. xviii.

37. N. Nakicenovic, 1986. "Patterns of Change: Technological substitution and long waves in the United States," IIASA working paper WP-86-13.

38. Electrolysis at nearly 100% efficiency is technically feasible, so an increase to 2.3 times 1988 efficiency is not unrealistic, assuming efficiency of liquefaction technologies will improve substantially as well. Note, however, that opportunities for efficiency improvement may be larger for oil-fired

power plants (currently assumed at 37% efficiency) than for gas-fired plants (assumed at 50% efficiency today).

39. Oil releases 0.020256 g C per BTU of energy; natural gas releases 0.0144535 g C per BTU of energy; from J.A. Edmonds, W.B. Ashton, H.C. Cheng, and M. Steinberg, 1989. "A preliminary analysis of U.S. $CO_2$ emissions reduction potential from energy conservation and the substitution of natural gas and coal in the period to 2010." DOE/NBB-0085. I have assumed that oil products (e.g. jet fuel) have about the same emissions per BTU as oil.

40. C. Marchetti, 1988. "How to solve the $CO_2$ problem without tears." Plenary speaker, 7th World Hydrogen Conference, Moscow, Sept. 25-29.

41. Includes oil, gas, coal, and electricity inputs to refineries divided by the total oil energy requirement for OECD countries. Different fuel sources corrected for different carbon contents (electricity corrected based on the current fuel mix and standard powerplant efficiency). Calculated from 1986 statistics for all OECD countries in OECD, 1988. Energy Balances of OECD Countries (Paris: OECD) pg 4.

42. United Nations Environment Programme, 1987. "Montreal Protocol on Substances that Deplete the Ozone Layer: Final Act," done 16 September, 1987.

43. in W.C. Clark, ed., 1982. Carbon Dioxide Review: 1982 (New York: Oxford University Press), table 15, part 4.

44. J. Ausubel, A. Grübler, and N. Nakicenovic, 1988. "Carbon Dioxide Emissions in a methane economy," Clim. Change 12:245-263.

45. TASS, 1989. "Planes will fly on natural gas, Soviet experts believe," 19 January.

46. In an advanced or ideal case, LNG may be slightly less efficient than $LH_2$ since the energy density of LNG is higher than $LH_2$ so the LNG plane may be slightly heavier. However, this may be offset by potential LNG advantages over $LH_2$ such as a higher boiling point and presumably easier handling and storage characteristics.

47. The energy required for this step depends on the design tradeoff between pressure and temperature. At higher pressures LNG does not have to be as cold. Based on the liquid hydrogen cooling process which cools $LH_2$ to $19^{o}K$ in three steps I have computed the 4 KWH requirement using one stage and liquid nitrogen to cool the LNG to $111^{o}K$.

48. This represents a reasonable share of the total 1% per year efficiency improvement for the electrolysis process discussed earlier. Since LNG does not require electrolysis it is not appropriate to take the full efficiency increase.

49. I would like to thank J. H. Ausubel, A. Grübler, N. Nakicenovic, and J. Van de Vate for their helpful comments on the model and this paper. This research was supported by a grant from the Center for International Studies at the Massachusetts Institute of Technology for three months of research at the International Institute for Applied Systems Analysis.

## Captions

Figure 1: Summary of model structure.

Figure 2: Top curve: penetration of liquid hydrogen aircraft into that portion of the world air market (70%) that is suitable for liquid hydrogen aircraft. Notice that it takes 40 years to penetrate from 10% of the suitable market (2010) to 90% of the market (2050). Bottom curve: penetration of liquid hydrogen aircraft into the entire air market.

Figure 3: Changing world market shares for liquid hydrogen and conventional jet aircraft based on the pattern of penetration summarized in figure 2.

Figure 4: High demand scenario for growth in world air market measured in annual revenue ton-km performed. Assumed 5% growth per year to 2075.

Figure 5: Low demand scenario for growth in world air market measured in annual revenue ton-km performed. Assumed 5% per year growth to 2000 then gradual growth reductions to 0%.

Figure 6: World air transport demand in annual revenue ton-km per capita for high and low demand scenarios.

Captions, cont.

Table I: Summary of assumptions for high and low demand scenarios.

Figure 7: Efficiency increases over time (1% per year) for world fleet of supersonic and subsonic liquid hydrogen aircraft and subsonic conventional jet aircraft. Historical efficiency statistics based on data for OECD countries; world efficiency may actually be lower.

Figure 8: Changes in annual worldwide $CO_2$ emissions due to air transport (2000 = 0%) with the high demand scenario.

Figure 9: Changes in annual worldwide $CO_2$ emissions due to air transport (2000 = 0%) with the low demand scenario.

Table II: Absolute levels of annual $CO_2$ emissions (in $10^{12}$ g C per year) under the different scenarios shown in figures 8 and 9.

Figure 1

**Structure of the model**

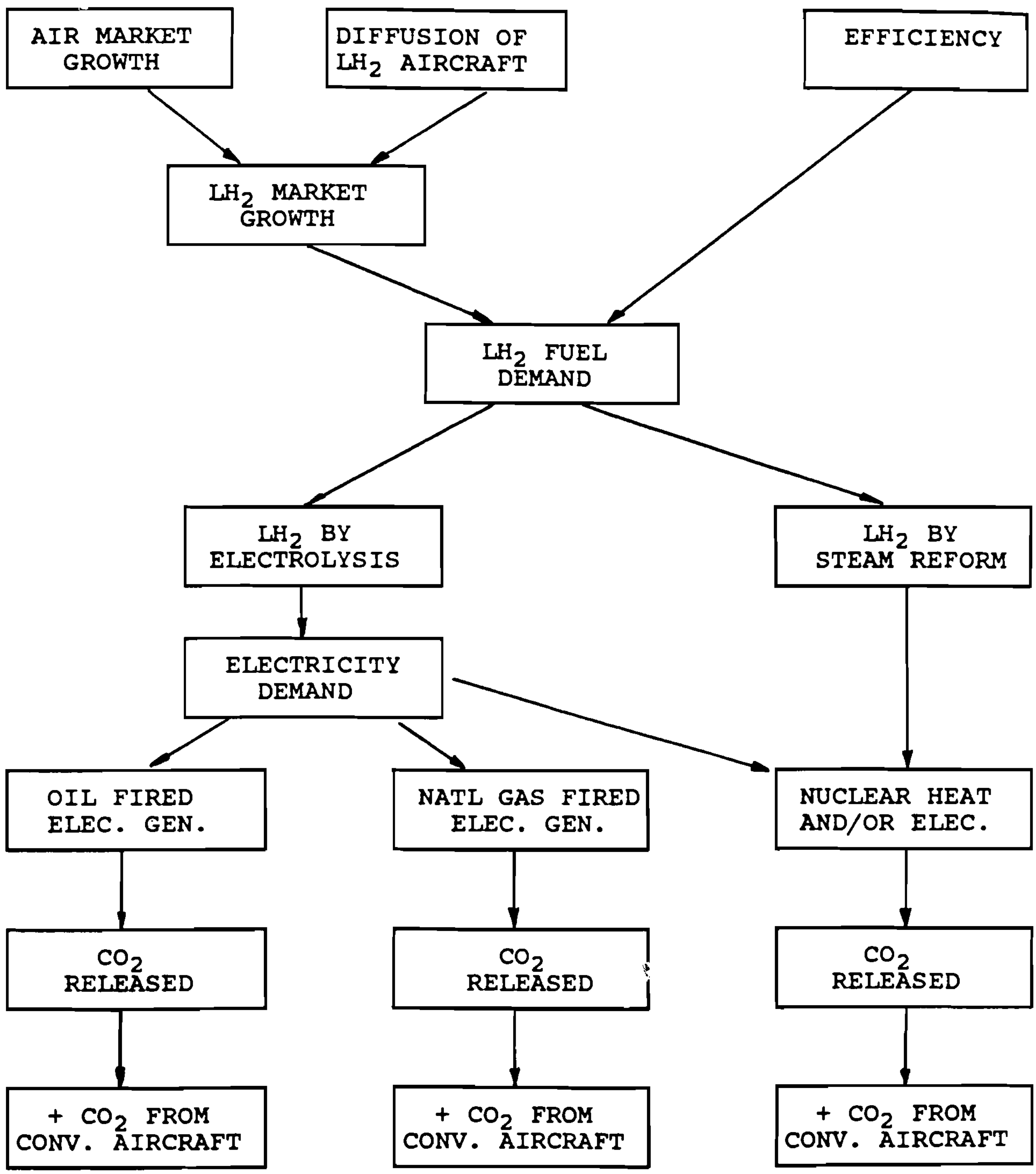
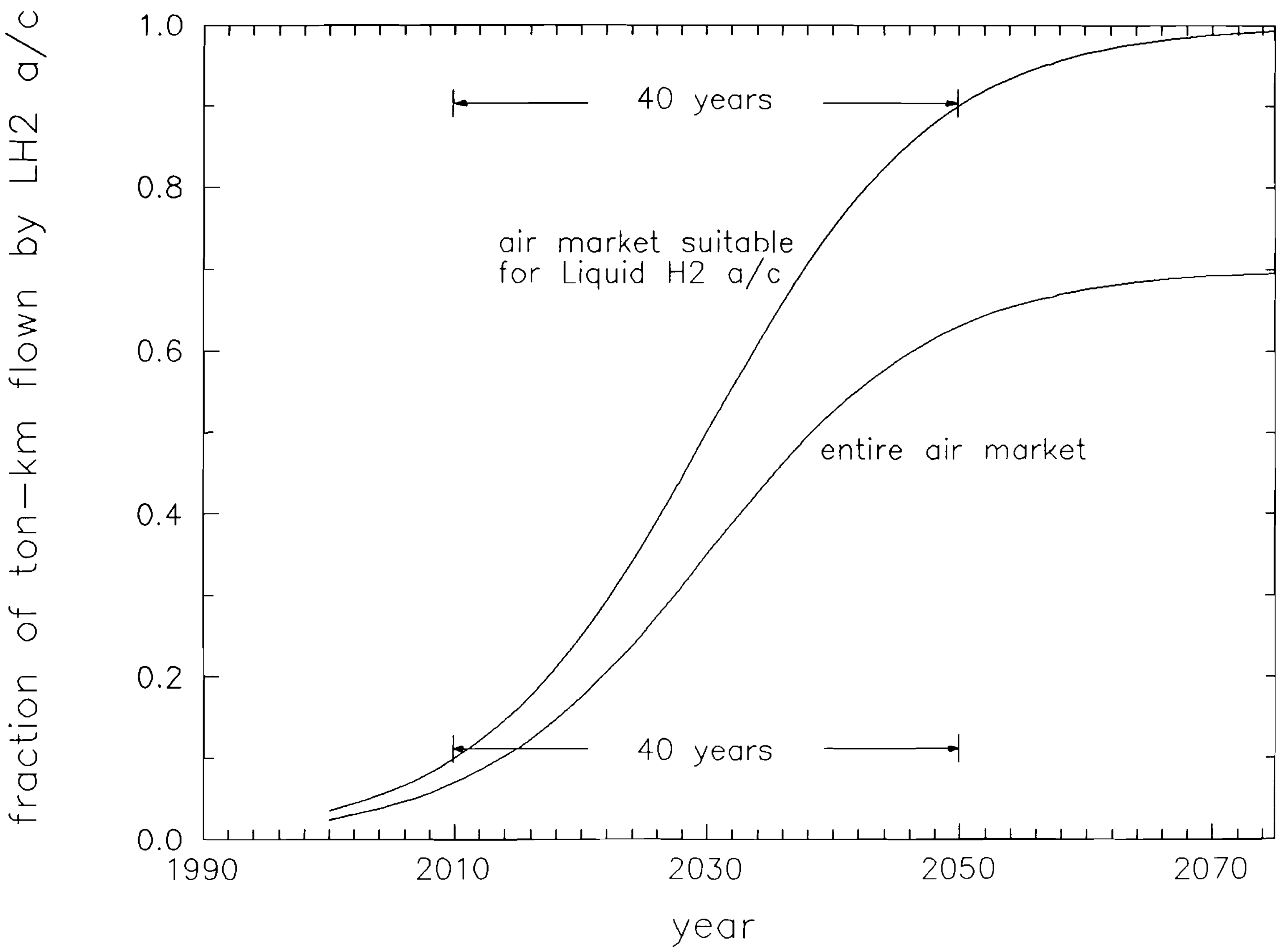


Figure 2



fraction of ton-km flown by LH2 a/c
1.0
0.8
0.6
0.4
0.2
0.0
1990
2010
2030
2050
2070
year
40 years
40 years
air market suitable
for Liquid H2 a/c
entire air market

Figure 3

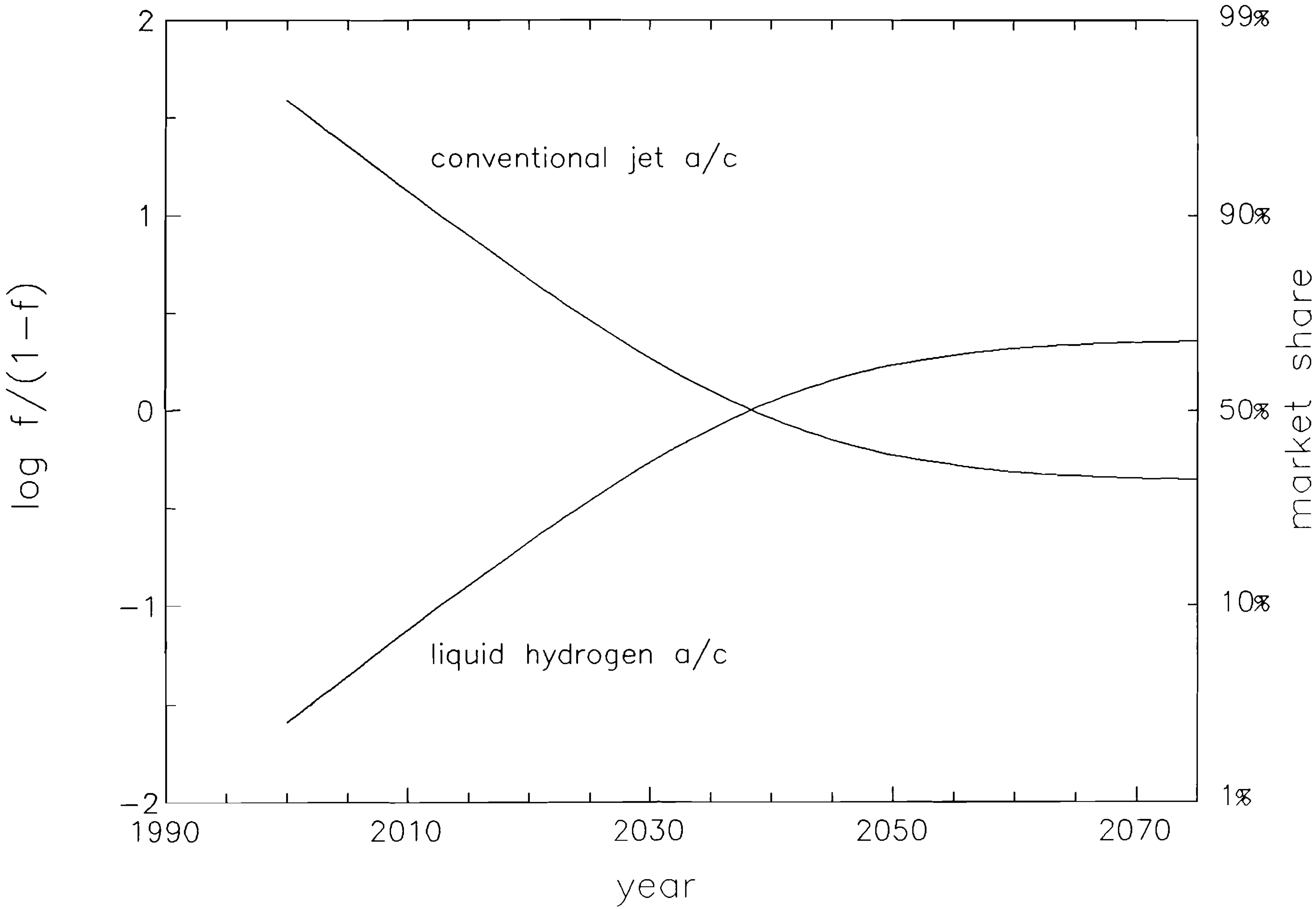

conventional jet a/c
liquid hydrogen a/c
log f/(1−f)
market share
year
2
1
0
−1
−2
1990
2010
2030
2050
2070
99%
90%
50%
10%
1%

Figure 4

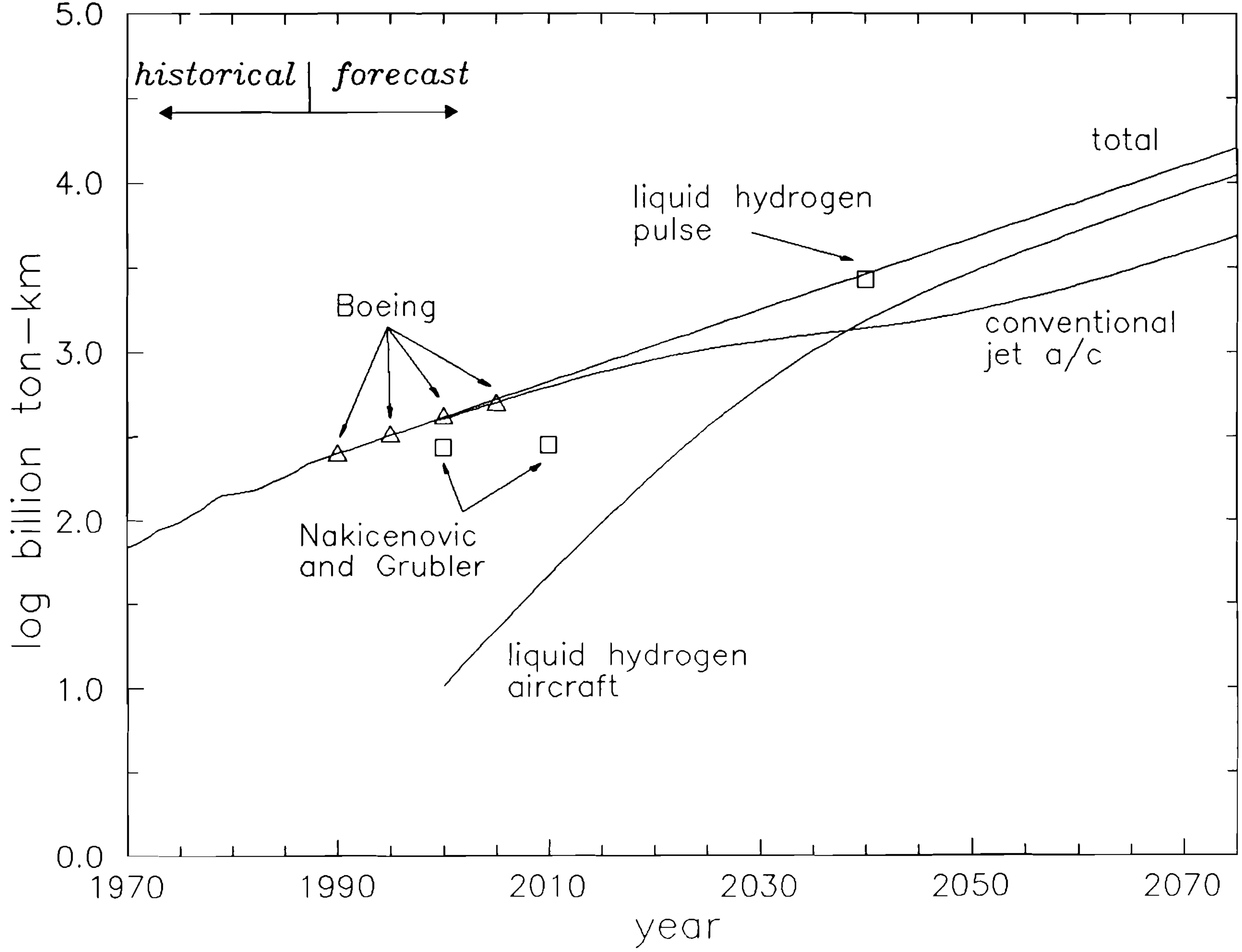

historical
forecast
Boeing
Nakicenovic and Grubler
liquid hydrogen pulse
total
conventional jet a/c
liquid hydrogen aircraft
log billion ton-km
year
5.0
4.0
3.0
2.0
1.0
0.0
1970
1990
2010
2030
2050
2070

Figure 5

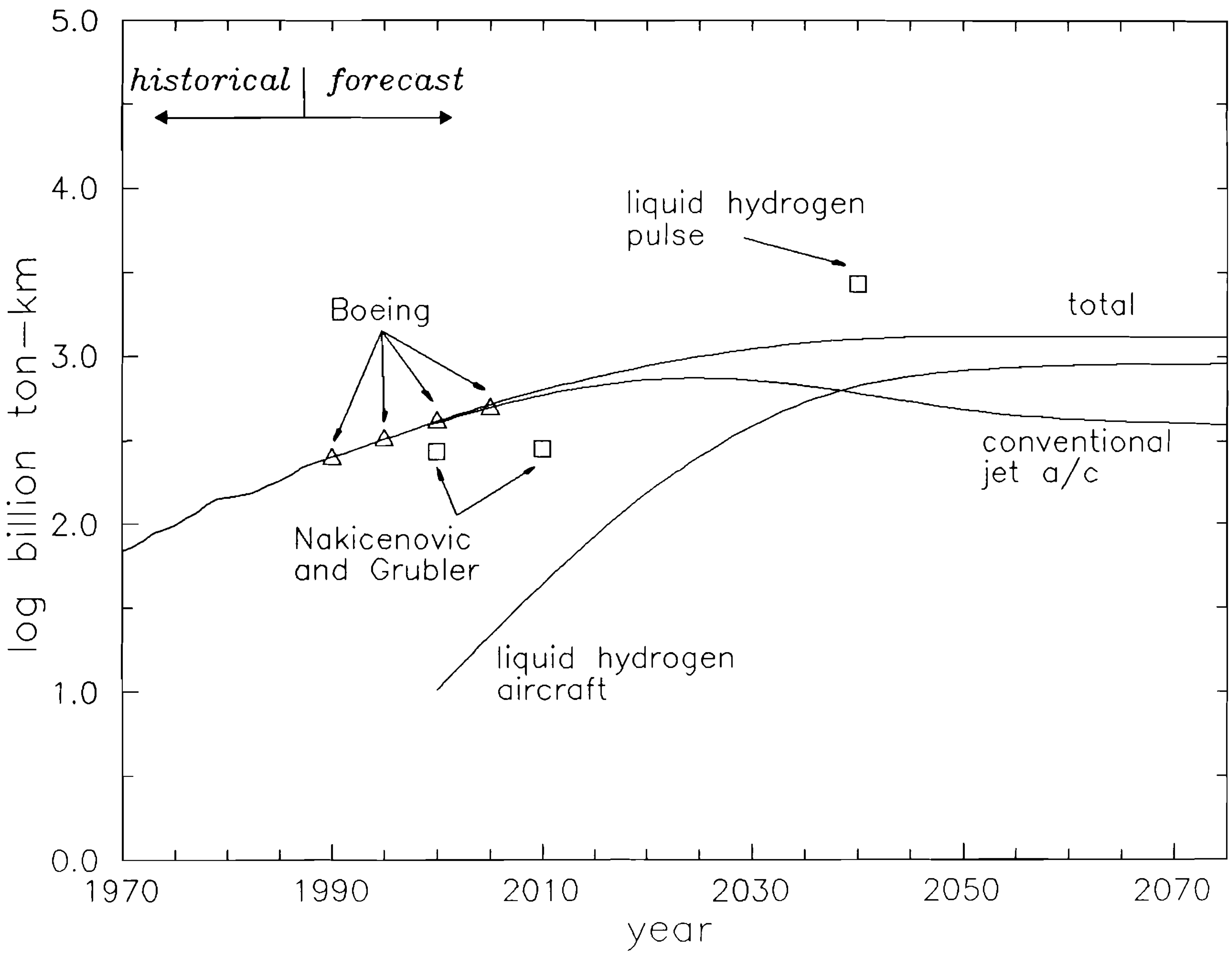

historical
forecast
liquid hydrogen
pulse
Boeing
total
conventional
jet a/c
Nakicenovic
and Grubler
liquid hydrogen
aircraft
log billion ton-km
5.0
4.0
3.0
2.0
1.0
0.0
1970
1990
2010
2030
2050
2070
year

Figure 6

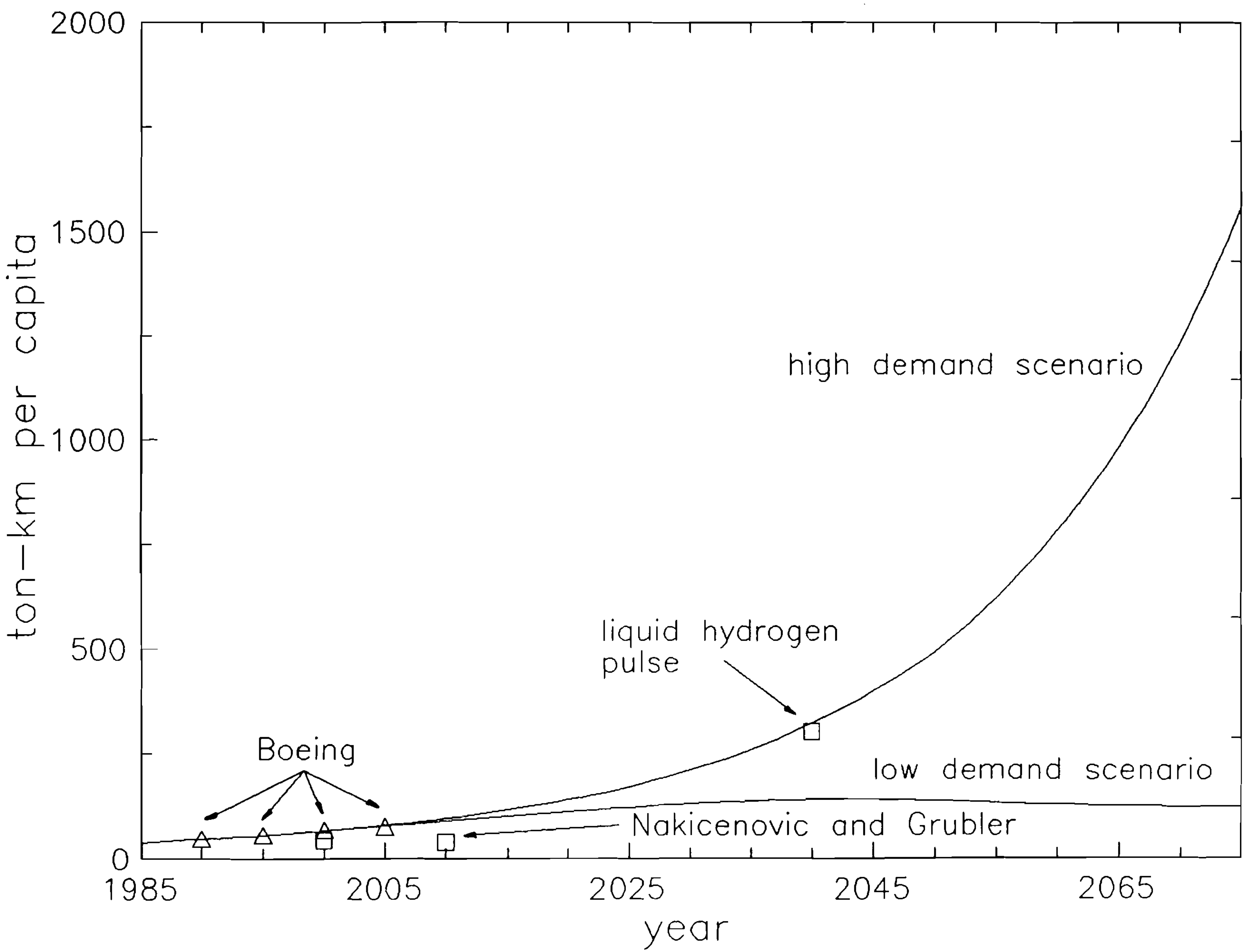

ton–km per capita
2000
1500
1000
500
0
1985
2005
2025
2045
2065
year
high demand scenario
liquid hydrogen
pulse
low demand scenario
Boeing
Nakicenovic and Grubler

Figure 7

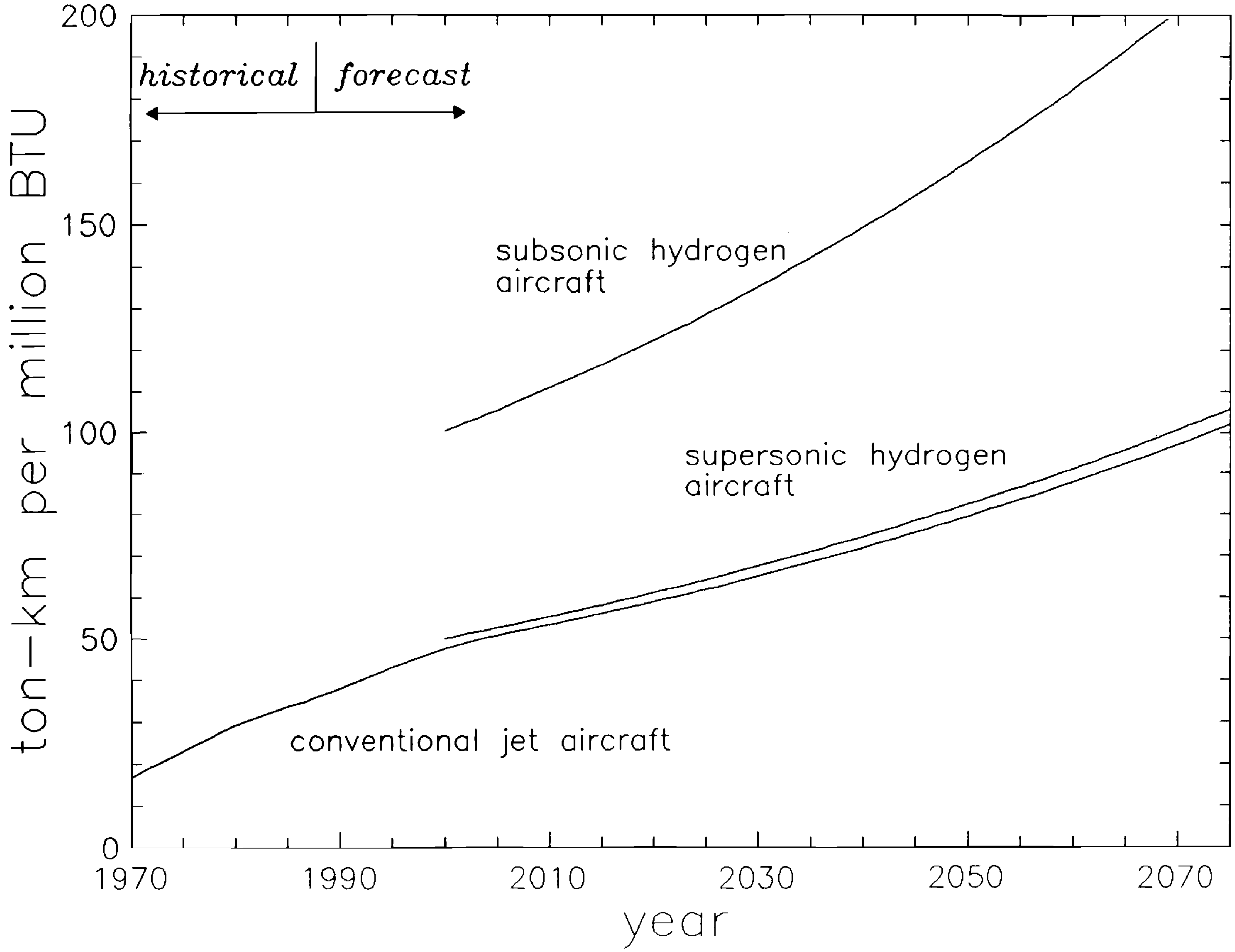
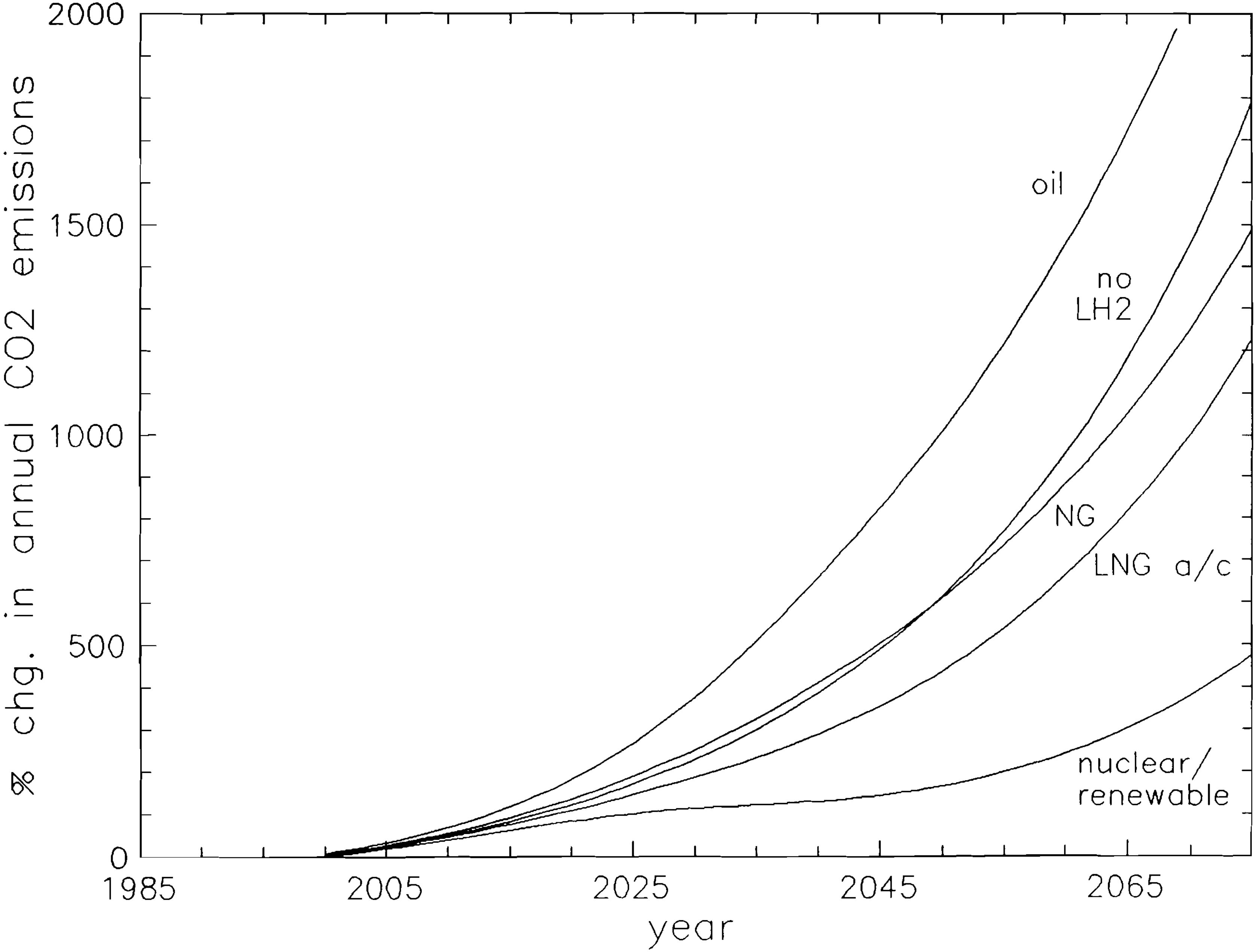

historical
forecast
subsonic hydrogen aircraft
supersonic hydrogen aircraft
conventional jet aircraft
ton-km per million BTU
200
150
100
50
0
1970
1990
2010
2030
2050
2070
year

Figure 8



% chg. in annual CO2 emissions
2000
1500
1000
500
0
1985
2005
2025
2045
2065
year
oil
no
LH2
NG
LNG a/c
nuclear/
renewable

Figure 9

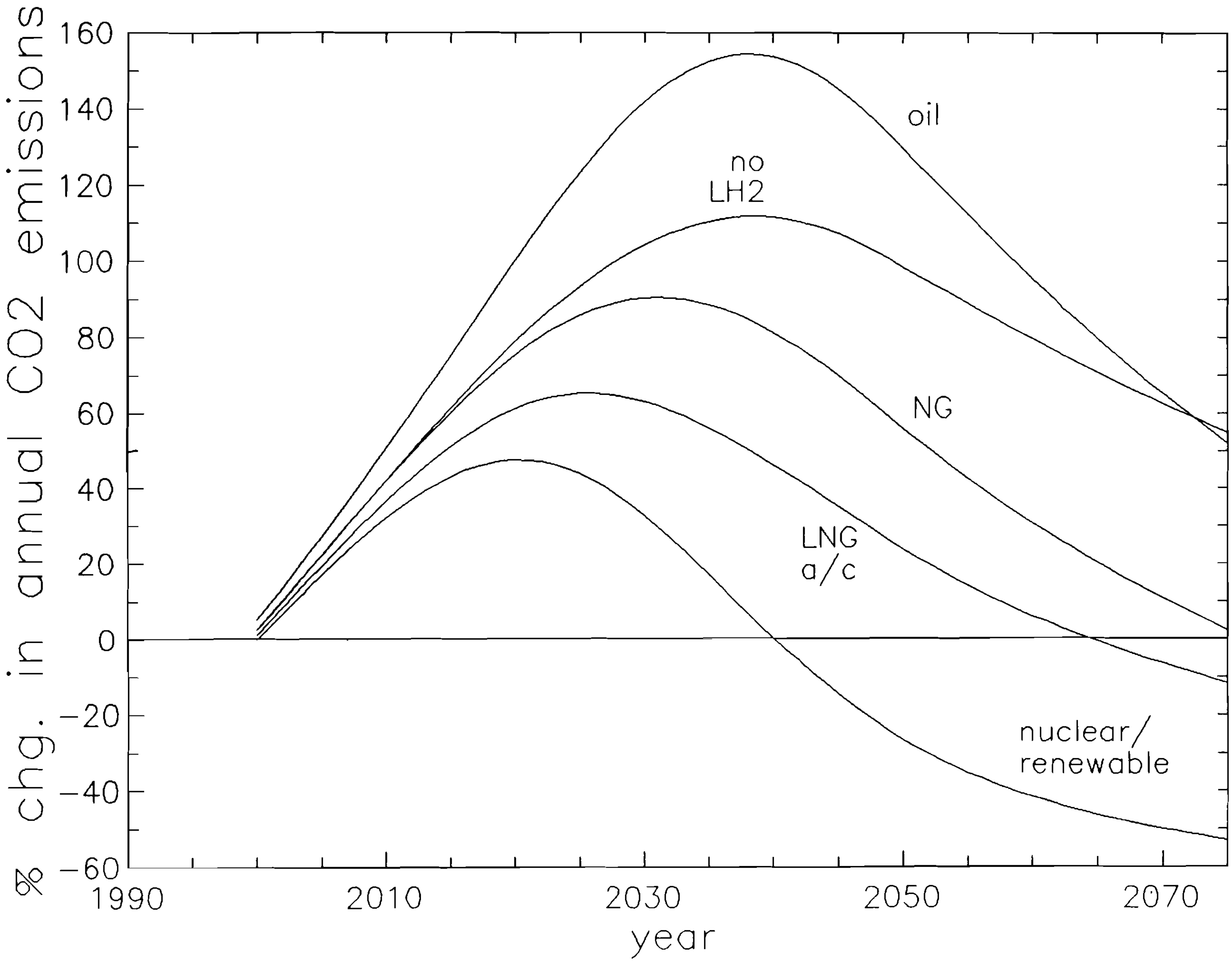

160
140
120
100
80
60
40
20
0
-20
-40
-60
% chg. in annual CO2 emissions
1990
2010
2030
2050
2070
year
oil
no
LH2
NG
LNG
a/c
nuclear/
renewable

Table 1

# SUMMARY OF SCENARIOS

High Demand Scenario

- Unrestricted growth (5% per year) from 1989 to 2075
- Liquid hydrogen aircraft diffuse into 70% of the market with Δt of 40 years
- Half of liquid hydrogen aircraft are supersonic
- Aircraft efficiency improves 1% per year
- Efficiency of electrolysis system improves 1% per year

Low Demand Scenario

- Unrestricted growth (5% per year) from 1989 to 2000 then gradual growth reduction to 0%.
- Liquid hydrogen aircraft diffuse into 70% of the market with Δt of 40 years
- All liquid hydrogen aircraft are subsonic
- Aircraft efficiency improves 1% per year
- Efficiency of electrolysis system improves 1% per year

**Table II**

Emissions of $CO_2$ under different scenarios

(in $10^{12}$ g C per year)

| Scenario | $CO_2$ emissions (in $10^{12}$ g C per yr.) | | | |
|---|---|---|---|---|
| | 2000 | 2025 | 2050 | 2075 |
| **High Demand:** | | | | |
| oil elec. w/hyrdol. | 200 | 700 | 2200 | 4900 |
| NG elec. w/hydrol. | 190 | 540 | 1400 | 3100 |
| nuclear/renewable | 180 | 360 | 480 | 1000 |
| no $LH_2$ aircraft | 190 | 450 | 1000 | 2600 |
| LNG aircraft | 190 | 490 | 1300 | 3400 |
| **Low Demand:** | | | | |
| oil elec. w/hyrdol. | 190 | 420 | 450 | 300 |
| NG elec. w/hydrol. | 190 | 340 | 300 | 200 |
| nuclear/renewable | 180 | 260 | 130 | 85 |
| no $LH_2$ aircraft | 190 | 300 | 230 | 170 |
| LNG aircraft | 190 | 350 | 360 | 280 |