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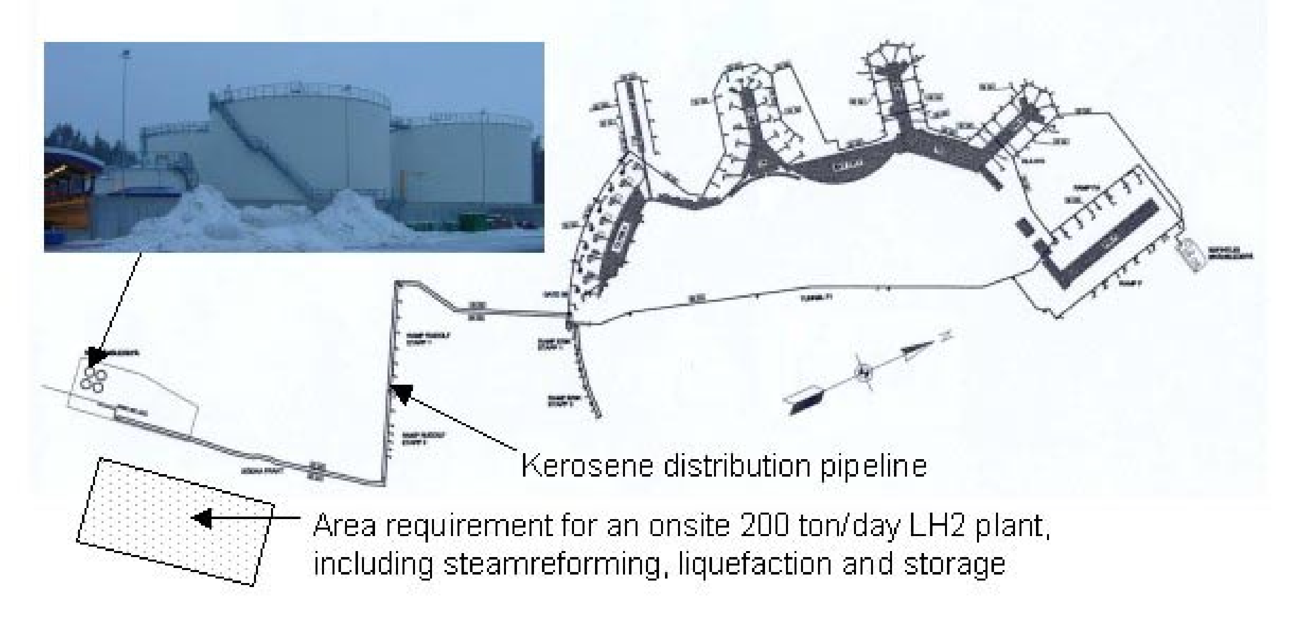
Fredrik Svensson, Anders Hasselrot

Introduction of Liquid Hydrogen-fuelled Aircraft into the Swedish Domestic Air Traffic



Fuel Distribution System at Arlanda Airport. (picture by Bracha, 2002)

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Introduction of Liquid Hydrogen-fuelled Aircraft into the Swedish Domestic Air Traffic

Abstract (not more than 200 words)

In this report the practical feasibility of using hydrogen for civil aviation is evaluated by the compilation of a number of transition scenarios, which imply changing from a conventional fleet of aircraft to a LH_2-fuelled fleet, over a certain time period. In order to accomplish this, SAS's share of the Swedish domestic air traffic is investigated. Realistic transition scenarios are compiled, and the emissions related to these scenarios are estimated, and presented in relation to emissions of the conventional fleet. The fuel sources and infrastructure changes needed at the airport, and for distribution of the LH_2 are identified and assessed.

It may be concluded that an essential increase in airport capacity, at all airports, is required to cope with the increasing traffic demand. In all scenarios it is reasonable to change to a fleet powered with liquid hydrogen, solely, by 2050. The overall airport layout and procedures should not change, and the aircraft can be refuelled at gate positions exactly like conventionally fuelled aircraft. Largely, the required changes have to do with refuelling procedures. To make sure that no or very little fossil-based energy sources are used for the LH_2 production, development and extension of renewable energy sources parallel to the introduction of cryoplanes is essential.

Keywords
Traffic growth, transition scenarios, emission scenarios, airport infrastructure and hydrogen production

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Införande av vätgasdrivna flygplan i svensk inrikestrafik

Sammanfattning (högst 200 ord)

I denna rapport studeras genomförbarheten med ett införande vätgasdrivna flygplan i svensk inrikestrafik. Ett antal övergångsscenarier definieras och avgasutsläppen för dessa beräknas och presenteras i relation till utsläpp från en konventionell flygplanflotta. Nödvändiga förändringar på flygplats till följd av att ett nytt bränsle hanteras identifieras och studeras.

Slutsatserna visar att flygplatser kommer att behöva byggas ut för att klara den ökande trafikvolymen, men att det är rimligt att byta till en flotta enbart driven av vätgas till år 2050 utan att flygbolagen belastas oskäligt. Flygplatslayouten kommer inte att behöva ändras då vätgas introduceras; de största förändringarna har att göra med tankningsproceduren. För att lite eller ingen vätgas skall produceras från fossila källor bör förnyelsebara energikällor utvecklas och byggas ut parallellt med att vätgasdriven flygtrafik introduceras.

Nyckelord
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Summary

In addition to solving the technical problems related to the airframe, propulsion system, fuel system architecture, etc., there is also a need for the evaluation of the practical feasibility of using hydrogen for civil aviation. This could be accomplished by the compilation of a number of transition scenarios, which imply changing from a conventional fleet of aircraft to a LH_2-fuelled fleet, over a certain time period. In doing so, one may either change over on a global or on a more specified regional level, as in this report. They provide information on which transition rate is feasible without burdening the airline too much. Furthermore, each scenario indicates the amount of LH_2 required for a realistic transition scenario, and one may discuss different methods of hydrogen production at the airport. The infrastructure changes that are required if changing to hydrogen as fuel could also be investigated.

In order to accomplish this, SAS's share of the Swedish domestic air traffic is investigated. According to two different assumed traffic growth curves – one low-growth and one high-growth – and through consideration of the airline's approach to fleet development, two different conventional fleet developments are assessed. Next, four realistic transition scenarios are compiled, and the emissions related to these scenarios are estimated, and presented in relation to emissions of the conventional fleet. The fuel sources and infrastructure changes needed at the airport, and for distribution of the LH_2 are identified and assessed.

The results indicate that, according to the traffic growth scenarios assumed for these studies, the number of passengers will increase three to four times by 2050. During the same time period the number of movements will have increased, but by less than the number of passengers, due to the larger aircraft types commencing on the domestic market. Depending on the scenario, the number of movements has increased by 70-90%. Hence, it may be concluded that an essential increase in airport capacity, at all airports, is required to cope with the increasing traffic demand. In all scenarios it is reasonable to change to a fleet powered with liquid hydrogen, solely, by 2050.

Regarding the changes needed at the airport when using hydrogen, there are a number of measures that need to be taken to ensure that the safety level at the airport is preserved. In order to avoid a fire hazard, spark ignition engines should be avoided. A very pleasing and feasible solution would be to power all airport vehicles by fuel cells driven by hydrogen. The overall airport layout and procedures should not change, and the aircraft can be refuelled at gate positions exactly like conventionally fuelled aircraft. Largely, the required changes have to do with refuelling procedures. Since hydrogen is a cryogenic fuel, what really needs to be changed is the interface between the fuel supplies and the aircraft fuel tanks, as well as most of, if not all, the fuel system components. However, the intention is that hydrogen should be distributed in a way similar and parallel to that of kerosene. Hence, from an airport infrastructure point of view, it is certainly feasible to change to hydrogen use. No significant changes on turn-around times are expected with cryoplanes.

Taking the local conditions, with respect to the availability of energy, it would be reasonable to change from kerosene to LH_2 as fuel for all civil aviation refuelling in Sweden. However, the development and extension of renewable energy sources parallel to the introduction of cryoplanes, is important to make sure that no or very little fossil-based energy sources are used for the LH_2 production. If electrolysis of water or gasification of biomass would be used for the LH_2 production, considerable amounts of electrical energy and biomass sources, respectively, would be required, but not unreasonably much.

Nomenclature

A/C	Aircraft
SCAA	Swedish Civil Aviation Administration
CO	Carbon Monoxide
CO_2	Carbon Dioxide
H_2	Gaseous Hydrogen
H_2O	Water Vapour
ICAO	International Civil Aviation Organisation
LCA	Life Cycle Assessment
LH_2	Liquid Hydrogen
MTOW	Maximum Take-off Weight
N_2	Nitrogen (gaseous)
NM	Nautical Mile
NO_x	Oxides of Nitrogen
RQL	Rich-burn Quick-quench Lean-burn (combustor)
SAS	Scandinavian Airlines
SCB	Statistics Sweden
SFC	Specific Fuel Consumption
SMR	Steam Methane Reforming
SO_x	Oxides of Sulphur
TET	Turbine Entry Temperature
UHC	Unburned Hydrocarbons

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Appendix A. Aircraft Types used in the Emission Scenarios

1 Introduction

Introduction of Cryoplanes in civil aviation has several advantages, both on a regional and on a global scale. Their use reduces the unhealthy emissions in the airport's vicinity, and maybe even more importantly, they are likely to bring a significant reduction of the civil aviation's contribution to global warming. While offering great prospects, use of liquid hydrogen (LH_2) as aviation fuel also poses many challenges regarding technical development, and making LH_2 economically compatible with kerosene.

In addition to solving the technical problems related to the airframe, propulsion system, fuel system architecture, etc., there is also a need for the evaluation of practical feasibility by compilation of a number of transition scenarios, which imply changing from a conventional fleet of aircraft to a LH_2-fuelled fleet over a certain time period. In doing so, one may either change over on a global or on a more specified regional level. By having a global approach, the global consequences of the introduction of cryoplanes related to required investments, production of LH_2 and emissions may be evaluated. In order to perform a detailed study, where a realistic transition of a specific airline's fleet change to cryoplanes is investigated, it is appropriate to compile regional transition scenarios, providing information on what transition rate is feasible without burdening the airline too much. Furthermore, each scenario indicates the amount of LH_2 required for a realistic transition scenario, and one may discuss different methods of hydrogen production at the airport. The required infrastructure changes of changing to hydrogen as fuel could also be investigated.

1.1 Scope and Objectives

The objectives of this study are to explore the feasibility, potential and consequences of introducing a LH_2-fuelled aircraft fleet on a regional scale. In order to accomplish this, SAS's share of the Swedish domestic air traffic is investigated. According to two different assumed traffic growth curves – one low-growth and one high-growth – and through consideration of the airline's approach to fleet development, two different conventional fleet developments are assessed. Next, four realistic transition scenarios are compiled, and the emissions related to these scenarios are estimated, and presented in relation to emissions of the conventional fleet. The fuel sources and infrastructure changes needed at Arlanda airport and for distribution of the LH_2 are identified and assessed.

1.2 Methodology

The approach in this regional study is to explore a small air traffic segment, where the feasibility for the introduction of Cryoplanes is high. The chosen air traffic segment is the Swedish domestic traffic, operated by the major airline in the region. Traffic growth curves are compiled by means of forecasts performed by the aviation authority in Sweden, namely, the Swedish Civil Aviation Administration (SCAA). When assessing the conventional fleet development for the investigated airline, today's fleet and its future plans are taken into consideration. Thereafter, the conventional fleet is changed to be LH_2-fuelled, according to different scenarios, i.e. transition scenarios. By means of aircraft simulation tools and the actual timetable, emission scenarios related to the different transition scenarios are compiled. When the amount of hydrogen to provide the fleets is determined, different hydrogen production methods applied at Arlanda are addressed.

2 Traffic Growth Scenarios

Attempting to predict the future, particularly the far future, is always associated with major uncertainties. What one can do is to explore the past and by a number of reasonable assumptions try to describe the future. There is a distinction between a forecast and a scenario. Forecasting implies that the near future is predicted by reasonable assumptions. When considering a longer time period, the uncertainties increase essentially, and hence, scenarios would be a better tool. When defining scenarios, the extremes of the possible outcome may be encircled. Then it may be claimed that the actual outcome is somewhere between the extremes. For being successful in scenario and forecast compilation, the future should be predicted by knowledge of the present situation and by making reasonable assumptions about the future, rather than merely extrapolating the past.

2.1 Traffic Growth Scenarios for Stockholm/Arlanda Airport

In order to perform transition scenarios, scenarios for the future development in air traffic need to be compiled. In this investigation, two different traffic growth figures – one high-growth and one low-growth – for Stockholm/Arlanda airport have been compiled. These figures have been assumed to be applicable for the whole Swedish domestic traffic.

When examining forecasts for the traffic growth of civil aviation, one notices that forecasts performed by the industry often tend to be higher than those performed by aviation authorities. The low traffic growth scenario used in this study is therefore based upon forecasts for Arlanda performed by the Swedish Civil Aviation Administration (SCAA). The high-growth scenario is more in line with forecasts performed by the larger aircraft producing industries.

The Swedish CAA has conducted a number of traffic growth forecasts, for different time periods and regions, which are based upon assumptions for the airport situation in Stockholm. Besides Arlanda there are two other airports with heavy air traffic in the Stockholm region, namely, Bromma airport close to the city centre and Skavsta airport, about 100 kilometres south of Stockholm. Mainly due to complaints from the inhabitants close to the airport, the Bromma airport may be closed when the airport owner's (the Swedish CAA) contract with the local authority expires in 2011. The development at Arlanda is dependent on whether Bromma will close in 2011 or not, along with the future growth in passenger demand. Depending on those local conditions and the development of new runways at Arlanda, traffic growth figures at Arlanda for 10 and 30 years, respectively, have been performed by SCAA (Jonforsen, 1999 and Åhlgren, 2000a). Based on these figures and on personal communication with Åhlgren (2000b) at the Swedish CAA, the low-traffic growth scenario for 2001-2050 used in this study for the Swedish domestic traffic has been created (Table 2-1). One should bear in mind that as the number of passengers increases, a certain percentage increase implies a higher increase in absolute terms. The result of the low-growth curve is roughly a linear passenger growth at Arlanda (Figure 2-1). Generally the passenger growth will decrease with time.

Table 2-1. Assumed Annual Growth Rates for the Swedish Domestic Air Traffic.

Low-Growth Scenario		**High-Growth Scenario**	
Years	**Yearly Growth [%]**	**Years**	**Yearly Growth [%]**
2001-2015	3.5	2001-2010	6
2016-2035	2.5	2011-2020	4
2036-2050	1.5	2021-2035	2
		2036-2050	0.5

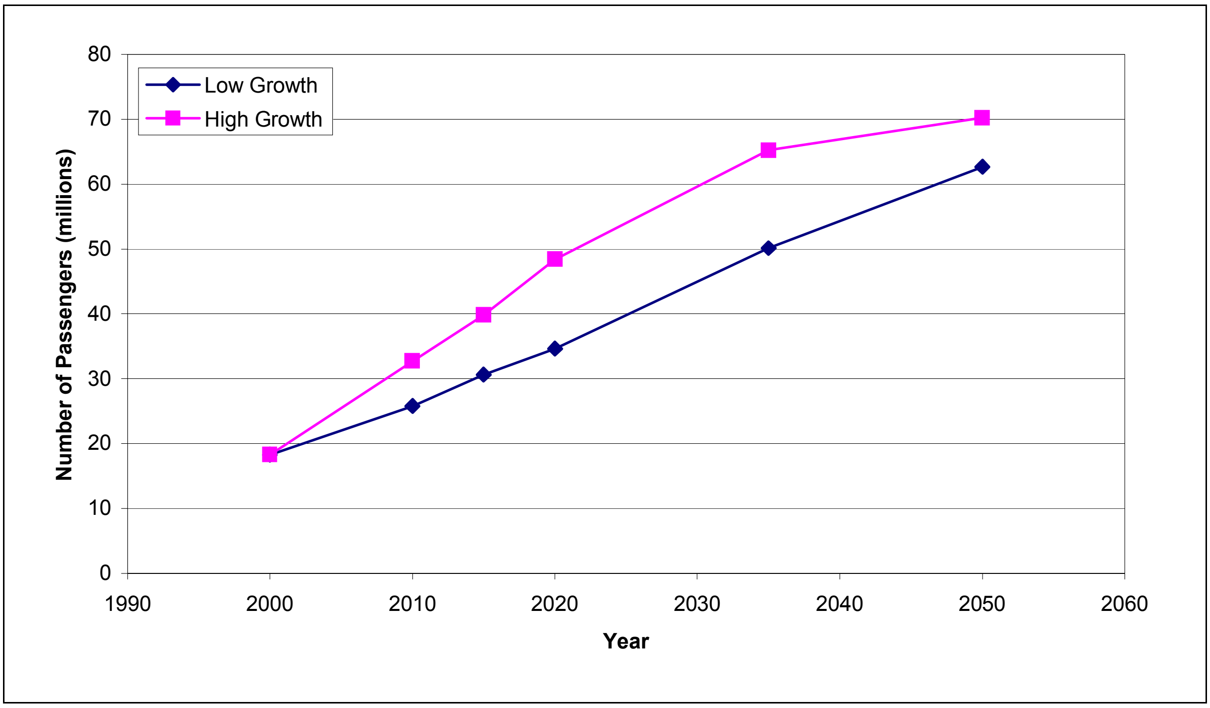

Figure 2-1. Passenger Growth Scenario for Stockholm/Arlanda Airport 2000-2050.

In the high-growth scenario, an essentially higher growth rate is expected during the first 20 years, but then the growth rate will decrease considerably. During the first 19 years the traffic growth rate is similar to that assumed by Boeing and Airbus Industry, namely, about 5% increase per year (Kappers and Essers, 2001). The reasons for significantly reducing the growth rate after 2020 are mainly to avoid predicting unrealistic annual passenger increases for the relatively small population of about nine million in Sweden, and to limit the number of passengers at the end of the investigated period, 2050. In order to evaluate whether the number of passengers of about 70 million in 2050 – which is about four times the number of passengers at Arlanda in 2000 – resulting from the high-growth scenario, is reasonable, the theoretical maximum travelling that the population of about 10 million may perform is assessed. If it is assumed that each person makes one leisure travel each year, that one-fourth of the population makes one business trip once a week during 45 weeks a year and that 60% of the population travels via Arlanda, the number of passengers at Arlanda in 2050 will be about 150 million. This is roughly twice the result according to the high scenario, and it may be concluded that the traffic growth according to the high scenario is reasonable.

The transition scenarios presented in the next section are based on these two traffic growth figures.

3 Transition Scenarios

In order to compile realistic transition scenarios, a specific airline and its aircraft fleet have been studied. The airline under consideration is Scandinavian Airlines (SAS), which dominates the Swedish domestic aviation market. About 70% of the Swedish domestic traffic, in terms of passengers, is operated by SAS. Related to the total air traffic in Sweden, comprising both domestic and international flights, the corresponding number is about 35%. The following transition scenarios should be interpreted as transition scenarios, compiled to show the feasibility and gains of introducing cryoplanes into the Swedish domestic traffic, and not as SAS's future plans for their aircraft fleet.

Firstly, the aircraft fleet development based on conventional airplanes is compiled according to the two traffic growth scenarios. Secondly, four transition scenarios are compiled – two for each conventional fleet development.

After having taken a closer look at SAS's time table, showing the operation routes for each aircraft individual, it may be concluded that Stockholm/Arlanda serves as a hub airport for the Swedish domestic air traffic, i.e. almost every scheduled flight within Sweden departures from or arrives at Arlanda airport. This makes Arlanda a sensible choice for the production of liquid hydrogen. In order to restrict the complexity and costs, the implementation of production facilities for liquid hydrogen as well as infrastructure build-up is limited to Arlanda, only. As time passes this system of hydrogen production facilities may be expanded, eventually covering the whole world. This will affect the fuel burn of the cryoplanes detrimentally, since the aircraft will need to carry fuel for the return trip as well. However, this drawback is relatively modest and is acceptable in this connection. When the transport capacity needs to be increased in the future, the number of aircraft individuals will be increased; alternatively, larger aircraft types will be introduced, but it is assumed that the operation routes are unchanged.

In Table 3-1, data for a simplified current fleet, as well as for aircraft types that will be introduced when the capacity needs to be increased, are given. Data for the projected cryoplanes are also given in the table. The choices of aircraft types and their performance will be explained below.

Table 3-1. Data for SAS's Current and Future Aircraft Fleet.

A/C Type	**No. of seats**	**Design Range [nm]**	**Engine Type**[1]
Current			
B737-800	179	1000	CFM56-7B26-2p
B737-600	123	1000	CFM56-7B20-2p
Future			
A321-100	220	1000	V2530-A5
A330-200	278	1500	RR Trent 772B
Cryoplanes			
CMR1-300	220	2000	V2527-A5
CMR1-400	278	3000	V2527-A5

The design ranges of the current and future aircraft fleets are chosen according to recommendations from SAS. Since all airplanes are used for a shorter range than traditionally when they operate internationally, they are designed for a shorter range and with

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[1] The engines used in the simulations have the same performance as those stated in the table, but are scaled with respect to size according to a procedure explained in section 3.3.2.

a higher payload. Thus, the aircraft are re-designed to suit the required demands. The basis for the liquid hydrogen-fuelled aircraft, CMR1-300, is taken from Oelkers and Prenzel (2001). A picture of the CMR1-300 showing the tank arrangement is presented in Figure 3-1. The CMR1-400 (our notation) is a fuselage-stretched and wing scaled-up version of the CMR1-300. The cryoplanes are designed for a range twice as large as for the corresponding conventional aircraft. The reason for this is that these aircraft need to be able to carry double the amount of fuel, since Arlanda airport is the only refuelling station for liquid hydrogen. More details of the aircraft are given in section 3.3.

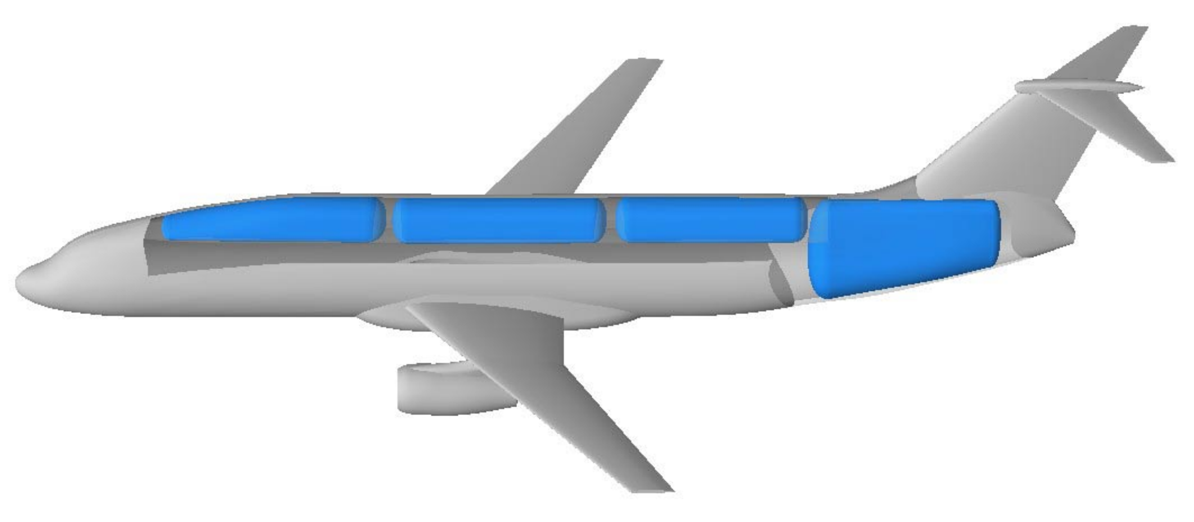

Figure 3-1. Tank Arrangement for the Studied Cryoplane Configuration, CMR1-300 (Oelkers and Prenzel, 2001).

Before the compilation of transition scenarios, SAS's expected fleet development for the next 50 years needs to be assessed.

3.1 Development of the Conventional Fleet

In the beginning of the considered period (2001), the SAS fleet operating as domestic in Sweden, solely, consists of eleven B737-800, seven B737-600 and two MD-87. Furthermore, a number of MD-81 operate partly within Sweden and partly within Europe. All together, the MD80s correspond to about two aircraft operating solely domestically. In addition, there are a few regional aircraft, such as the Dash8-Q400, operating partly domestically, but due to its low passenger capacity these are neglected in the study. The MD-87s and the MD-81s will, however, be transferred to operations on the European market within the next few years, and will be replaced by the B737-600 and B737-800, respectively, in the domestic traffic. It is therefore assumed that the SAS domestic fleet in the beginning of the considered period, 2001, consists of thirteen B737-800 and nine B737-600.

The choice of future aircraft types is based on SAS's plans for the future. SAS is presently putting a number of A321 (184 seats) into international service, and in the future when more capacity is required, a domestic version of the A321 (220 seats) will also commence commercial service. The situation is similar for the A330, but as far as the author knows, no dates for introduction are established yet.

When assessing the development of the conventional fleet, which means that no cryoplanes are involved, the airline's fleet development philosophy needs to be considered. An airline's transport capability can be increased either by adding aircraft individuals or by replacing the current aircraft by larger types. The choice is dictated by the desire of maximising the overall profit for the airline. Figure 3-2 gives an illustration of how this might be solved. In general, one may claim that an average load factor of 50% corresponds to break even, i.e. for load factors higher than 50% the flight is profitable. The profit will increase with the average load factor until 75%. At this point it is, as shown in the figure, most favourable to change to a larger aircraft type. If the average load factor would be allowed to increase above 75%, there is a risk that the capacity is insufficient in peak hours. An airline strives to have about 30-40% difference in size between their aircraft types (Näs, 2001).

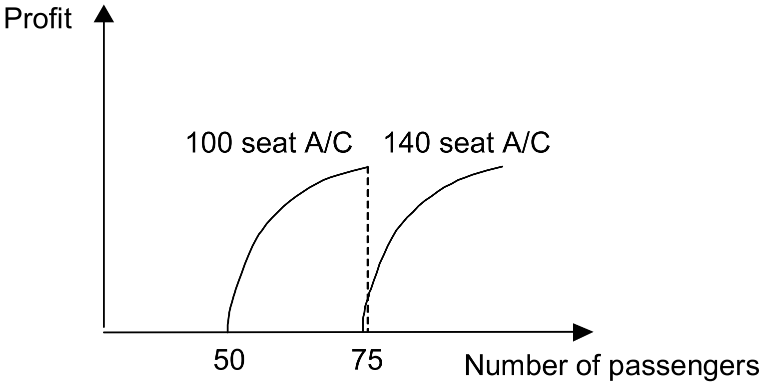

Figure 3-2. An Airline's choice of Aircraft size depending on Load Factor for Maximum Profit (Näs, 2001).

This is a simplified theoretical model; the reality is somewhat more complex, but still, the objective is to stick to these numbers as far as possible, with regards to types of aircraft available on the market.

Due to increased traffic demand as time passes, the average load factor will increase, and reach 75%. Then, the airline may either add aircraft types or change to a larger aircraft type. The number of airplanes that may be added is limited by the allowable increase in movements at the airport, without any rebuilding and expansion of the airport. Thus, the number of aircraft that may be added without congestion is very much dependent on the airport capacity.

In this study, the demand of increased traffic is satisfied by adding aircraft, provided that the number of movements is sufficiently low. At a certain point, depending on the assumed traffic growth, the aircraft type is replaced by a larger aircraft type. Another occasion when the aircraft are replaced by new ones, is when the retirement age of 30 years, as assumed in this study, of the aircraft is reached. In this case, the airplanes are not necessarily replaced by larger ones; they could also be replaced by aircraft of the same size. Replaced aircraft that have not reached their retirement age are assumed to be used on other routes, operated by SAS or another airline, i.e. they are no longer included in the scenarios.

In the beginning of the considered period, 2001, the average load factor is assumed to be 65%. This number is often used for the Swedish domestic traffic. In 2000, the average load factor of SAS's Swedish domestic traffic was 64% (Näs, 2001).

Figure 3-3 shows SAS's domestic fleet development for the period 2001-2050, according to the low passenger growth scenario. During this time period of 49 years, the number of aircraft increases from 22 to 39. This implies that the number of movements increases by 77%, or 1.2% on average per year. Accordingly, an essential increase in airport capacity is required. In 2045 the A321s need to be replaced by new ones, since they will have reached their retirement age. At the end of the scenario period, in 2050, the fleet operating within Sweden consists of airplanes in the size of he A321 and the A330.

Figure 3-4 shows the corresponding graph for the high-growth passenger scenario. When a higher traffic growth is assumed, specifically notable in the first 20 years, the capacity in terms of increased number of aircraft individuals needs to be increased earlier, and the change to a larger aircraft type also needs to be applied earlier. At the end of the transition period, in 2050, airplanes of the same size as for the low-growth scenario are used, but another three individuals are in service. This means that the number of movements increases by 91%, or 1.3% on average per year, over this time period of 49 years. Another difference is that the A321s will reach their retirement age of 30 years seven years earlier, since they were introduced earlier.

From this exercise it may be concluded that an essential increase in airport capacity, at all airports, is required in order to cope with the increasing traffic demand.

So far only conventional technology has been treated, and the next step is to introduce liquid hydrogen-fuelled aircraft when the capacity needs to be enlarged.

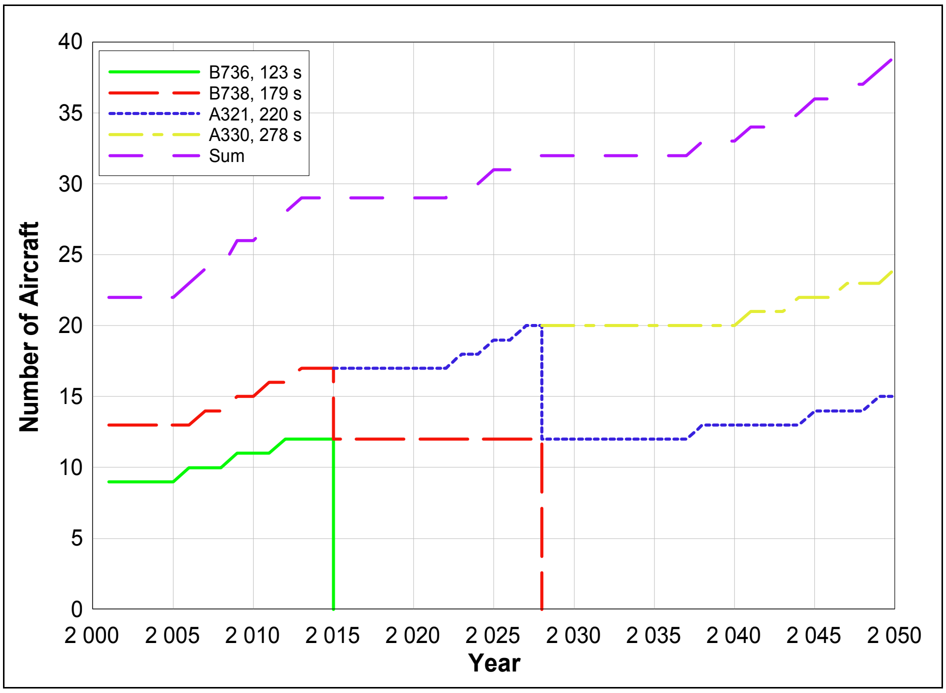

Figure 3-3. SAS's Domestic Fleet Development, according to the Low Passenger Growth Scenario, for the period 2001-2050.

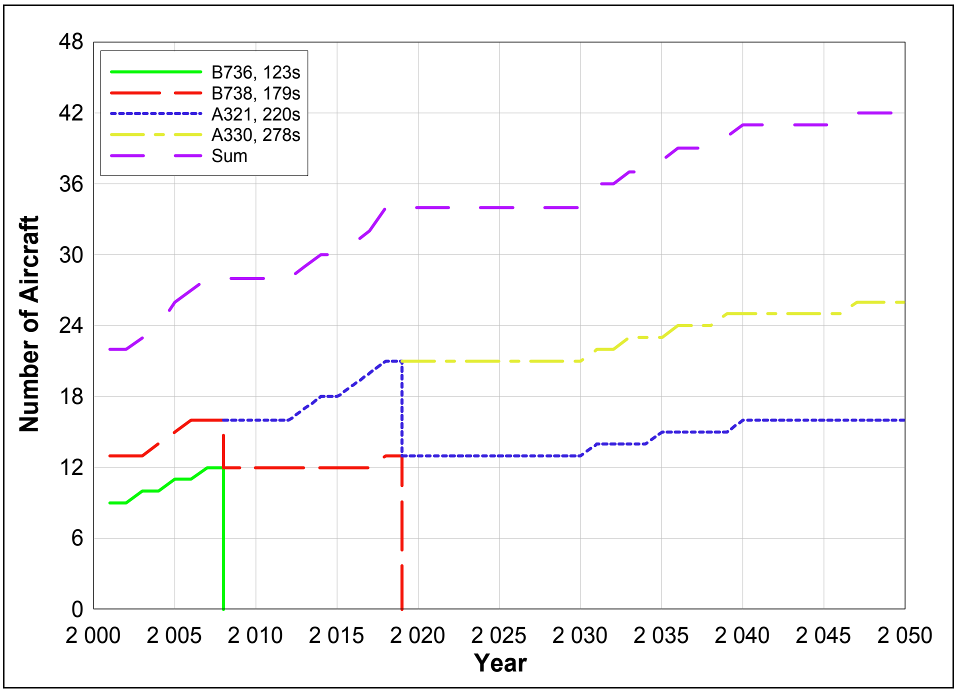

Figure 3-4. SAS's Domestic Fleet Development, according to the High Passenger Growth Scenario, for the period 2001-2050.

3.2 Fleet Development with Introduction of Cryoplanes

One of the main issues to consider when defining transition scenarios, is the reasonable point of time to start introducing the new unconventional aircraft types. Before any cryoplane may be put into scheduled service, much research and development is required. After the CRYOPLANE – System Analysis – is finished in mid-2002, a phase of basic research and development, lasting about two and a half years, needs to be carried out. In addition to the research work, a demo-type aircraft may, if desirable, be developed and tested. An early introduction implies that much of the research and development work needs to be done in parallel, consequently increasing the risk of higher development costs. Later introduction of cryoplanes will allow more time for research and development, and thereby minimises the risk of early cost increases. On the other hand, an extended programme may imply that the total cost of the project increases, and that interests paid on invested capital will go up (Klug, 2001).

In this study, two different dates are assessed for the introduction of cryoplanes. In two of the scenarios, all new aircraft that are put into service in 2015 and afterwards are cryoplanes, and in the other two, all aircraft that are put into service in 2025 and afterwards are cryoplanes. To enable an introduction of cryoplanes in 2015, the European Commission has to take the lead, and for an introduction in 2025, ICAO (International Civil Aviation Organisation) has to take the right measures. In general, reducing the environmental burden from civil aviation should be met by means of incentives, policy and legislative changes, without specifying any particular technology that should be used. It should be up to the industry to choose the proper technology in order to meet future demands.

Figure 3-5 shows Scenario 1, which is a transition scenario with the introduction year 2015, where the low traffic growth scenario is applied. In practice, this is the same graph as Figure 3-3; the only differences are that cryoplanes with the same passenger capacity are introduced instead of the A321 and the A330. In this scenario, the SAS domestic fleet is operating on liquid hydrogen, solely, in 2028. In Figure 3-6, the introduction year is unchanged, but the high traffic growth figure is assumed (Scenario 2). The higher traffic growth results in the changes to the larger aircraft types being required earlier, which means that the switch from the B737-800 to the A321 is needed in 2008. By this year, introduction of cryoplanes is unfeasible and not in line with the scenario. This implies that only a small number of cryoplanes in the size of the A321 may be introduced in 2015, i.e. to satisfy the capacity demand. However, when airplanes with the size of the A330 need to be introduced in 2019, cryoplanes are a feasible alternative. In this scenario, the fleet is powered by LH_2, solely, in 2038 – ten years later than when the low traffic growth scenario was assumed.

In the next two scenarios it is assumed that all the aircraft that need to be introduced in 2025 and afterwards are LH_2-fuelled. In Figure 3-7 (Scenario 3) the low passenger traffic growth numbers are assumed, and in Figure 3-8 (Scenario 4) the high traffic growth numbers are assumed. In Scenario 3 the introduction of cryoplanes starts on a small scale in 2026 with airplanes the size of the A321, followed by the introduction of larger cryoplanes, like the A330 with 278 seats, in 2028. In 2045, the major part of the conventional A321s will have reached their retirement age, and therefore are replaced by cryoplanes of the same size. In Scenario 4, where the high traffic growth has been assumed, the broad-scale introduction of cryoplanes is much delayed compared to the other scenarios. The introduction of both 220- and 278-seat cryoplanes starts simultaneously in 2030. In the same way as for Scenario 2, the conventional A321s are replaced in 2038 by cryoplanes when the former should be phased out. When airplanes with the capacity for 278 passengers are required in 2019, it is, according to the prerequisites of the scenario, too early to introduce cryoplanes. A small number of cryoplanes of this size is required in 2030 and the next 20 years, but a broader introduction is not required until 2049, when the conventional ones will have reached their retirement age and therefore need to be replaced.

All four scenarios, with respect to the percentage increase of cryoplanes by time, are summarized in Figure 3-9.

After compiling these four scenarios, it may be concluded that in all scenarios it is feasible to change the fleet to be solely LH_2-fuelled over the considered time period of 50 years. Furthermore, high traffic growth results in a delayed broad-scale introduction of cryoplanes.

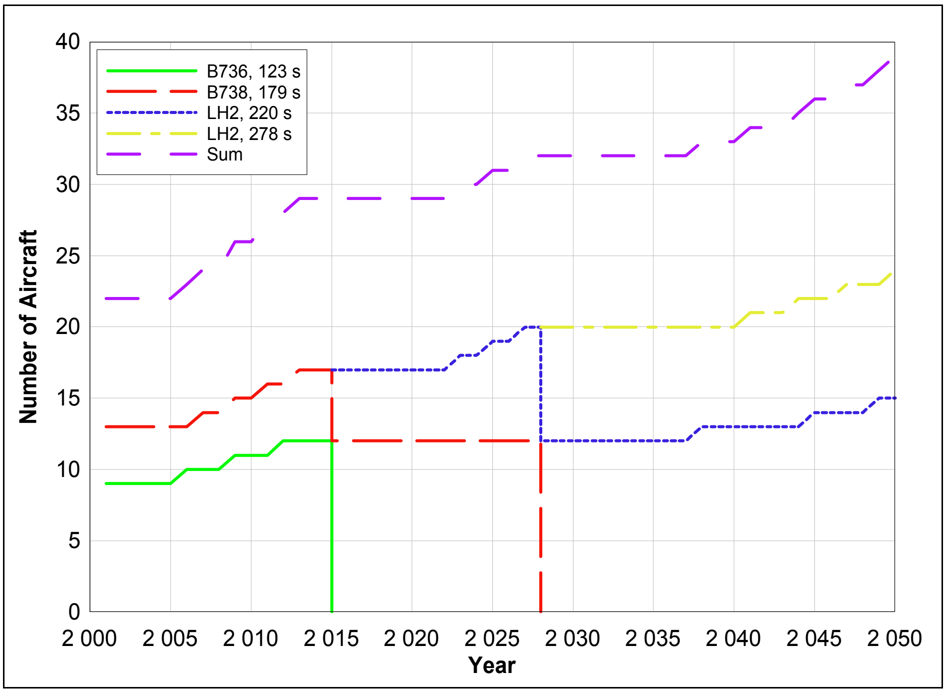

Figure 3-5. Scenario 1: All Aircraft Introduced in 2015 and Afterwards are LH_2-Fuelled; Low Passenger Growth Scenario is Assumed.

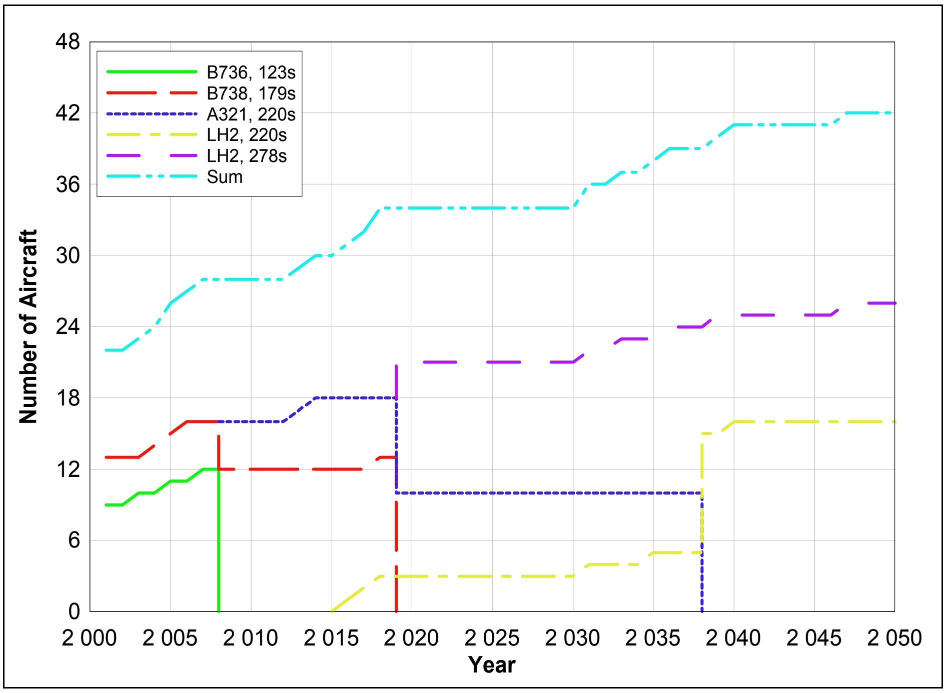

Figure 3-6. Scenario 2: All Aircraft Introduced in 2015 and Afterwards are LH_2-Fuelled; High Passenger Growth Scenario is Assumed.

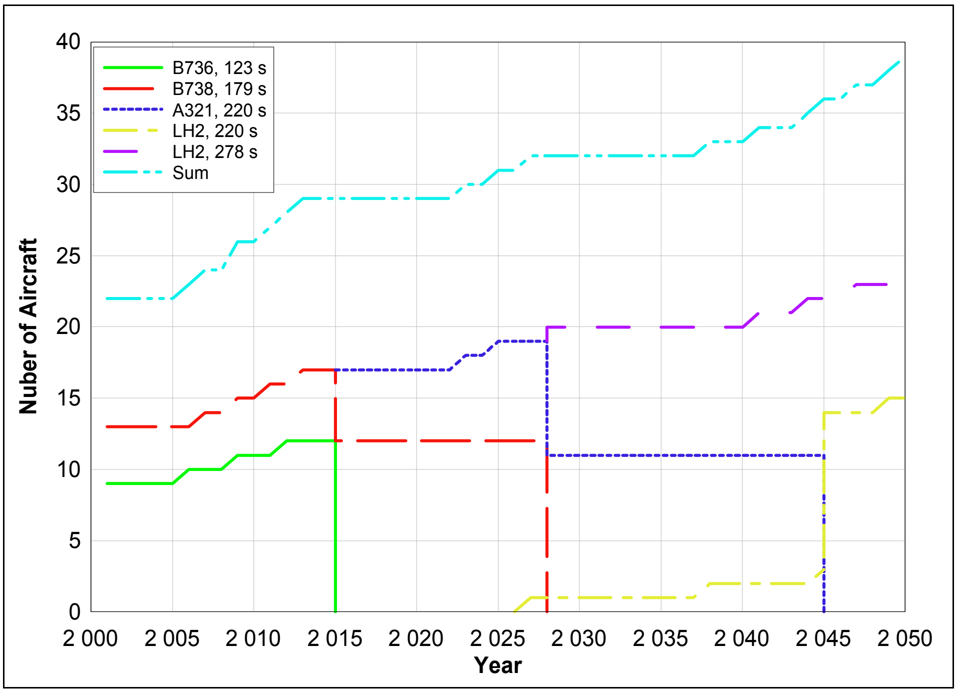

Figure 3-7. Scenario 3: All Aircraft Introduced in 2025 and Afterwards are LH$_2$-Fuelled; Low Passenger Growth Scenario is Assumed.

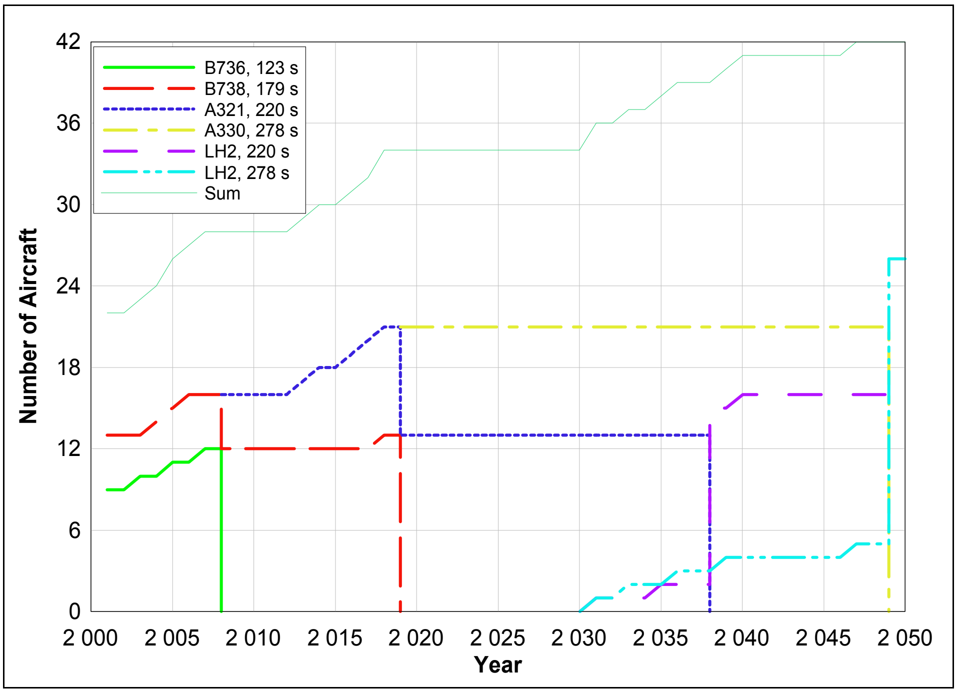

Figure 3-8. Scenario 4: All Aircraft Introduced in 2025 and Afterwards are LH$_2$-Fuelled; High Passenger Growth Scenario is Assumed.

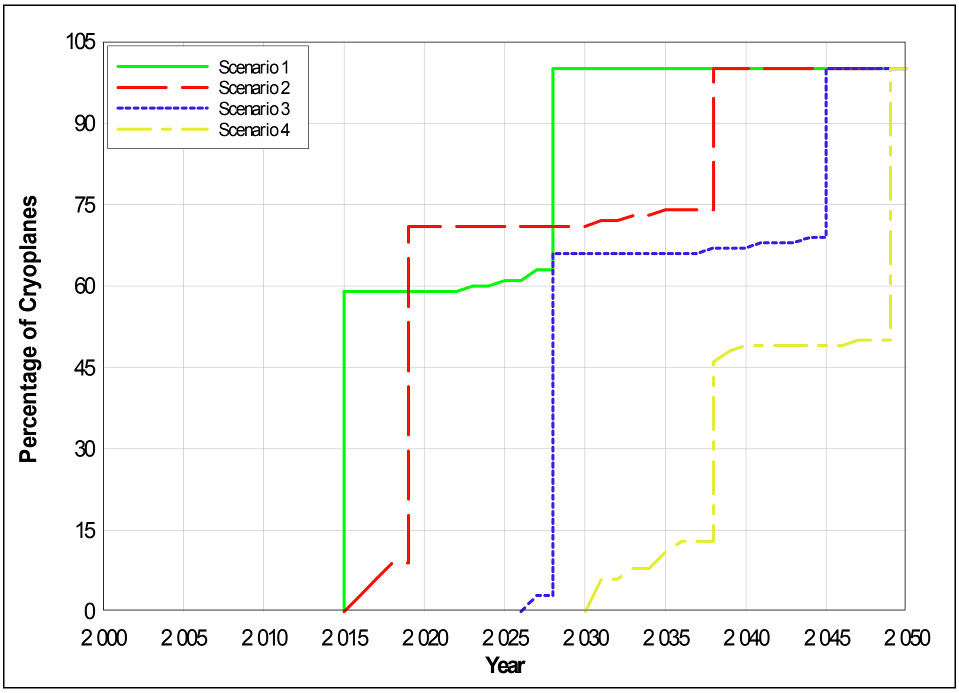

Figure 3-9. Percentage Introduction of Cryoplanes, according to Scenarios 1-4.

3.3 Emission Scenarios

Having established a number of transition scenarios, the quantity of emissions for each of these may be determined. In order to reflect the changes in emissions of each scenario and assumed traffic growth, the total amount of emissions on a typical day (July 6) will be calculated for SAS's domestic traffic in 2001, 2010, 2020, 2030, 2040 and 2050. In order to do this, each aircraft individual's operation schedule is simulated according to SAS's timetable by means of the commercial aircraft design software PIANO (Simos, 2000) and Excel. When the number of aircraft types and movements needs to be expanded later on, it is assumed that operation routes are unchanged and that Arlanda still serves as the hub airport.

Since the time horizon for the scenarios is as much as 50 years, technology developments need to be taken into account. In doing so the time period has been divided into periods, each reflecting a certain technology level. For the conventional aircraft, the periods are 2001-2012 (today's technology level), 2013-2025, 2026-2037 and 2038-2050. Corresponding time periods for the cryoplanes are 2015-2032 and 2033-2050.

The idea is that each aircraft is at first designed for the range and the number of passengers given in Table 3-1, to obtain performance owing to today's technology level. Then, fuel consumption is decreased and emissions performance is improved to reflect a technology development; the size of the improvements is predicted by the time period it is meant to reflect. With these improvements taken into account, the aircraft is re-optimised, and hence, the performance is increased, i.e. reduced fuel consumption for the same range. The technology level assigned to a certain aircraft individual is determined by the introduction year of the aircraft.

3.3.1 Technology Levels

When considering technology improvements for aircraft, there are three main parameters, basically independent of each other, that need to be taken into consideration, namely, aerodynamic efficiency, structure weight and the specific fuel consumption (SFC) of the engines. In addition, the emissions, particularly oxides of nitrogen (NO_x), are of interest and subjected to improvements over time.

Improved aerodynamic efficiency is equivalent to generating the aerodynamic lift at a cost of less aerodynamic drag. This may be achieved in several ways: smoother surfaces, improved aerodynamic shapes, boundary layer control, lift distribution control, etc. Based on some rough estimations, it has been assumed that a reasonable improvement in aerodynamic efficiency within the next 50 years would be about 20%, i.e. the total drag may be reduced by 20% until 2050. Numbers for each time period are given in Table 3-2.

As to the structure weight, there may be an even greater potential for improvements. By introducing new light materials, improving the manufacturing process of new composites, using load monitoring, etc., weight savings of about 45% may be achieved by 2050 (Ireman, 2001). In this study a somewhat more conservative number has been assumed, namely, 30% until 2050. In order to simulate this, the weights of the fuselage and the wing box mass, i.e. those parts that make up the main part of the aircraft weight, have been reduced by the corresponding number depending on the technology level. Numbers for each time period are given in Table 3-2.

Finally, there will be improvements on the engine side as well. One or two decades ago most of the research on aircraft engines, including both engine cycle and combustor concept, was focused on improving the engine efficiency, whereas most effort during the last decade and at present is laid on reducing oxides of nitrogen (NO_x). The overall engine efficiency – the product of the thermal and the propulsion efficiency – is inversely proportional to the specific fuel consumption SFC, i.e. fuel flow for a given engine thrust. Consequently, improved engine efficiency decreases SFC and thus decreases the total fuel burn for a specific mission. Measures for achieving reduction in fuel burn deal with improving the thermal and the propulsion efficiencies. The propulsion efficiency is favoured by a high by-pass ratio, and the thermal efficiency may be increased through a higher overall pressure ratio (OPR) and higher turbine entry temperature (TET); two measures which are both detrimental for the production of NO_x. Accordingly, there are, without doing any closer investigations, difficulties in estimating improvements in SFC and NO_x production at the same time. Therefore, it has been decided that changes of SFC are not taken into account in this investigation, i.e. the SFC level during the 50-year period is constant and equal to the level of 2001.

However, there will, during the next decades, be improvements in carbon dioxide (CO_2) emissions, which are proportional to the fuel consumption. In accordance with the European project “The Efficient and Environmentally Friendly Aero Engine (EEFAE)”, the aim is to reduce the CO_2 emissions by 12 and 20% for the so-called ANTLE and CLEAN engines, respectively (Sjunnesson, 2001). At the same time the NO_x reduction targets are 60 and 80%, respectively. The latter, with the highest CO_2 reduction target, will probably not commence commercial service before 2020. Hence, a fuel burn reduction of 20% or somewhat more would have been reasonable to assume for the end of the transition period, 2050.

The potential of improving NO_x emissions differs for kerosene and for LH_2 engines, and is mainly dependent on the combustor concept. According to Dahl and Suttrop (2001), the minimum achievable level of emission index for NO_x ($EINO_x$ [g/kg Fuel]) for kerosene combustion is approximately 60% of today’s level. For LH_2-powered engines, 10% (based on the kerosene energy equivalent) of $EINO_x$ of kerosene-fuelled engines in 2001 is considered as the minimum achievable level. These low levels may, for the conventional engines, be achieved by using staged or RQL-combustion, and for the hydrogen engines, this level may be achieved by using premixed combustion (Dahl and Suttrop, 2001). The numbers assumed for $EINO_x$ as a function of the time period for kerosene and for LH_2-fuelled engines are given in Table 3-2.

Measures for NO_x reduction tend to increase emissions due to incomplete combustion, namely, carbon monoxide (CO) and unburned hydrocarbons (UHC). If it is assumed that efforts for reducing primary NO_x, but also CO and UHC, are made at the same time, it would be reasonable to assume that the CO and UHC are kept unchanged when the emissions of NO_x are decreased. Hence, in this study it is assumed that the emissions of CO and UHC are retained at 2001's values for all technology levels.

To sum up, the assumptions for SFC reduction are very conservative, and reductions for aerodynamic drag and structure weight may also be somewhat on the low side.

Table 3-2. Specifications of Technology Levels for Specified Conventional and Cryoplanes.

Technology Level	**Introduction Year**	**Aero-dynamic Drag Level [%]**	**Structure Weight Level [%]**	**$EINO_x$ Level [%]**	**SFC Level [%]**
Kerosene 0	2001	100	100	100	100
Kerosene 1	2013	92.5	90	80	100
Kerosene 2	2026	85	80	60	100
Kerosene 3	2038	80	70	50	100
Cryo 1	2015	92.5	90	30[2]	100
Cryo 2	2033	82.5	75	15[2]	100

3.3.2 Aircraft Design Process

Before technology improvements may be applied to the different aircraft configurations, a basic version of each of these, representing the technology level of today, needs to be created. The conventional aircraft are re-designed in the sense that the MTOW is adjusted to achieve payloads and ranges as recommended by SAS. This modification may involve a slight fuselage lengthening in order to accommodate the required number of passengers. The wing configuration of each aircraft is, however, kept constant regardless of the technology level.

In Oelkers and Prenzel (2001) the cryoplane configuration (CMR1-300) is designed to reflect a technology level of 2010, which implies that the total drag, aircraft weight and SFC of the engines (basically V2527-A5) are slightly decreased compared to the general levels of 2001. Hence, these levels need to be restored to the levels of 2001. In order to find a sensible cryoplane configuration for the larger of the two studied aircraft, a new configuration has been created by FOI, where the fuselage has been stretched and the wing size up-scaled. The larger version has been denoted CMR1-400. The wing size was found by an optimisation process using the original technology level (2010) for a range of 4000 nautical miles, with a fixed wing shape (fixed sweep and aspect ratio). Before the scenario aircraft could be designed, the technology level needed to be restored to the level of 2001. The wing size was kept unchanged when the aircraft were re-designed for the shorter ranges required in this study, 2000 and 3000 NM, for the CMR1-300 and the CMR1-400 aircraft, respectively.

Having found reasonable configurations for the aircraft needed in the transition scenarios, the technology improvements are applied, i.e. the total drag and the weight (of fuselage and wing box) are decreased according to the technology levels defined in Table 3-2. Reduced

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[2] The numbers are given related to the NOx emissions of kerosene in 2001, i.e. kerosene 0.

drag and weight either increases range or reduces fuel burn, with the latter leading to reduced MTOW. In this study, the MTOW is adapted to obtain the proper range. With a lower take-off weight, a smaller take-off thrust is required for the same take-off performance. Therefore, the aircraft is re-optimised with the engine thrust and the MTOW allowed to vary. Then a take-off thrust 20% larger than optimum is used as a safety margin to ensure that no engine deterioration will prevent the aircraft from taking off within the allowable field performance. Finally the proper MTOW is found with the proper engine thrust.

Table 3-3 below presents an overview of the main characteristics of all aircraft combinations that will be used to quantify the emissions for each transition scenario.

Table 3-3. Main Characteristics of Aircraft Combinations Used in the Transition Scenarios.

A/C Type	Technology Level	Engine Thrust [kN]	MTOW [kg]	Fuel for Climb, Cruise and Descent [kg]
B737-600	0	79,2	54200	4414
B737-800	0	96,6	66800	5498
A321-100	0	143,1	83200	6876
	1	132,9	78600	6136
	2	116,9	73800	5318
	3	104,5	69900	4821
A330-200	(0)	212,9	143000	14532
	1	193,7	134500	12987
	2	170,3	125500	11521
	3	149,0	117900	10501
CMR1-300	(0)	169,3	98800	2866
	1	152,0	92100	2492
	2	144,0	84000	2106
CMR1-400	(0)	203,9	118000	4648
	1	182,6	110000	4039
	2	154,9	98900	3316

3.3.3 Results

In Figure 3-10 and Figure 3-11 the fuel consumption for the low- and high-growth passenger scenarios, respectively, are shown. Figure 3-12 to Figure 3-14 show emissions of CO_2, H_2O and NO_x of the low-growth scenario. The corresponding emission figures for the high-growth scenarios are not shown, since they do not give any new information. The trends are the same; the only difference is that the changes occur earlier, owing to the high-growth rate in the beginning of the period. Fuel consumption and emissions are calculated using SAS's timetable of 6 June 2001. This day is believed to be representative of the average daily fuel consumption of SAS's domestic fleet (Näs, 2002). There will, however, be some periods of reduced traffic on some routes; hence, the fuel consumption and emissions presented are slightly higher than the daily average. The aircraft types that were used when the emissions were calculated are presented in Appendix A.

Without introducing any cryoplanes, the daily fuel consumption is estimated to increase from about 320 tons in 2001 to about 950 tons in 2050 (Figure 3-10). This implies a threefold increase in fuel consumption during this period of 49 years. Simultaneously the number of passengers has increased 3.6 times (Figure 2-1), and the number of movements has increased 1.8 times. Thus the fuel consumption has increased more than the movements, caused by using larger and larger aircraft types. It could also be observed that the increase in fuel use is lower than the increase in passengers, which is a consequence of technology improvements. When comparing the absolute numbers for kerosene and LH_2 use, it needs to be pointed out that the numbers for kerosene represent the total amount of fuel that needs to be supplied, divided on all Swedish airports that are involved; whereas the numbers given for LH_2 refer to the amount that needs to be supplied at Arlanda only, since this is the only refuelling station for hydrogen.

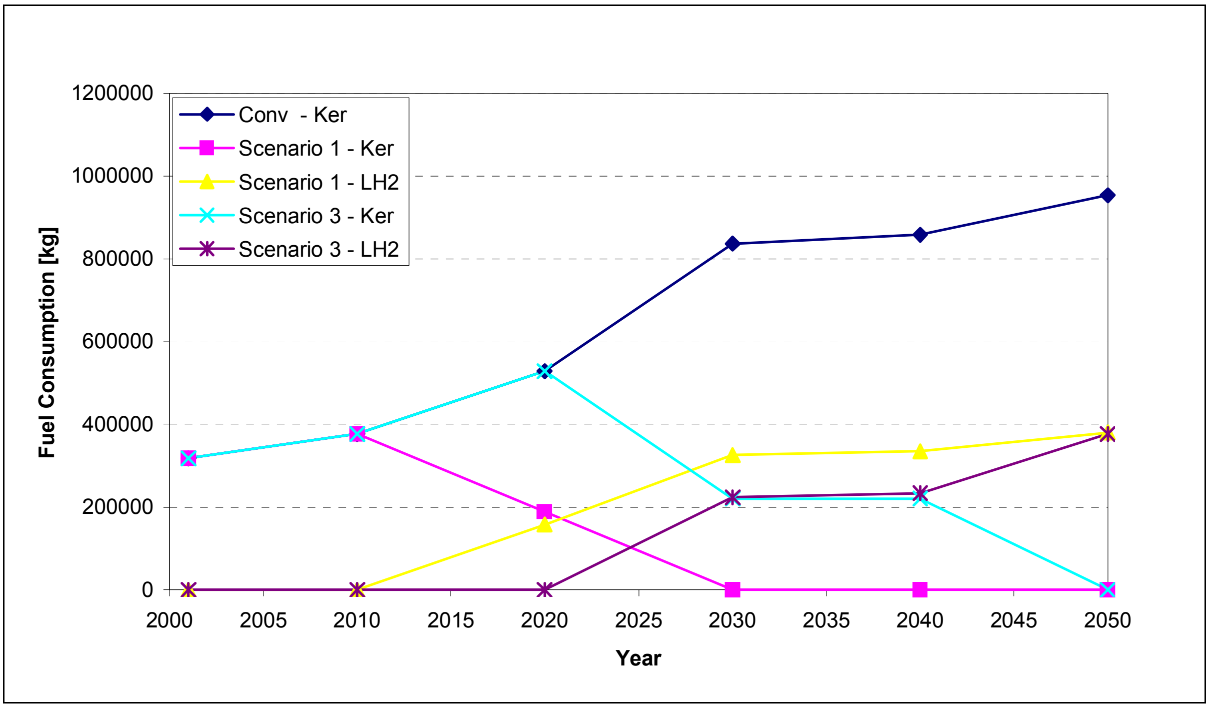

Figure 3-10. Daily Consumption of Kerosene and LH_2 for the Low Passenger Growth Scenario.

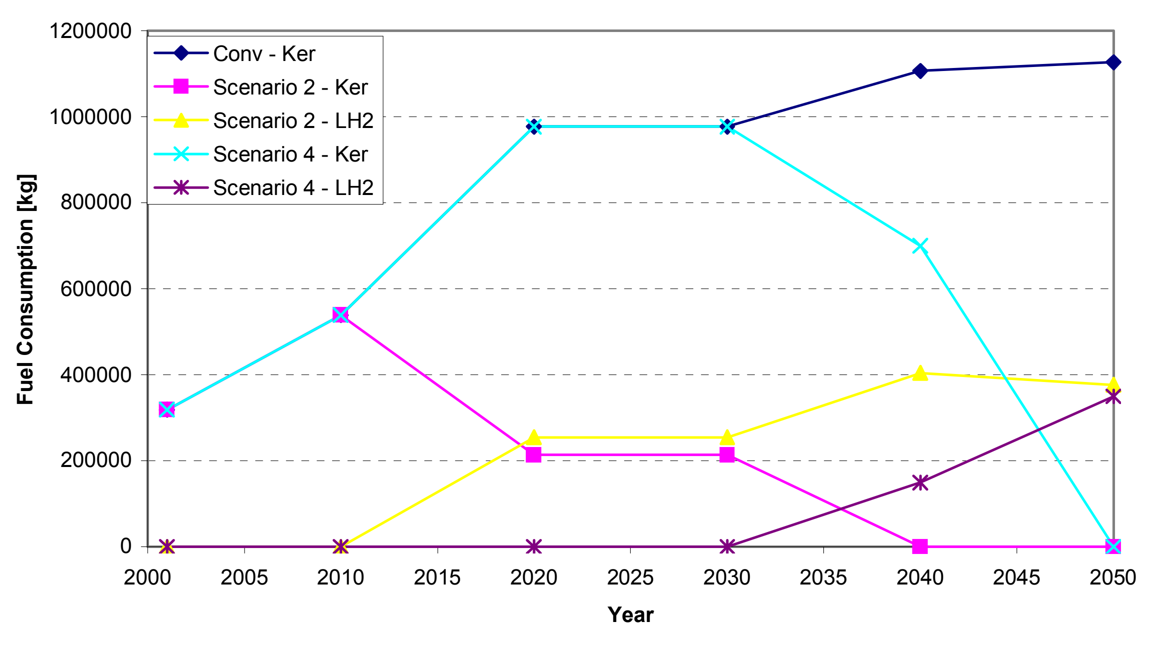

Figure 3-11. Daily Consumption of Kerosene and LH$_2$ for the High Passenger Growth Scenario.

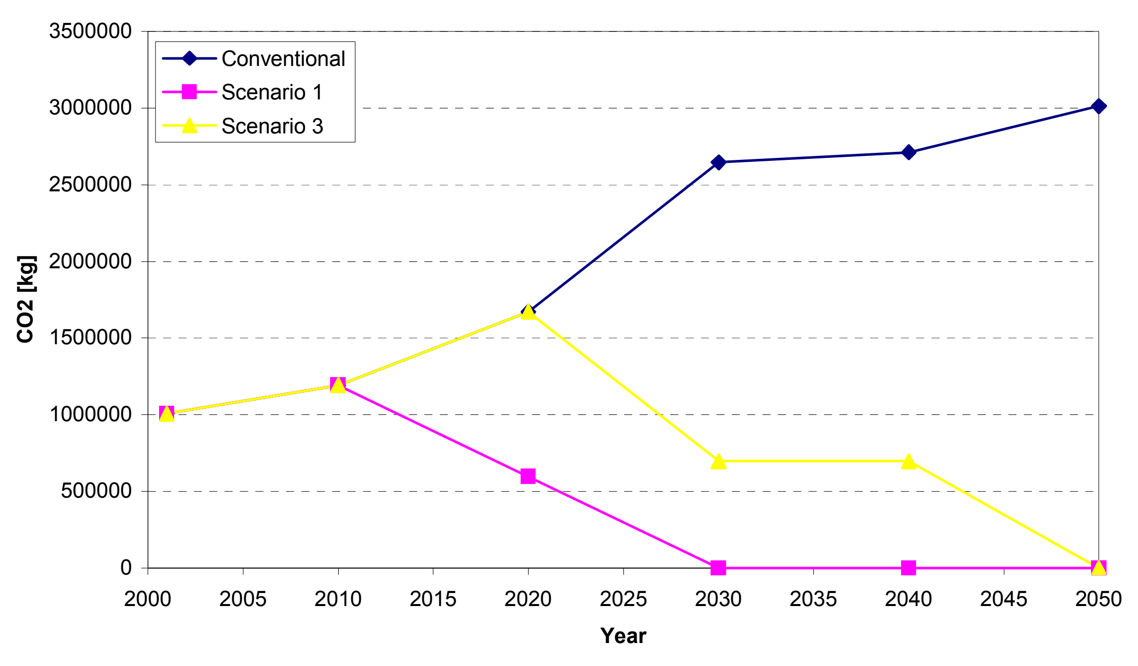

Figure 3-12. Daily Emissions of CO$_2$ for the Low Passenger Growth Scenario.

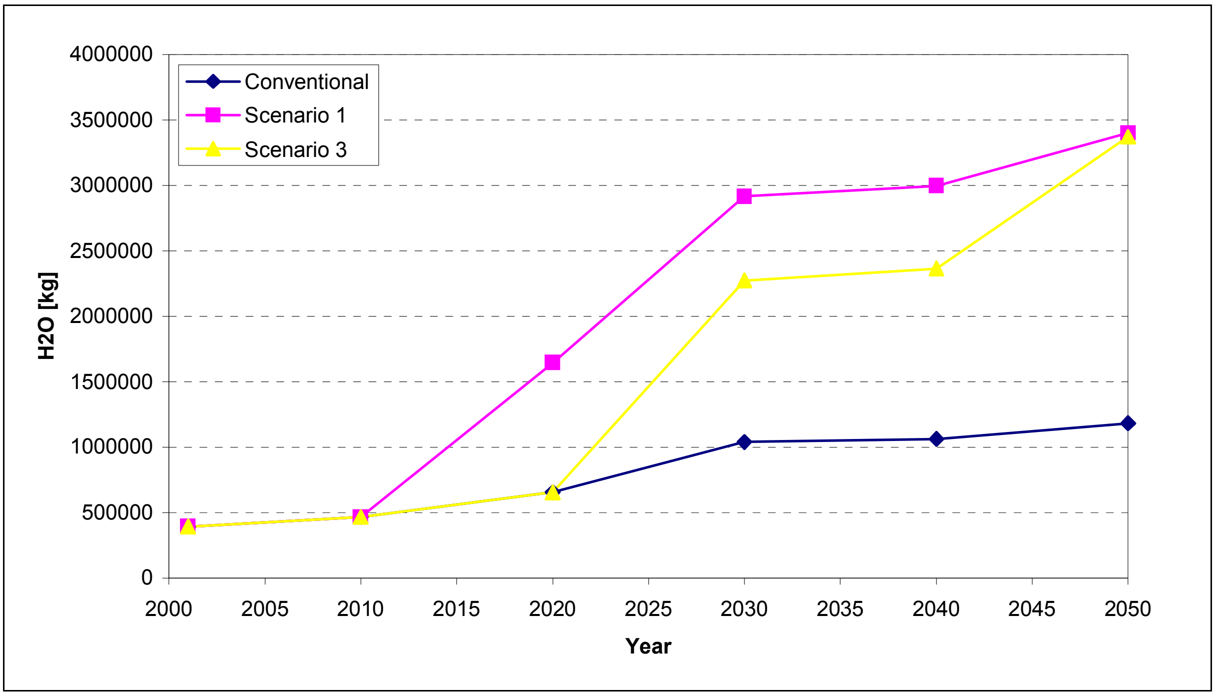

Figure 3-13. Daily Emissions of H_2O for the Low Passenger Growth Scenario.

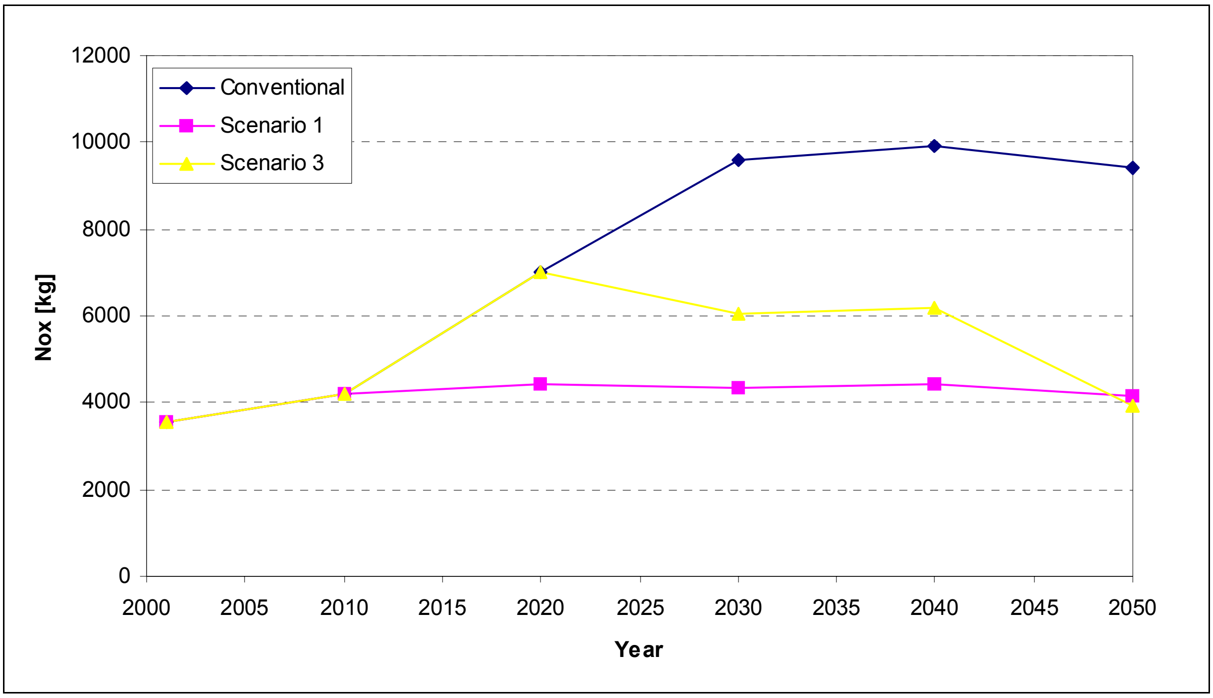

Figure 3-14. Daily Emissions of NO_x for the Low Passenger Growth Scenario.

The kerosene consumption drops when the cryogenic fuel is introduced, finally falling to zero at the end of the period, 2050, for all scenarios. As to the demand for LH_2, it increases from zero in 2015 or 2025 (in Figure 3-10 and Figure 3-11 it appears that LH_2 is needed from 2010 and 2020, respectively, but this is due to the situation that only values every tenth year were used when drawing the curves) depending on the scenario to almost 400 tons a day in 2050. In general, the higher growth rate implies that the introduction of new aircraft types is needed earlier; hence, more generations of aircraft will be involved by 2050. A high growth rate, therefore, results in a more modern aircraft fleet in the end of the period than the low-growth rate does. This is the reason why the demand for hydrogen is roughly the same in 2050 for the low- and high-growth scenarios, even though the high traffic growth rate gives a larger aircraft fleet in 2050.

According to Figure 3-12 and Figure 3-13, the emissions of CO_2 and H_2O follow the same trends and have the same percentage changes as does the fuel consumption. This was expected, since these emissions are proportional to the fuel consumption. Note, however, that whereas the CO_2 emissions diminish when cryoplanes are introduced, the H_2O emissions increase. This is due to the fact that a cryoplane emits about 2.6 times more water than a conventional aircraft, provided that they consume the same amount of energy.

The NO_x emissions are presented in Figure 3-14. By introducing cryoplanes early, according to scenario 3, the amount of NO_x may be retained at a level not much higher than today's level. If a conventional fleet scenario is assumed, the NO_x emissions will be about 2.8 times higher in 2050 than in 2001.

Other emissions of kerosene-powered air traffic, such as CO, UHC, sot and SO_x, are not shown in any figures, but since cryoplanes emit none of these, these emissions will drop off in a manner similar to CO_2 when cryoplanes are introduced.

For the domestic traffic of SAS with the assumptions made in this study, it may be concluded from the figures that a delay in the introduction of cryoplanes would result in a lagging in emissions reduction that is larger than the delay in their introduction, i.e. starting to introduce cryoplanes in 2025 instead of 2015 would mean that it takes more than ten years for the emissions to be at the same level as those of the aircraft fleet that would be introduced in 2015.

Having defined the consequences of the different scenarios in terms of fuel consumption, the fuel sources at Arlanda airport may be considered.

4 Fuel Sources at Stockholm/Arlanda Airport

This section gives an overview of current conditions at Arlanda airport, deals with implications for the airport of using liquid hydrogen and describes different methods for hydrogen production.

4.1 Current Conditions

Arlanda is the largest airport in Scandinavia and Europe’s sixth largest airport. During 2000 18.3 million people travelled to or from Arlanda; two out of three travelled on international flights (SCAA, 2002). It is considered to be one of Europe’s most modern airports, having, for instance, a high-speed railway to central Stockholm and a new 80-metre control tower featuring the world’s most PC-based air traffic management system. At present two runways are in use, but in the latter part of 2002 a third runway will be taken into operation as well.

Currently, the kerosene is transported by trucks from a harbour in Stockholm (Värtahamnen) to Arlanda airport. About 40 trucks a day are normally in service. In the future, the fuel distribution system will probably be changed, such that the fuel will be transported by rail from Gävle harbour (about 200 km north of Stockholm) to Brista (about 5 km north of Stockholm). From here it will be piped to Arlanda. At Arlanda the fuel is stored in tanks located 2-4 km south of the gates and about 1 km from the closet runway, which is well beyond the 305 meters that is suggested as a safety distance in case of any aircraft accident (Sefain and Jones, 2001). The fuel is stored in four tanks, in total giving a storage capacity of 20 000 m^3 (Figure 4-1). From the tanks the fuel is pumped in buried pipelines to the gates, i.e. hydrant system. At the gates the fuel is taken from pits (Figure 4-2) and passed via a dispenser truck (Figure 4-3) that cleans the fuel before it enters the aircraft tanks. The majority, about 85%, of the fuel is provided in this way; the other 15% is provided by tankers, which are equipped with cleaning facilities as well.

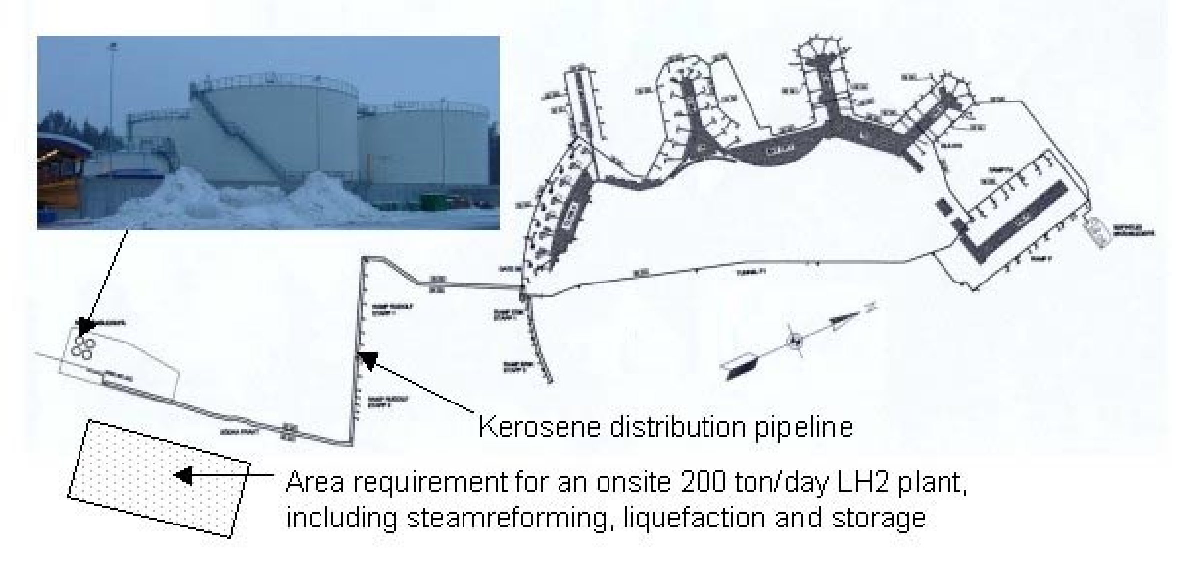

Figure 4-1. Current Kerosene Distribution System at Arlanda Airport. For Comparison the Area Requirement for a Plant Producing 200 ton LH_2/day is shown (Bracha, 2002). (picture by Bracha, 2002)

Figure 4-2. A Pit where Fuel is taken for Refuelling. (picture by Bracha, 2002)

Figure 4-3. Dispenser Truck in Operation during Refuelling. (picture by Bracha, 2002)

Arlanda airport covers a large area of about 32 km^2, and in the future another 25 km^2 will be occupied. Additional buildings, such as a cargo terminal and large post terminal, are planned to be built, but considering the large unused areas, there should still be areas left for new facilities.

The current total consumption of electrical energy, used for light, computers, etc., at Arlanda is about 160 GWh/year. This amount would be enlarged to 1095 GWh without any modifications of the electrical network.

4.2 Special Requirements and Infrastructure Changes Needed for Operation of Cryoplanes

There are a number of measures that need to be taken to ensure that the safety level at the airport is maintained when changing to hydrogen fuel use. Since hydrogen is a colourless and odourless gas, new safety detection equipment will be required. At any airport, vehicles used for the various ground support activities, such as towing aircraft, cleaning, catering and galley service, are required. In general these are powered either by diesel or spark ignition engines. In order to avoid a fire hazard, spark ignition engines should be avoided. A solution would be to provide the spark ignition engines with spark-arrestors, but better would be not to use any vehicles powered by such engines at all near cryoplanes or their fuel infrastructure. At Arlanda the majority of the vehicles in use are diesel-powered, hence, this requirement would not cause any major measures to be taken. A very pleasing and feasible solution to this constraint would be to power all airport vehicles by fuel cells driven by hydrogen. This would be very convenient, since the infrastructure and production facilities are already there and thus easily accessible. One obstacle for fuel cell-driven vehicles today is their limited range, but this is a limitation that does not have any relevance at an airport. Furthermore, it would eliminate the pollutant emissions at and around the airport, thereby significantly improving the working environment for the personnel who are working at the ramp.

Using hydrogen for aviation will also involve the personnel who are working at the airport, in the training of new of emergency and personnel safety procedures for all ramp personnel.

Largely, the required changes have to do with the refuelling procedures. However, the intention is that the hydrogen should be distributed in a way similar and parallel to that of the kerosene. For several decades there needs to be infrastructure for handling both kerosene and hydrogen. The hydrogen should be liquefied and stored in the vicinity of the current kerosene storage, and transported to the aircraft by pipelines in a similar manner as for kerosene (Figure 4-1). The overall airport layout and procedures should not change, and the aircraft can be refuelled at gate positions exactly like conventionally-fuelled aircraft, thus guiding and gate operating systems can remain the same. Considering general safety aspects of handling and using hydrogen for aviation, studies have shown that the overall safety level is at least as high as when using kerosene (Sefain and Jones, 2001 and Schmidtchen and Geitmann, 2001). According to Schmidtchen and Geitmann (2001), future hydrogen aircraft might even be safer than today's aircraft, if recommended additional precautions are realized. It will, however, involve other safety considerations. There are no reasons to change the overall airport layout. Such changes would increase costs of infrastructure build-up unnecessarily. For instance, fuelling at isolated locations would probably yield excessive turn-around times, and it would require a system of taxiways.

Since hydrogen is a cryogenic fuel, what really needs to be changed is the interface between the fuel supplies and the aircraft fuel tanks, as well as most of if not all the fuel system components (Sefain and Jones, 2001). A question that arises is what to do with the boil-off of hydrogen. Preferably, this could be compressed and used as fuel for H_2 buses operating at the airport. In fact, this is what is presently being done at Munich airport where a small infrastructure for hydrogen and liquid hydrogen production has been established, powering cars and busses operating at the airport (Bracha, 2002). This implies that H_2 recovery lines need to be established.

In order to avoid that any combustible mixture of hydrogen and air occurs, tanks need to be purged prior to refuelling by an inert gas that does not liquefy upon exposure to LH_2 (Sefain and Jones, 2001). Only a few inert gases fulfil this requirement, and amongst them, helium seems to be the most feasible one. Therefore, additional facilities handling helium, such as storage tanks and pipes, are required at the airport. The storage may be located quite close to the gates, since there are no safety risks with such storage. Connections to all aircraft refuelling places, as well as to the maintenance area, need to be established.

One important challenge of introducing cryoplanes is maintaining turn-around times as close as possible to current schedules. What undergoes the most change is the refuelling process. Changes in the rest of the turn-around activities are small in comparison. Mainly owing to the higher volume of liquid hydrogen required compared to the amount of kerosene, this process will be longer (in the order of twice as long). In spite of this, the refuelling time is not judged to be a critical factor (affecting the turn-around time) for cryoplanes, since it may be performed whilst other turn-around activities are being performed (Sefain and Jones, 2001). Instead the embarking/disembarking of passengers and cleaning operations, which are the most time consuming elements, are considered to be the critical path. Neither for conventional aircraft does the refuelling process constrain the turn-around time. To conclude, no significant changes on turn-around times are expected with cryoplanes.

To sum up concerning the airport infrastructure, the demand for new facilities for conversion to operation of cryoplanes is evident; however, the changes required at the airport seem to be practicable and no major obstacles are expected. Similar conclusions have been drawn in other studies too, such as Schmidtchen and Geitmann (2001) and Hoyt (1976).

4.3 Methods for LH_2 Production

Considering the technologies for hydrogen production that are feasible at present, there are a number of technologies, both renewable and fossil-based, that may be adopted. Later on, these technologies will be more efficient, and new ones will be introduced. For instance, using sunlight to produce hydrogen offers large environmental benefits, especially if the efficiency of the process could be improved and the costs could be lowered. Gasification of biomass and electrolysis of water are methods that may be based on renewable energy sources. Gasification of biomass involves hydrogen being extracted from hydrocarbons, originated in a renewable energy source, by a gasification process. This process will always be renewable. Electrolysis of water means that water is decomposed into hydrogen and oxygen by letting an electric current run through water. In order to state whether this method is renewable or not, one needs to know how the electric energy is produced. It could be produced from renewable energy sources, such as wind, water, solar, geothermal or biomass, but it could also be produced from fossil sources, such as oil, coal or gas. As to the fossil-based LH_2 production methods, the feedstocks are hydrocarbons, such as gas, coal or residual oil and water. The products are hydrogen and other by-products, for instance the greenhouse gas CO_2. Steam Methane Reforming (SMR), which uses methane from natural gas and steam as feedstocks, is the most efficient and widely used method.

Comparing the different methods for hydrogen production in terms of efficiency and costs, the fossil-based are more favourable. In general, the fossil-based methods have the highest overall efficiency for liquid hydrogen production and delivery. It is estimated to be around 40% for biomass and just over 50% for fossil fuels, with gas having the highest of about 53% (Schnieder and McKay, 2001). The fossil-based methods are also cheaper than the renewable ones to install. For a plant producing 50 ton/day, the investment of a SMR plant is about one-third of an electrolysis plant and about one-fifth of a biomass gasification plant (Bracha 2002). In terms of cost per GJ produced liquid hydrogen, Schnieder and McKay (2001) assess that solar- and wind-based hydrogen production from electrolysis is unlikely to be competitive with biomass or fossil fuels for many decades.

Sarigiannis and Kronberger (2001) have examined different renewable based methods for producing hydrogen by carrying out Life Cycle Assessments (LCA) of the technological system. All are based on producing electricity by a renewable energy source and then producing hydrogen by electrolysis of water. They conclude that wind and hydropower energy sources lead to very low emissions, even for long distance transports. Biomass also leads to low emissions of greenhouse gases, provided that the biomass is produced locally, thus avoiding transportation. Extensive transportation could lead to large amounts of emissions that contribute to acidification as well as to smog formation.

From Figure 3-10 and Figure 3-11 it was concluded that the amount of liquid hydrogen that needs to be produced varies from zero in 2015-2025 to about 400 ton/day in 2050. Therefore, the production capacity should be continuously increased, starting with a module capacity of 50 ton/day, and end up with eight modules each producing 50 ton/day in 2050. The minimum storage capacity for each module is two tanks, one being constantly filled and the second one being in supply operation. A storage volume of at least one average day LH_2 consumption is reasonable to install as a minimum. However, as more modules will be added within a reasonable time, it is sensible to start with larger and more tanks. Furthermore, having more modules will give more flexibility. Having three tanks would imply that one may be used for filling, one for consumption and the third one for peak shaving and to cover plant failure demand (Bracha, 2002). With respect to the demand of SAS's domestic traffic, it would be reasonable to start with a capacity of three to four tanks at 1500 m^3 each. This would be enough for the demand in 2050.

In addition to the regular production facilities for liquid hydrogen at Arlanda, mobile refuelling facilities are required for an aircraft that if for some reason would land at an airport other than Arlanda without enough fuel for the return trip. The most economical and efficient mobile supply would probably be using LH_2 containers transported via rail. At airports where no railway connection is established, trucking the LH_2 is probably the most sensible way to transport the fuel.

Three different methods for the hydrogen production at Arlanda, namely, SMR (conventional method), electrolysis of water and gasification of biomass, will be considered. The liquefaction process, which is needed independently of the hydrogen production, will also be addressed.

4.3.1 Electrolysis of Water

Using electrolysis of water would have the very large benefit that the hydrogen could be produced from any energy source; preferably from renewable ones, but it could also be produced from fossil resources. The method requires large amounts of desalted water, and above all, electrical energy. Consumption data for the electrolysis plant are given in Table 4-1 and for the liquefaction plant in Table 4-2. In addition to the data given in Table 4-2, instrument air and city water are needed. The electrolyser and liquefier would need about 1.14 TWh/year per module of 50 ton/day. This is about seven times the consumption of electrical energy today at Arlanda and less than one percent of the total net supply of electricity in Sweden in 2000, which was about 160 TWh (SCB, 2002). In 2050 when SAS's domestic fleet, according to the scenarios, will be operated on hydrogen, solely, eight times this amount will be required, namely, 9.2 TWh/year.

Table 4-1. Consumption Data for an Electrolysis Plant Producing 50 ton/day (Kronberger, 2002).

Electric Energy	105 MW
Water	28 m^3/h desalted water (efficiency: 80%)

Table 4-2. Consumption Data for a Liquefaction Plant Producing 50 ton/day (Allidieres, 2002).

Main electrical energy	25 400 kW (95% para[3] H_2)
Utilities/Control electrical energy	155 kW
Cooling water (ΔT 10°C)	4000 m^3/h
N_2 (gaseous)	90 kg/h

In order to get an understanding of the amount of electrical energy that would be required to fuel the complete aircraft fleet operating at Swedish airports in 2050, the amount required for the Swedish domestic traffic of SAS's fleet could be up-scaled. This is a very rough estimation, but still it gives some important information. SAS's domestic fleet makes up about 70% of the total domestic and about 35% of the total traffic, including both the domestic and the international traffic that arrive at or depart from Swedish airports. For doing this assessment, it is assumed that the concept of using hydrogen for aviation is spread all over the world; hence, hydrogen refuelling facilities are available at the arrival/departure airport outside Sweden. Likewise, it is assumed that the average flight distance for the international routes is as long as the average flight distance for the domestic flights. In reality the average international flight is somewhat longer. This limitation will result in a slightly underestimated fuel consumption. However, this effect is probably cancelled by the rather conservative technology improvements assumed for the aircraft fleet, that are to reflect new technology and more efficient aircraft with time.

Based on the traffic growth figures and technology improvements with time presented earlier, the amount of electrical energy needed to power all aircraft refuelling with liquid hydrogen in Sweden in 2050, produced by electrolysis of water, would be about 20 TWh. This is about 12% of the total net supply of electricity in Sweden in 2000 (160 TWh). In 2050 the electricity production will be considerably larger than in 2000, but still the comparison gives some indication of the magnitude of the required electrical energy in order to completely use hydrogen for aviation. In order to calculate this value, today's efficiency of producing LH_2 has been used. If electrolysis of water is still the most feasible way of producing hydrogen in 2050, the efficiency of the process probably will be higher, thus reducing the requirement of electrical energy.

Next, one needs to ask whether these amounts of electricity are reasonable and from where the additional electricity will come. Today, the electricity in Sweden comes mainly from waterpower and nuclear power, and is therefore more or less free from greenhouse gas emissions. To be more specific, the total gross supply of electricity in 2000 was 163.3 TWh, based on 48.1% waterpower, 35.0% nuclear power, 5.4% conventional thermal, 0.3% wind power and 11.2% imported power (SCB, 2002). However, if a considerably extra amount of electrical energy would be required, the water power and nuclear power would not be able to deliver this without extending the facilities, since they are operating at almost full capacity already (Söder, 2002). Instead, there is a risk that the additional power will be imported from sources that probably are not renewable based. Thus, the electrical energy would be less "clean". Therefore, it is really important that the renewable sources, such as wind, solar and biomass will be extended in Sweden parallel to the implementation of cryoplanes. Expanding the water power would also be an acceptable solution from a global warming point of view. However, mostly owing to the disturbance of the local ecology and the exploitation of unspoiled countryside, no extension of waterpower is at present planned to take place in Sweden. If the airlines could assert that they only produce hydrogen from renewable energy

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[3] Para refers to the spin of the hydrogen molecule. There are two possible states – para and ortho hydrogen. At atmospheric conditions there is a mixture of 25% and 75% ortho hydrogen. In the liquid state the equilibrium is almost 100% para hydrogen (Bracha, 2002).

sources, they would gain much goodwill. One possible way to obtain that would be for the aircraft industry to support the development of renewable energy sources.

4.3.2 Gasification of Biomass

Biomass could either be used as a primary energy source for electricity production, which is utilised for hydrogen production via electrolysis, or the hydrogen could be extracted from the biomass by a gasification process. Consumption data for such a gasification plant is presented in Table 4-3. This technology, however, needs further development before it may enter the commercial market. Owing to the very large supply of biomass in Sweden (more than half of Sweden's area is covered by forest), using biomass for hydrogen production seems an attractive solution.

Table 4-3. Consumption Data for a Biomass Gasification Plant Producing 50 ton/day (Kronberger, 2002).

Biomass	490 ton/day (dry basis)

Each year a plant producing 50 ton/day would require about 179 000 tons dry substance of biomass. In 2015 one such plant would be enough, whereas eight would be needed in 2050. In a similar manner as the amount of electricity required to produce all hydrogen by electrolysis of water, the amount of biomass required could be estimated. Taking into account the part that SAS's domestic traffic makes up, the amount of biomass to power all traffic refuelling in Sweden in 2015 and in 2050 could be estimated to be 386 000 and 3 087 000 ton (dry substance)/year, respectively. In order to compare these numbers to the biomass supply in Sweden today and in the future, the mass requirement is transformed to the energy unit TWh. If it is assumed that all the biomass is logging residuals with 40% moister content, the heating value is about 4.9 MWh/ton (dry substance) (Lantz, 1996). Using this value, the energy requirement in terms of biomass in 2015 and in 2050 would be 1.9 and 15.1 TWh/year, respectively.

In 1999 the total use of biomass, including biofuels, peat, etc., in Sweden was a little more than 90 TWh (Swedish Energy Agency, 2000). Taking ecological considerations into account, the biomass supply may be expanded to about 200 TWh/year by 2020 (Svebio, 2002). 120-130 TWh/year of this would be wood fuel (Parikka, 1997 and Svebio, 2002). Comparing the numbers of energy, in terms of biomass, that would be required to power all aviation refuelling in Sweden with hydrogen, with the potential of biomass supply in Sweden, it may be concluded that the amounts that the aviation would need are not unreasonably large. However, it requires that the biomass use would be enlarged.

4.3.3 Steam Methane Reforming (SMR)

Producing hydrogen by SMR is the most commonly used method, and today it is the most efficient and cheap. It would also require the smallest amount of ground area for the plants. According to Bracha (2002) each plant occupy about 2 000 m^2, whereas an electrolysis plant and a biomass gasification plant occupies 8 000 and 16 000 m^2, respectively. However, in the very long run this method is not preferable, because it is based on a fossil energy source, namely, natural gas. In addition, there is at present no supply of natural gas in the Stockholm region, and the closest pipeline is located in Gothenburg, about 400 km southwest of Stockholm. Nor is any pipeline planned to be established in the near future. If there should be a pipeline established in the future this method could, if necessary, be used as an intermediate method before renewable methods have been improved, expanded and made more attractive. A way to avoid CO_2 emissions and still use SMR would be to extract the CO_2 in the process and sequester it in deep reservoirs or utilise it, for instance, in the chemical industry. This would make the method more expensive, but it would still probably be economically competitive with renewable-based production methods.

In addition to gas, SMR requires relatively large amounts of electrical energy (Table 4-4). Having such a plant and a liquefier in operation one year would consume about 229 GWh, which would mean that the consumption would be about 2.4 times higher than currently at Arlanda. Related to the net total supply of electricity in Sweden in 2000 (160 TWh), the consumption is 0.2%. So, the requirement of extra electrical energy would not be any obstacle, not even for the end of the considered period when eight modules would be required. The electrical network would need to be increased in terms of capacity when several modules are taken into operation.

Table 4-4. Consumption Data for a SMR Plant Producing 50 ton/day (Bracha, 2002).

Natural gas	9800 Nm^3/h
Demin water	10.7 ton/h
Cooling water (ΔT 10°C)	520 m^3/h
Electricity	640 kW
Instrument air	Approx. 140 Nm^3/h
Export steam	12 800 kg/h

4.3.4 Conclusions concerning LH_2 Production

In the very long term, aviation, just as the energy and other transportation sectors, needs to stop using fossil-based energy. When introducing cryoplanes in aviation, with the ultimate goal of reducing emissions of greenhouse gases, renewable energy sources should be used to the largest possible extent. Preferably in the long run all hydrogen should be produced from renewables, but during the transition phase, SMR and/or nuclear power may be used where sensible to reduce costs and/or emissions of greenhouse gases.

The amount of electrical energy needed to power all aircraft refuelling in Sweden in 2050, using liquid hydrogen produced by electrolysis of water, would be about 20 TWh. This is considerably much, but not any unreasonably large number, particularly not if considered that today's technology level of LH_2 production has been used. In 2050, the technologies for hydrogen production will probably be considerably improved compared to today, and some will possibly be driven out of competition by other more efficient ones. However, development and extension of renewable energy sources parallel to the introduction of cryoplanes is important to make sure that no or very little fossil-based energy is used for the LH_2 production. Gasification of biomass is also a feasible alternative for hydrogen production; particularly when observing that Sweden has large sources of biomass. Related to the estimated biomass supply in Sweden, about 8% would be required to power all civil aviation refuelling with hydrogen in Sweden in 2050. The most feasible renewable energy sources to extend in Sweden are probably biomass and wind power.

The options that have been discussed are all methods that would be feasible in the near future. Producing hydrogen by means of sunlight in a way much more efficient and cheap than today, probably offers the largest environmental benefits in the very long run.

It is clear that powering civil aviation with hydrogen does not obviously imply that all emissions of greenhouse gases are eliminated, since that depends on the hydrogen production method. The really important issue is that using hydrogen offers the possibility to use renewable energy sources for aviation. This is impossible as long as kerosene is used.

5 Conclusions

According to the traffic growth scenarios assumed for these studies, the number of passengers will increase three to four times by 2050. During the same time period, the number of movements will have increased, but by less than the number of passengers, due to the larger aircraft types that will have commenced on the domestic market. Depending on the scenario, the number of movements will have increased by 70-90%. Hence, it may be concluded that an essential increase in airport capacity, at all airports, is required to cope with the increasing traffic demand.

Based on the two different prerequisites, saying that all new aircraft introduced in 2015 and in 2025 and afterwards, respectively, should be cryoplanes, four different scenarios may be compiled. In all scenarios, it is reasonable to change to a fleet powered solely on liquid hydrogen by 2050. A high traffic growth rate results in a delayed broad-scale introduction of cryoplanes. In general, the higher growth rate implies that introduction of new aircraft types is needed earlier, hence, more generations of aircraft will be involved by 2050, and a more modern fleet will be in operation at that time.

By starting to introduce cryoplanes in 2015, the amount of NO_x may be retained on a level not much higher than today's level, provided that the emission indices of NO_x for the hydrogen engine are 15-30%, depending on the technology level, of the conventional engine in 2001. If a conventional fleet scenario is assumed, the NO_x emissions will be about 2.8 times higher in 2050 than in 2001.

Regarding the changes needed at the airport when using hydrogen, there are a number of measures that need to be taken to ensure that the safety level at the airport is preserved. In order to avoid a fire hazard, spark ignition engines should be avoided. A very pleasing and feasible solution would be to power all airport vehicles by fuel cells driven by hydrogen. The overall airport layout and procedures should not change, and the aircraft can be refuelled at gate positions exactly like conventionally fuelled aircraft. Largely, the required changes have to do with refuelling procedures. Since hydrogen is a cryogenic fuel, what really needs to be changed is the interface between the fuel supplies and the aircraft fuel tanks, as well as most of, if not all, fuel system components. However, the intention is that the hydrogen should be distributed in a way similar and parallel to that of the kerosene. Hence, from an airport infrastructure point of view, it is certainly feasible to change to hydrogen use. No significant changes on turn-around times are expected with cryoplanes.

Taking the local conditions into account, with respect to the availability of energy, it would be reasonable to change from kerosene to LH_2 as fuel for all civil aviation refuelling in Sweden, according to the scenarios compiled in this report. However, development and extension of renewable energy sources parallel to the introduction of cryoplanes, is important to make sure that no or very little fossil based energy is used for the LH_2 production. If electrolysis of water or gasification of biomass would be used for the LH_2 production, considerable amounts of electrical energy and biomass sources, respectively, would be required, but not unreasonably much.

It is worth mentioning that the cost penalty of changing the fleet to use LH_2 is not thoroughly assessed in this study. In order to fully cover the implications with respect to costs of changing the fleet, several aspects comprising difficulties need to be addressed. As the scenarios stretch several decades ahead and as some technologies need further development, it is crucial to assess the costs of all new facilities. Moreover, to make a fair comparison between cryoplanes and conventional aircraft, future price trends of kerosene needs to be taken into account. The price of kerosene will rise in the future, both due to dwindling oil resources and possibly due to future taxation (e.g. CO_2-tax). Besides, to fully understand the cost implications of introducing hydrogen in aviation, other sectors, such as the other transportation sector and the power industry, should the considered as well. Possible co-ordination gains could have a significant effect on the cost penalty. A study addressing all these issues is beyond the scope of the present study.

Powering civil aviation with hydrogen does not obviously imply that all emissions of greenhouse gases are eliminated, since that depends on the hydrogen production method. The really important issue is that using hydrogen offers the possibility to use renewable energy sources for aviation. This is impossible as long as kerosene is used.

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Appendices

Appendix A. Aircraft Types used in the Emission Scenarios

A/C Type	Tech. level	2001	2010	2020	2030	2040	2050
B737-600	0	9	11	-	-	-	-
B737-800	0	13	15	12	-	-	-
A321-100	0	-	-	-	-	-	-
	1	-	-	17	12	12	-
	2	-	-	-	-	1	-
	3	-	-	-	-	-	15
A330-200	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	20	20	20
	3	-	-	-	-	-	4
CMR1-300	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
CMR1-400	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
Sum		22	26	29	32	33	39

Figure A-1. Aircraft Types Used in the Emission Scenarios of the Conventional Fleet Development, Assuming the Low Passenger Growth Scenario.

A/C Type	Tech. level	2001	2010	2020	2030	2040	2050
B737-600	0	9	-	-	-	-	-
B737-800	0	13	12	-	-	-	-
A321-100	0	-	16	8	8	-	-
	1	-	-	5	5	5	-
	2	-	-	-	-	2	2
	3	-	-	-	-	9	14
A330-200	(0)	-	-	-	-	-	-
	1	-	-	21	21	21	-
	2	-	-	-	-	3	3
	3	-	-	-	-	1	23
CMR1-300	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
CMR1-400	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
Sum		22	28	34	34	41	42

Figure A-2. Aircraft Types Used in the Emission Scenarios of the Conventional Fleet Development, Assuming the High Passenger Growth Scenario.

A/C Type	**Tech. level**	**2001**	**2010**	**2020**	**2030**	**2040**	**2050**
B737-600	0	9	11	-	-	-	-
B737-800	0	13	15	12	-	-	-
A321-100	0	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
A330-200	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
CMR1-300	(0)	-	-	17	-	-	-
	1	-	-	-	12	12	3
	2	-	-	-	-	1	12
CMR1-400	(0)	-	-	-	-	-	-
	1	-	-	-	20	20	20
	2	-	-	-	-	-	4
Sum		22	26	29	32	33	39

Figure A-3. Aircraft Types Used in the Emission Scenarios of Scenario 1.

A/C Type	**Tech. level**	**2001**	**2010**	**2020**	**2030**	**2040**	**2050**
B737-600	0	9	11	-	-	-	-
B737-800	0	13	15	12	-	-	-
A321-100	0	-	-	-	-	-	-
	1	-	-	17	11	11	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
A330-200	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
CMR1-300	(0)	-	-	-	-	-	-
	1	-	-	-	1	2	-
	2	-	-	-	-	-	15
CMR1-400	(0)	-	-	-	-	-	-
	1	-	-	-	20	20	20
	2	-	-	-	-	-	4
Sum		22	26	29	32	33	39

Figure A-4. Aircraft Types Used in the Emission Scenarios of Scenario 3.

A/C Type	**Tech. level**	**2001**	**2010**	**2020**	**2030**	**2040**	**2050**
B737-600	0	9	-	-	-	-	-
B737-800	0	13	12	-	-	-	-
A321-100	0	-	16	8	8	-	-
	1	-	-	2	2	-	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
A330-200	(0)	-	-	-	-	-	-
	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
CMR1-300	(0)	-	-	-	-	-	-
	1	-	-	3	3	4	1
	2	-	-	-	-	12	15
CMR1-400	(0)	-	-	-	-	-	-
	1	-	-	21	21	23	2
	2	-	-	-	-	2	24
Sum		22	28	34	34	41	42

Figure A-5. Aircraft Types Used in the Emission Scenarios of Scenario 2.

A/C Type	**Tech. level**	**2001**	**2010**	**2020**	**2030**	**2040**	**2050**
B737-600	0	9	-	-	-	-	-
B737-800	0	13	12	-	-	-	-
A321-100	0	-	16	8	8	-	-
	1	-	-	5	5	-	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
A330-200	(0)	-	-	-	-	-	-
	1	-	-	21	21	21	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
CMR1-300	(0)	-	-	-	-	-	-
	1	-	-	-	-	1	1
	2	-	-	-	-	15	15
CMR1-400	(0)	-	-	-	-	-	-
	1	-	-	-	-	2	2
	2	-	-	-	-	2	24
Sum		22	28	34	34	41	42

Figure A-6. Aircraft Types Used in the Emission Scenarios of Scenario 4.