MEASURING THE LONG-TERM SUSTAINABILITY OF AIR TRANSPORT – AN ASSESSMENT OF THE GLOBAL AIRLINE FLEET AND ITS CO_2-EMISSIONS UP TO THE YEAR 2050

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1. INTRODUCTION

Environmental concerns play an increasingly important role in the air transport system. The term "sustainability" can be found everywhere in both industrial publications as well as political documents.[1] It has become a buzz word in an industry, whose sustainability is questionable, as it currently relies fully on finite resources.[2] In recent months and years, air transport organisations have publicised a number of environmental objectives, particularly with respect to climate change and the reduction of CO_2 emissions. Among the most prominent objectives publicised in the air transport industry concerning CO_2 reductions are the following:

- ACARE, the Advisory Council for Aeronautics Research in Europe, which is a cooperation of research establishments, manufacturers, airports, airlines and Member States of the European Union, has published in 2004 in its Strategic Research Agenda 2 (SRA2) objectives for the improvement of the future air transport system in Europe. In the research agenda, environmental objectives play a prominent role. The targets laid out by ACARE include a 50% reduction in specific fuel consumption in air transport until the year 2020.[3] Various elements of the air transport system shall contribute to this target, e.g. airframe design by 25%, engine improvements by 15-20% and air traffic management/operations by 5-10%.[4]

- IATA, the international air transport association, published in July 2007 its vision of a carbon-free air transport industry to be reached by the year 2050.[5]

- In a joint industry declaration, signed during the 3rd Aviation and Environment summit in Geneva, ACI, ATAG, CANSO, IATA, ICCAIA and several manufacturers declared that they are "committed to a carbon-neutral growth" and "aspire to a carbon-free future" without specifying any concrete time-frames or targets.[6]

- The Swedish airport operator Luftfartsverket as well as the Schiphol Group in the Netherlands aim for carbon neutrality in the operation of their airports.[7]

Tackling CO_2 emissions is important for two reasons: On the one hand, CO_2 is perceived to be a major contributor to the total climate change effects of aviation.[8] On the other hand, as CO_2 emissions are directly connected to fuel consumption[9], airlines have a strong incentive to reduce consumption and emissions, particularly as fuel prices have increased more than six-fold from 71

US-cents per gallon in January 2000 to a peak of 439 US-cents in May 2008.[10] Reducing fuel consumption and costs, which in the meantime have a share of 30-50% of total operating costs, therefore is an important element for airlines to maintain profitability. In this regard, airlines have an incentive to reduce emissions, even without any additional instruments like emission trading or fuel taxation.

However, considering the long lead times from technological innovation to introduction into service, the long service life of aircraft and long production cycles of aircraft models, the objectives and timeframes stated by industry organisations seem to be rather ambitious. This paper tries to shed some light into the question how new technologies, from the point of becoming available, will propagate throughout the air transport system and what their impact on total and specific CO_2 emissions will be. To answer this question, a method for the estimation and prognosis of aircraft fuel consumption and CO_2 emissions will be developed. Based on historical fleet composition and air transport forecasts, a growth path for the future passenger aircraft fleet up to the year 2050 will be elaborated. The future fleet and emissions forecast relies on a set of assumptions among others e.g. on the introduction of new aircraft types, their efficiency and the improvement of other elements in the air transport value chain such as air traffic management and the use of biofuels, which will be derived from an extensive literature review.

As a starting point and to derive plausible assumptions on technology developments used to quantify future emissions, a brief review of the major elements contributing to efficiency increases in air transport will be provided. Subsequently, the model used to quantify future CO_2 emissions and the assumptions on which the forecast is based will be described. Finally, the results of the quantification will be presented and the paper closes with some general concluding remarks concerning the interpretation of the presented results.

2. ELEMENTS CONTRIBUTING TO EFFICIENCY INCREASES

2.1 General considerations

When speaking about the efficiency of the air transport system, first of all a definition of the term “efficiency” is required. Reviewing the literature, one comes to the conclusion that not a single definition of efficiency in air transport exists. McLean (2006) shows that at least five types of efficiency are applied in aviation.[11] For the purpose of an assessment of environmental impacts, or to be more precise, CO_2 emissions, which is aspired in this paper, the term efficiency relates to fuel efficiency, measured as the ratio of fuel use per unit of output (usually RPK):

(1) $$Specific\ Fuel\ Consumption\ of\ Passenger\ Transport = \frac{Amount\ of\ fuel\ used\ (in\ kg)}{Transport\ Performance\ (in\ RPK)}$$

As CO_2 emissions are directly linked to fuel consumption, fuel efficiency can therefore directly converted into specific emissions by applying a constant emissions factor, measured in kg CO_2 per kg of fuel burned:

(2) $$CO_2\ Emissions\ Factor\ of\ Fuel_i = \frac{Amount\ of\ CO_2\ (in\ kg)}{Amount\ of\ Fuel_i\ burned\ (in\ kg)}$$

The emissions efficiency metric is then measured as the amount of CO_2 generated per RPK.

(3) $$Specific\ CO_2\ Emissions\ of\ Passenger\ Transport = \frac{Amount\ of\ Fuel_i\ used\ (in\ kg) \times Emissions\ Factor\ of\ Fuel_i}{Transport\ Performance\ (in\ RPK)}$$

This equation holds, as long as the fuel used has a constant emissions factor. As in this paper also the impacts of fuel substitution shall be explored, the respective emissions factors for each fuel used must be applied to translate the fuel efficiency metric into the metric for specific emissions:

(4) $$Specific\ CO_2\ Emissions\ of\ Passenger\ Transport = \frac{\sum_i^n Amount\ of\ fuel_i\ used\ (in\ kg) \times Emissions\ Factor\ of\ Fuel_i}{Transport\ Performance\ (in\ RPK)}$$

As a next step in setting up plausible assumptions on expectable future efficiency increases an overview of the elements potentially contributing to increased fuel efficiency and lowered specific CO_2 emissions will be provided. IATA's so-called "four pillar strategy" covers the main elements concerned:[12]

1. Technology
2. Infrastructure
3. Aircraft Operations
4. Economic Instruments

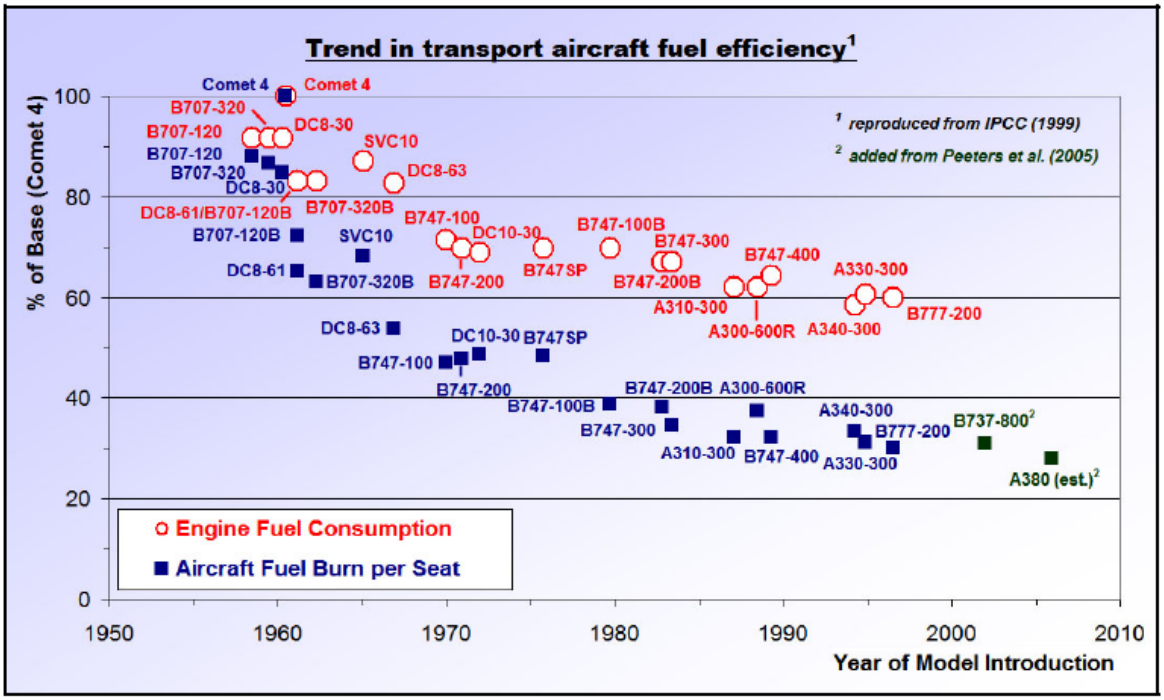
The following discussion of each of these elements tries to shed some light into the question, what the potential of each of these elements for future CO_2 emissions reductions of air transport is. The block "Technology" is split in aircraft and engine technology on the one hand and the development of biofuels on the other hand. For the block "Infrastructure", air traffic management is considered to play the most important role, while capacity constraints of airport infrastructure also contribute to inefficient fuel use. Finally, also operational aspects, such as the choice of aircraft size and load factors will be discussed, as well as incentives created by the introduction of economic instruments, such as emission trading schemes.

2.2 Aircraft and Engine Technology

The contribution of aircraft and engine technology to fuel efficiency of the air transport system can be assessed as substantial. Figure 1 shows the long-term

development of medium- and long-haul aircraft and engine fuel efficiency between 1950 and 2010. Each aircraft is compared to the first commercial jetliner, the de Havilland Comet. From the figure it can be concluded, that particularly in the early jet age between the late 1950s and the 1970s substantial increases in fuel efficiency could be achieved. From the 1980s to present, the steps became smaller, as it apparently became more difficult to achieve substantial efficiency increases. The law of diminishing returns, frequently found in many areas of economics, seems to be at work. Moreover, the product life cycles seem to have increased considerably, as aircraft remain in production for a longer time than in previous decades.

Figure 1: Long-term development of aircraft and engine fuel efficiency



Source: Schaefer (2006).

The increase in product life cycles can also be observed on the market for short- and medium-haul jetliners. Up to the late 1990s new types where released on average every 6.3 years in this segment.[13] The Airbus A320-200 for example, introduced in 1989, will remain in production until at least the middle of the next decade. Also Boeing's 737NG, introduced in 1997 is likely to remain in production for a total of about 20 years.

In the market for large long-haul aircraft, the Airbus A380, introduced 20 years after the Boeing 747-400 is perceived to consume 10-15% less fuel per passenger kilometre than the 747-400, which is partly attributable to new technology, partly also to the design, which depending on the exact configuration allows for some 150-200 more seats than the 747-400.[14]

The medium-sized long-range jetliners Airbus A350XWB and Boeing 787 are perceived to achieve fuel consumption reductions in the area of 20% per passenger kilometre in comparison to equally sized Airbus A330 and Boeing 767

types.[15] With airframe weight reductions due to the use of composite materials and engines that provide higher by-pass ratios (and therefore a higher degree of efficiency) it seems to be easier to reduce fuel consumption in the long-range segment than with short-haul aircraft. Aircraft manufacturers so far have claimed, that investments into new models are only beneficial if certain efficiency steps, which are in the area of 15-20% compared to predecessor models can be accomplished.[16] This could be a reason, why neither Airbus nor Boeing has yet come up with definite plans for an A320/737 replacement type.[17]

When taking a look at the projected service entries of new aircraft models, it becomes apparent, that these dates are set earlier than the ACARE goals, which should be achieved in 2020. For instance, the A350XWB is planned to be introduced in 2011, achieving presumably a 20% efficiency increase over the A330, which was designed in the 1990s. Considering the long product life cycle of 20-30 years, it can be expected that the ACARE goal of a 40-45% reduction in specific fuel consumption from airframe and engine technology will practically not be achieved until a successor for the A350XWB enters into service presumably between 2030 and 2040. The same could be true for very large twin aisle jets, as an A380 successor is not reasonably entering service before 2030. Also for the narrow-body replacement for the A320, which is scheduled to enter service some time between 2017 and 2020,[18] it seems at present not very likely that with technologies currently under development (carbon fibre structures and geared turbofan engines) the objective of a 40-45% reduction in specific fuel consumption can be achieved by improvements of aircraft technology alone.[19] Although some of the objectives might be achievable, such as a 20%-reduction in engine fuel consumption by applying the open rotor/prop-fan concept, this would result in a trade-off concerning noise and a potential miss of the respective noise-reduction target laid out by ACARE.[20]

However, another conclusion that can be drawn is that the aircraft currently under development like the A350XWB, the 747-8 and 787 as well as the A380, which already entered into service in 2008 will be the dominating aircraft types in the long-haul air transport market for at least until the year 2040. This is rather advantageous for a forecasting exercise like the one conducted in this paper, as the technological uncertainties concerning these types are relatively small.

2.3 Biofuels

Another technology-related aspect of reducing CO_2 emissions, which has gained more attention in recent months due to the price increases of fossil fuels, is the substitution of petroleum-based kerosene with biofuels. While fossil fuels are limited in supply, fuels generated from renewable sources are theoretically sustainable and have a reduction potential in life-cycle CO_2-emissions of up to 90% compared to fossil fuels.[21] However, a set of problems in different areas has yet to be overcome. First of all, the availability of biomass-to-liquid-fuels (BtL-fuels) produced from conventionally grown crops like corn or wheat is also limited by the size of available fertile land. Aviation in total consumed in the year 2005 about 229 million tonnes of jet fuel[22], which would require an agricultural area

about twice the size of Germany, if this amount was to be replaced entirely by BtL-fuels.[23] Already today at a much smaller scale, conventional ways of creating biofuels are ethically questionable, as either crops that could otherwise be used to nourish humans are directly converted into fuel or fertile grounds are used to grow energy plants instead of crops for the production of food. A long-term solution could be so-called 2nd or 3rd generation biofuels. These fuels are generated from sources not competing with food production like wood or algae. Besides the mentioned economic and ethical challenges also potential technical obstacles have to be overcome, e.g. it was found out that biofuels differ in lubrication and corrosion characteristics from petroleum-based fuels.[24] However, experiments conducted with a blend of BtL fuel and petroleum-based fuel for use with commercial aircraft, have shown adequate characteristics.[25] The major challenge is now to develop large scale production facilities in order to achieve availability of the quantities needed at competitive prices compared to petroleum-based fuel.

2.4 Aircraft Operational Efficiency

A further element of increased environmental performance is the operational efficiency of aircraft, a parameter that can be influenced mainly by airlines. Although there is no unambiguous definition of operational efficiency[26], for the purpose of this paper operational efficiency encompasses all circumstances associated with the fuel consumption of an aircraft that lie mainly in the sphere of influence of its operator, i.e. usually the airline.

However, the potential for efficiency increases in this area seem to be limited in future. Airlines already use many operational procedures and elements that save fuel, for instance by minimising reserve fuel carried onboard, reducing the weight of catering items and aircraft interiors as well as operational procedures like derated thrust takeoffs. Some additional reduction potential may be achieved in the area of ground operations, e.g. by substituting APU use by ground power or minimising fuel consumption during taxi operations by the use of tractors.

Yet another major contributing factor, aircraft seat load factors offer only limited scope for improvements. Low cost carriers are already flying at load factors between 80% and 90% and also for network carriers it can be observed in recent years, that load factors have increased considerably. EUROCONTROL (2007) states that "(…) load factors have reached historic highs (close to 80%) and cannot grow indefinitely. A continued decoupling of passenger numbers and CO_2 emissions would require more fuel efficient aircraft." Therefore, aircraft operational efficiency increases seem to be limited and are not considered for quantification of future emissions.

2.5 Air Traffic Management

According to EUROCONTROL, the influence of air traffic management on aviation's global emissions amounts to 7-11% equalling some 16 million tonnes

of CO_2 annually.[27] It is perceived, that in EUROCONTROL airspace 2.3 million tonnes of CO_2 could be saved cumulatively between 2007 and 2010, if EUROCONTROL's performance targets of increased flight efficiency can be met.[28]

Moreover, the projects of the Single European Sky and FAA's NextGen should contribute in the medium term to more direct routings and optimised vertical allocation of traffic, resulting in significant efficiency gains. However, the USA and Europe only account for a fraction of the global airspace. Equally, if not more important are also optimised flight corridors for intercontinental routes, for instance between Europe and South Africa or Europe and the Far East. Concerning the former, ICAO developed two new more direct routes between Western Europe and South Africa, which over time savings of about 30 minutes per flight.[29] Considering that a Boeing 747-400, a typical aircraft used on routes between Europe and South Africa, uses about 10t of fuel per flight hour, the CO_2 emissions reduction potential in this area seems to be substantial.

Considering the points mentioned, air traffic management improvements can significantly influence the environmental efficiency of air transport, but it also has to be mentioned that once vertical and horizontal inefficiencies are overcome, no further potential for the reduction of emissions in this regard exists. Therefore, the maximum efficiency gain of 7-11% is smaller than the reduction potential that can be achieved from airframe and engine technology.

2.6 Economic Instruments

Intensively discussed by aviation stakeholders is the introduction of an emission trading scheme (ETS) for aviation. The plans to introduce such a scheme are highly advanced in the European Union. At the time of writing, it seems highly likely, that all aircraft departing and arriving in the European Union will be included in such a scheme from 2012 onwards. The most important advantage of such a scheme from the environmental perspective compared to a fuel tax is the attainment of an emissions target, as in an ETS, the overall amount of emissions is capped. In other words, with the introduction of an ETS, emissions from aviation can immediately be capped or reduced to a predefined level. Any CO_2 emissions from aviation exceeding the cap can then be offset by buying allowances from other industries. Compared to this, with the introduction of a tax, the development of total emissions is dependent on the reaction of demand as a result of price increases following from the tax being shifted onto passengers and freight forwarders by the airlines.

For the further analysis in this paper, emissions trading is not considered. On the one hand, it is currently not realistic that an ETS will be introduced on a global scale. On the other hand, it will not be considered here as the focus of this paper is the evaluation of the emissions reduction potential in the air transport industry itself. Previous studies have shown, that an open ETS where allowances can be bought from other industries creates only very limited incentives to reduce emissions in the aviation sector itself, due to comparatively high abatement costs.

CE Delft concluded in a study that only between 1% and 3.6% of aviation's emissions would be reduced in the sector itself.[30] From the micro-economic perspective, the integration of air transport into an open emissions trading scheme, as envisaged by the European Commission, the European Parliament and the Member States, has a very similar impact like a moderate fuel price increase. For instance, if an emissions allowance would cost 25 € per ton of CO_2, the value of allowances needed per ton of fuel would equal 79 €. Given a price level of about 500 € per ton of fuel in August 2008, this would have the same consequences as a 15.8% increase in fuel prices or an increase of between 4.7% and 7.9% of total operating costs. However, as at least in the beginning of the EU-ETS a major share of allowances will be allocated for free, the costs for airlines will practically increase by a much smaller percentage. Moreover, in the EU-ETS, aviation has only a very small share of the total emissions cap, therefore it is not expected that the demand from aviation will influence allowance prices significantly.

3. METHODOLOGY AND ASSUMPTIONS

3.1 General considerations concerning the applied methodology

The methodology applied to quantify the future CO_2 emissions of air transport will be explained in this chapter. The modelling technique applied is non-responsive, i.e. air transport demand and supply is exogenous and is not influenced by different technological developments. To determine the development of passenger demand, in a first instance the forecasts of Boeing and Airbus have been reviewed. As it is the aim to quantify emissions up to the year 2050 and the market forecasts of the manufacturers have only a limited time horizon looking about 20 years into the future, additionally the scenario study CONSAVE 2050 has been used. In CONSAVE 2050, a set of scenarios was developed and quantified with the Dutch modelling system AERO-MS up to the year 2050.

3.2 Current fleet composition and fuel consumption

As starting point for the analysis of future emissions reduction potentials in air transport, an estimation of the current CO_2 emissions and fuel consumption has been conducted for the base year 2006.

For the estimation of fuel consumption, the block hour statistics of the ASCEND Online Fleets database has been used. The estimation of the fuel consumption per block hour of each aircraft is based on EUROCONTROL's Base of Aircraft Data (BADA). BADA provides technical aircraft characteristics for a total of 295 types and variants of commonly used aircraft, where performance data for 91 aircraft are directly available and another 204 are represented by equivalent types.[31]

Table 1 shows the fuel consumption for a major part of global air transport. Taking into account that military aircraft, the freighter fleet, regional jets,

turboprops and eastern built jets are excluded, the fuel consumption of the fleet under consideration accounts for about 70% of the total jet fuel consumed.

The highest fuel consumption by a single aircraft family is 22 million tons by the Airbus A318/319/320/321. By the end of 2006, 2911 aircraft of these types were in service. The A320-family is closely followed by the Boeing 747-400. The 457 aircraft active in passenger service consumed about 21 million tons of fuel in 2006. Overall, the fuel consumption split between narrowbody and widebody aircraft is estimated at 48 to 52%.

Table 1: Fuel Consumption of the world's passenger jet fleet with more than 90 seats (2006)

Aircraft Type	Passenger Aircraft in Service	Total number of block hours (in '000)	Avg. Annual Block Hours per aircraft	Avg. Fuel Consumption per Block Hour (in kg)	Fuel Consumption (in '000 t)
Airbus A300/310	347	801	2309	4865	3898
Airbus A318/319/320/321	2911	8241	2831	2709	22,324
Airbus A330	444	1710	3851	5355	9156
Airbus A340	336	1470	4376	6541	9619
Boeing 717	155	419	2704	2165	907
Boeing 727	107	38	352	4340	163
Boeing 737-200	385	616	1601	2546	1570
Boeing 737-300/-400/-500	1843	4707	2554	2647	12,459
Boeing 737NG	2019	6303	3122	2505	15,789
Boeing 747-100/-200	47	103	2191	10400	1071
Boeing 747-300	60	159	2654	11219	1787
Boeing 747-400	457	2114	4625	9887	20,898
Boeing 757	890	2719	3055	3743	10,177
Boeing 767	796	2805	3524	5076	14,240
Boeing 777	601	2357	3921	6670	15,718
McDonnell-Douglas MD-11	45	154	3415	8062	1239
McDonnell-Douglas MD-80	935	2349	2513	3016	7084
McDonnell-Douglas MD-90	110	242	2201	3016	730
Douglas DC-9	197	441	2238	2746	1211
Douglas DC-10	17	56	3300	6552	368
Regional Jets (>90 seats)	215	347	1614	988	343
Total Fleet	12,917	38,152	2954	4101	150,751

Source: Own production.

3.3 Estimation of the Future Fleet Composition and Emissions

The starting point for the estimation of the future fleet composition and its emissions are medium and long-term air transport forecasts. For the timeframe 2006-2025, the Airbus Global Market Forecast was chosen which contains a forecast of 4.8% average annual growth for worldwide passenger traffic in the timeframe 2006-2025.[32] As it is the aim of the paper to forecast emissions up to the year 2050 and the detailed Airbus forecast ends in 2025, the CONSAVE

scenario-based forecasts were used for the estimations between 2026 and 2050. An overall growth rate which lies in between the two CONSAVE scenarios “Unlimited Skies” and “Regulatory Push and Pull” was assumed. This results in growth rates of shortly below 3% p.a. for the years 2026-2050. The assumption concerning decreasing growth rates of passenger demand seems plausible, as it is perceived that effects of market saturation will become noticeable in the more distant future.

For the estimation of the future size of the world fleet, the following estimation technique has been applied: Each aircraft in service has a limited annual utilisation, which is determined by the airline’s business model, maintenance requirements etc. The past annual utilisation, measured in block hours can be obtained for a major part of the world’s fleet by ASCEND’s Online Fleets database.[33] This database also contains detailed information on each aircraft’s seating configuration. From the Official Airline Guide, it can be estimated which distance is covered per block hour. For narrow-body jets, which are predominantly used on short- and medium-haul flights, the distance flown per block hour is about 450 kilometres, for wide-body jets mainly used on long-haul flights it is between 720 and 750 kilometres. Finally, load factor data is required to estimate the annual transport performance that can be accomplished by each aircraft. Based on a compilation of data of major airlines, the passenger load factor for narrowbody jets was assumed with 70% and for widebody jets with 80%.

Therefore, the world fleet’s annual transport performance measured in Revenue Passenger Kilometres (RPK) can be estimated with the following equation:

(5) $$Annual\ Transport\ Performance\,(in\ RPK) = \sum_{i=1}^{n} U_i \times S_i \times LF_i \times SC_i$$

Where:

U_i = Annual utilisation of aircraft *i* in block hours
S_i = Speed of aircraft *i* in km per (block-)hour (measured by OAG data as Distance divided by scheduled flight time)
LF_i = Load Factor of aircraft *i* (measured by ICAO data)
SC_i = Seat Capacity of aircraft *i*

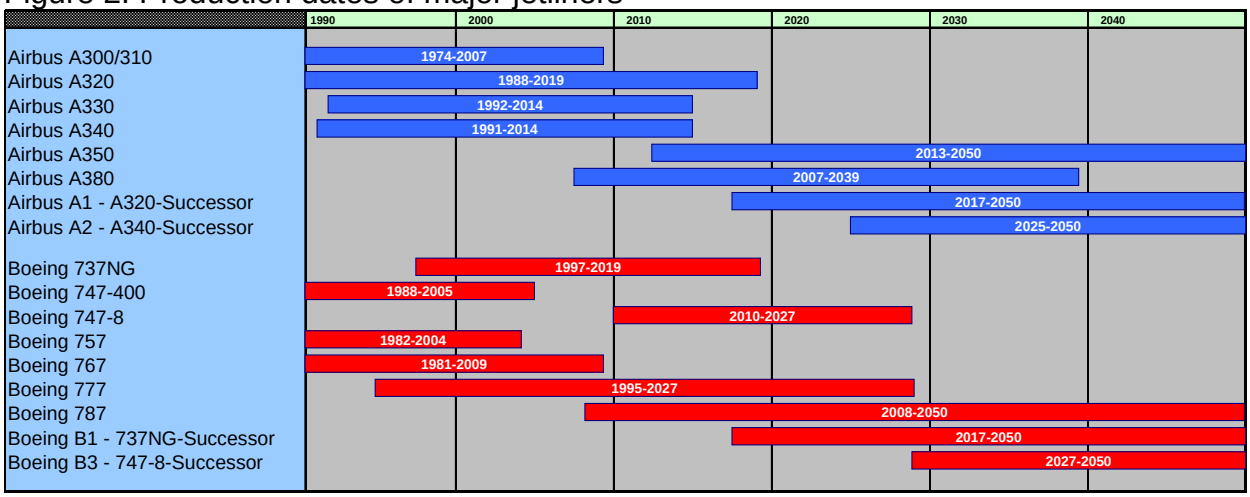
As the Airbus Global Market Forecast 2006 contains detailed information on the size of the world fleet in 2025, the applied technique could be verified and has shown a very good fit with a slight underestimation of about 2.2%. By applying the same RPK growth rate as Airbus, the forecasted fleet for the year 2025 contains 26,725 aircraft, in comparison to Airbus’ 27,307.[34]

An important set of assumptions concerns the life-span of aircraft (25 years for narrowbody aircraft and 30 years for widebody aircraft, retired aircraft are replaced by equally sized successor types) and the entry into service-dates of new types, which are shown in figure 2. These assumptions to a large degree

determine the qualitative composition of the world's fleet, the penetration rate of new types and ultimately the specific and absolute fuel consumption of air transport.

Figure 2 shows the assumptions concerning production dates of current and new aircraft. Concerning the service-life of aircraft it was assumed that widebody aircraft will be used for 30 years and narrowbody aircraft for 25 years.

Figure 2: Production dates of major jetliners



Source: Own production.

Concerning the fuel efficiency of new aircraft types, it was assumed that both the A350 and 787 consume 20% less fuel per block hour than the A330 and 767. For the A320 and 737 successors, a reduction of 15% compared to the A320 and 737NG was assumed. Finally, the A340 successor and the 747-8 successor are assumed to consume 25% less fuel per block hour compared to the A340 and the 747-400. This however, is considerably less than the ACARE objective of a 40-45%-reduction of new types entering service after 2020. Nevertheless, taking into account the gradual improvements in aircraft technology, it seems to be prudent to use in this regard rather conservative assumptions. If required, the presented model allows analysing also the impact of break-through technology revolutions, which could achieve more radical specific fuel consumption reduction potentials (e.g. flying wing aircraft).

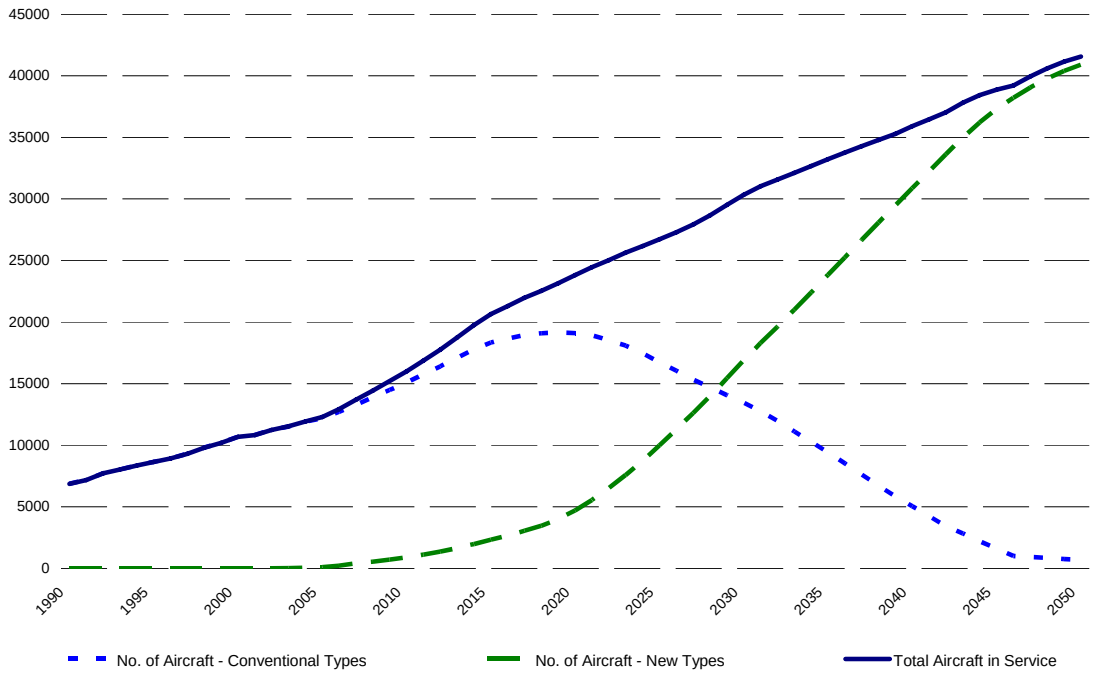
The impacts of these assumptions for the total fleet are shown in Figure 3. The group of "conventional types" includes all aircraft types, which were in service by 2006. The group "new types" consists of the new regional jets with more than 90 seats (Embraer 190/195, Bombardier CRJ900 and CRJ1000, Mitsubishi RJ, Suchoi SuperJet, China's Flying Phoenix and Bombardier's CSeries), Airbus A350XWB, A380 and the A320 and A340 successor types, as well as Boeing 747-8, 787 and the successor types of both the 737NG and 747-8.

It can be seen that in 2019 the current types reach their peak, just short of 20,000 aircraft. After this point, current types will no longer be in production and the retirement cycle will continuously decrease the number of aircraft in service to a residuum of 665 aircraft in 2050. At the same time, the number of new type

aircraft will increase up to more than 40,000. Nevertheless, it will take until the year 2029 that the majority of the fleet will be comprised of the “new types” of aircraft. This is a very good indicator for the general observation that individual aircraft have a long service life and also shows the rather long time span between the introduction of a new technology and the wide diffusion of this technology in the actual fleet.

From these numbers another interesting observation for the aircraft industry can be made: To keep up with the demand for new aircraft generated by both market growth and the retirement of older aircraft, more than 1,150 narrowbody aircraft with more than 100 seats will need to be produced annually in the third and fourth decade of the 21st century. This is almost twice the number of aircraft produced currently.

Figure 3: World Passenger Jet Fleet (>90 seats) Development 2000-2050



Source: Own production.

Beyond the aircraft technology-related assumptions, the development of air traffic control is taken into account. It is assumed, that between 2012 and 2025 an annual improvement of 0.8% in ATM efficiency can be reached. This results in a total efficiency gain of about 10%, which lies at the upper bound of EUROCONTROL’s estimation of ATM impact on air transport CO_2 emissions.

Further it was assumed that the blending of 2nd/3rd generation biofuels will linearly increase between 2010 and 2050 to a total of 25% of the fuel needed in aviation. This assumption meets the expectations of the International Energy Agency, which expects a quota of biofuels of up to 25% of total energy consumption in the transport sector.[35] While biofuels are produced from biomass, which removes CO_2 from the atmosphere as it grows, it has to be stressed that these fuels are

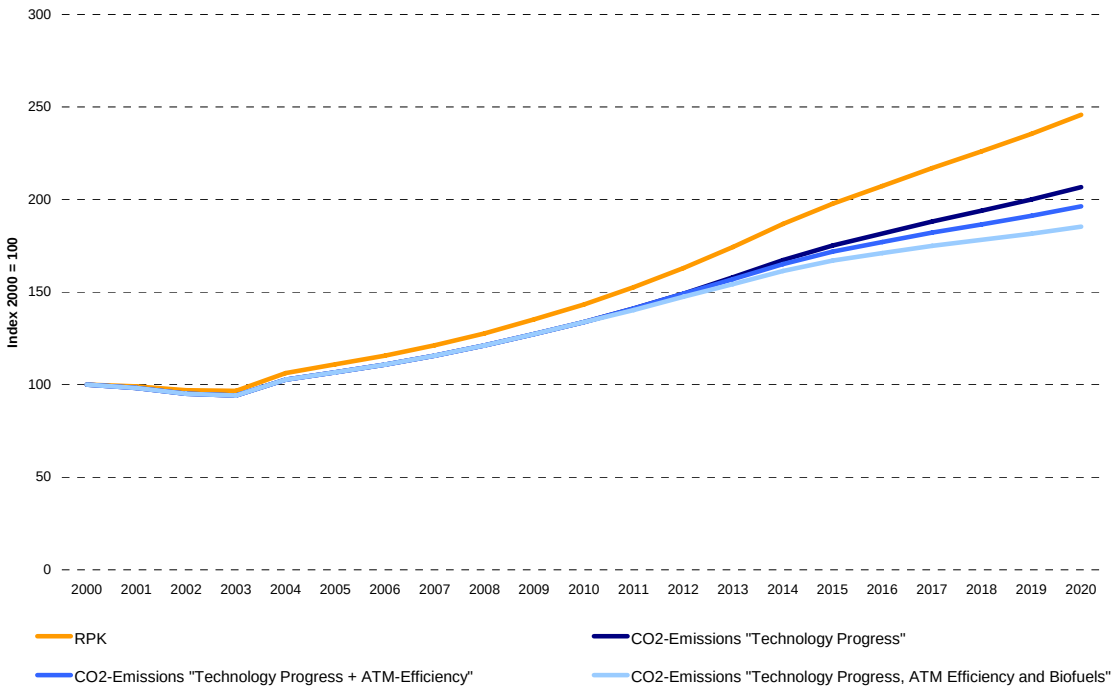
not fully carbon neutral when taking a product life-cycle perspective, as the production and distribution is associated with the use of fossil fuels. It is perceived that 1st generation biofuels reduce the life-cycle CO_2 emissions by about 50% compared to fossil fuel, while the potential for emissions reductions of 2nd/3rd generation BtL-fuels is estimated in the literature in the area of 80-95%.[36] For the calculations in this paper an emissions factor of 0.315kg CO_2 per kg of biofuel is assumed, which is one tenth of the emissions factor for petroleum based jet fuel.

4. RESULTS AND INTERPRETATION

Figures 4 and 5 show a graphical representation of the modelling results. The contributions of the different elements of the air transport system are shown separately.

The graph “Technology Progress” represents the emissions development, when aircraft as described in the preceding chapter will be introduced, while the rest of the air transport system remains unchanged. The graph “Technology Progress & ATM Efficiency” represents the emissions that can be estimated when in addition to new aircraft technology also the ATM efficiency as stated in the preceding chapter will be improved. Finally, the graph “Technology Progress, ATM Efficiency & Biofuels” shows the emissions development, when all three elements (aircraft technology, ATM efficiency and fuel substitution) are taken into account.

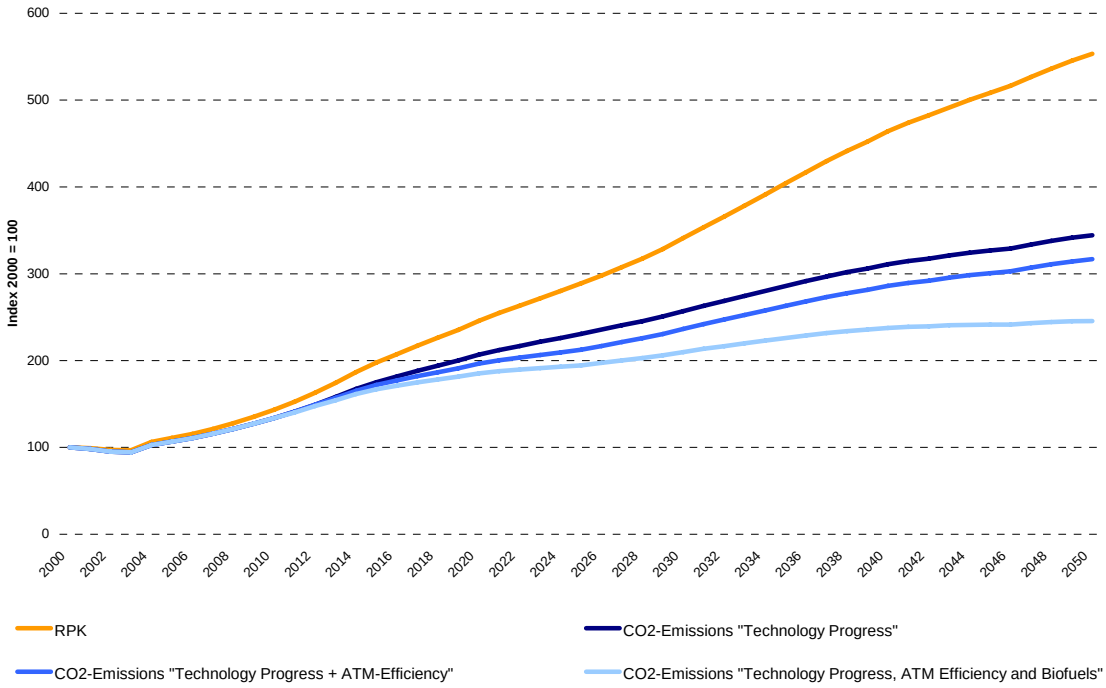
Figure 4: CO_2-Emissions forecast 2020



Source: Own production.

Figure 4 shows the slight dip in world passenger demand and fuel consumption following 2001. A slight decoupling can be noticed in the timeframe between 2003 and 2015, which can be attributed to the fact that older, less fuel efficient aircraft are continuously retired from service and replaced by best available technology. The decoupling of passenger demand and CO_2 emissions accelerates after 2015, as by this time the fleet built-up of A350XWB, A350, 787 and 747-8 has progressed and a substantial number of these aircraft will be in service.

Figure 5: CO_2-Emissions forecast 2050



Source: Own production.

The decoupling of transport demand and CO_2 emissions becomes more obvious in figure 5, which shows the long-term developments up to the year 2050. While the transport demand is forecasted to increase more than five-fold between 2000 and 2050, the CO_2 emissions will increase slightly more than threefold, when considering aircraft technology improvements only. Interestingly, CO_2 emissions almost stabilise after 2030, when aircraft technology, ATM efficiency and biofuels are taken into account. The graph explicitly shows the potentials of biofuels, which can have a significant contribution towards a more sustainable air transport system.

In table 2, the decoupling is furthermore shown by the main numerical results of the modelling approach. While passenger demand will grow by a factor of 2.46 between the years 2000 and 2020, fuel consumption will increase by a factor of 1.85 to 2.07. Transformed into compounded annual growth rates, traffic is estimated to grow by 4.6% annually, while emissions are estimated to grow by between 3.1% and 3.7%. In the long run up to the year 2050, the CAGR for traffic is about 3.5%, with emissions growth between 1.8% and 2.5% annually.

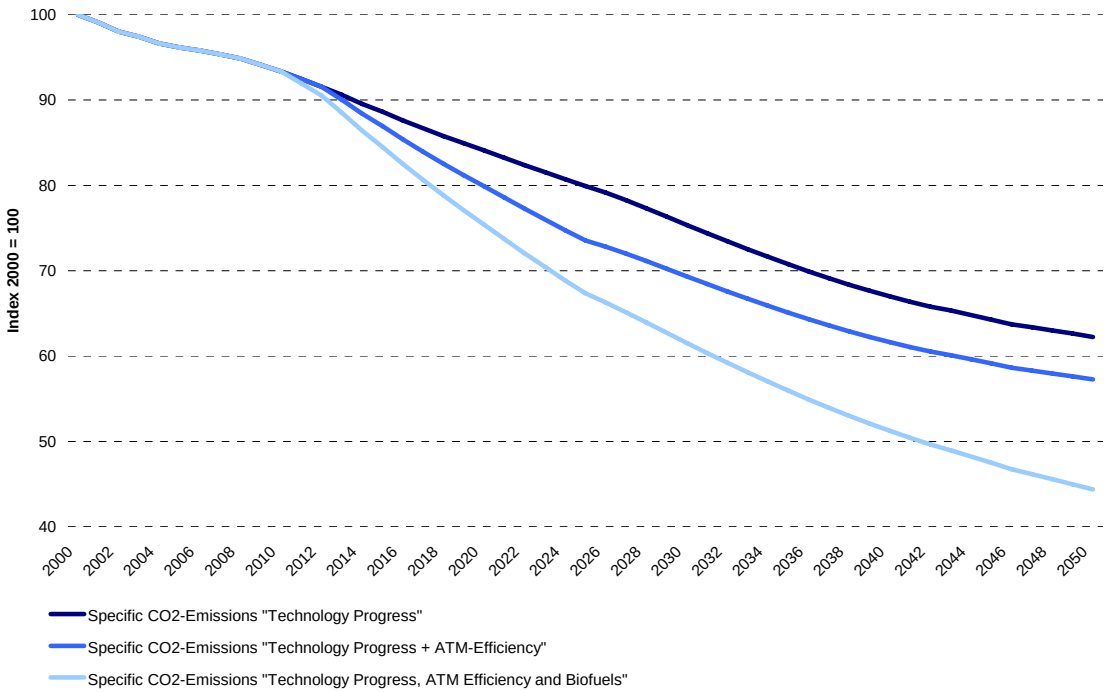
Table 2: Growth Factors of Passenger Demand and Emissions 2000-2020/2050

Growth Factors	2000-2020	2000-2050
Passenger Demand (RPK)	2.46	5.53
CO_2-Emissions, aircraft technology	2.07	3.44
CO_2-Emissions, aircraft technology and air traffic management improvements	1.96	3.17
CO_2-Emissions, aircraft technology, air traffic management improvements and fuel substitution	1.85	2.46

Source: Own production.

Finally, figure 6 shows the development of specific emissions for passenger transport until 2050 with the year 2000 indexed at 100. With the improvement of aircraft technology with the assumed characteristics, a reduction in specific fuel consumption by about 38% compared to the level of 2000 can be achieved. With the addition of ATM efficiency gains, this can be improved to a reduction of about 43%. Finally, after the addition of biofuels, the specific fuel consumption could be reduced to a level of 44% of the initial value of the year 2000, corresponding with a 56%-reduction in specific CO_2 emissions.

Figure 6: Specific emissions (CO_2 per RPK) in passenger air transport



Source: Own production.

From aircraft technology alone, slightly less than 1% compounded annual efficiency gain can be achieved in the total fleet. If considering also ATM efficiency gains and the use of biofuels, the compounded annual efficiency increase is slightly higher than 1.6%. The model results concerning the specific CO_2 emission reduction is in line with expectations that can be found in the literature.[37]

5. CONCLUSIONS

The conclusions that can be drawn from the presented results are manifold. First, it becomes indeed obvious when considering the long product life-cycles and the long service life of aircraft that efficiencies achieved by new aircraft only slowly diffuse in the overall fleet at the rate these aircraft enter into service and replace older types. Therefore, even with the availability of environmentally efficient technology, it takes a considerable timeframe until a number of aircraft are in service to influence overall emissions effectively.

Second, the optimisation of air traffic management is on the one hand an important element for improving the environmental efficiency of air transport. This does not only concern the introduction of the Single European Sky or FAA's NextGen, but also on intercontinental routes, like those over Siberia, China or Africa. But, on the other hand, the efficiency potentials are also limited in the sense that once aircraft are flying on the most efficient route in the optimal altitude, no further efficiencies can be gained from this element. Even if air traffic management would be optimised in a way that no vertical or horizontal inefficiencies would exist any more, the potential of this element is limited to an emissions reduction of 7-11%.

Third, biofuels provide an interesting potential for emissions reductions. Given the assumption that no break-through aircraft technology will yield in radical emissions reductions until 2050, blending petroleum-based kerosene with biofuels has the potential to either stabilise or even reduce total CO_2 emissions from air transport, even though transport demand will grow further. Moreover, given the high emissions abatement costs that can be found in the area of aircraft technology, this element has the potential to reduce emissions in the air transport industry very cost efficiently. Additionally, in the light of rising oil prices, airlines may have a monetary incentive to use biofuels, if they can be produced more inexpensively than fuels derived from crude oil. Moreover, the draft directive for the inclusion of aviation into the EU-ETS, adopted by the European Parliament in its second reading on 8th July 2008, explicitly incentives the use of biofuels by applying an emissions factor of zero.[38]

Finally, with the presented modelling results based on assumptions which have been validated by an extensive literature review, it could be shown that the objectives of ACARE, IATA and those laid out jointly by the air transport industry representatives in their declaration are likely not to be achieved fully. ACARE's main objective concerning specific CO_2 emissions is a 40-45% reduction for aircraft entering into service after 2020 compared to the state of technology of the year 2000. Given the efficiency potential of technologies currently under development and the innovation cycle in the aircraft manufacturing industry, combined with the actual and expected entry-into-service-dates of new aircraft (A380 – 2008; A350XWB – 2011; A320 successor type – around 2017) and the long product life-cycles in the aircraft industry needed for the amortisation of development costs, it is very likely that successor types of these aircraft matching ACARE objectives will not enter into service before the decade between 2030 and 2040. However, from this argumentation it should not be concluded that

research and development for new aircraft, engines and components can be delayed or postponed. The modelling results rather show that the quicker the introduction of elements increasing the efficiency of air transport, the better the environmental performance will be.

The model as presented in this paper may not only be used to derive a quantification of the development of future CO_2 emissions based on plausible assumptions as shown here. It may also be used in reverse for the quantification of normative scenarios, i.e. which efficiency gains need to be achieved for the various elements of air transport in order to achieve predefined absolute emissions. These air transport system-centric objectives could be a valuable addition to objectives oriented at individual aircraft.

Concerning absolute emissions, the modelling results show that without radical changes by break-through technologies, it seems plausible that a “carbon-free growth”, as stated in the industry declaration signed at the 2008 Aviation Environmental Summit in Geneva, can be achieved in the long-run, to a large extent resulting from a blending of petroleum-based jet fuel with BtL-based biofuel. If optimistic forecasts about the large-scale availability of $2^{nd}/3^{rd}$ generation biofuels come true, even an almost completely carbon-free air transport system might be achievable. It seems that to a large extent, the achievement of this goal relies on the ingenuity of researchers and engineers, while also an economic assessment must show, whether it is indeed cost-efficient to reduce or even completely eliminate CO_2 emissions in the air transport industry or if it might be more efficient to offset emissions in other areas and with the help of economic instruments like emissions trading. In either way, air transport can contribute to a more sustainable world.

6. COPYRIGHT NOTICE/DISCLAIMER

Aircraft performance data contained herein are based on data drawn from the EUROCONTROL Base of Aircraft Data (BADA). It is to be noted that the aircraft performance models and data contained in BADA have been developed by EUROCONTROL from a set of aircraft operational conditions available to EUROCONTROL. EUROCONTROL has validated BADA aircraft models only for those conditions and can therefore not guarantee the model's accuracy for operating conditions other then the reference conditions.

NOTES

[1] E.g. the sustainability reports of airlines, such as Lufthansa (2008) or SAS Group (2008), airports, such as Fraport (2008) or the masterplan for the development of airport infrastructure by the Initiative for Air Transport in Germany, cf. Initiative Luftverkehr für Deutschland (2006).

[2] Sustainable development, as defined by the World Commission on Environment and Development (WCED 1987) "is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The WCED therefore called for conserving resources, a reduction in per capita energy consumption and encouraged for a shift to non polluting sources and technologies.

[3] Cf. ACARE (2004), p. 56.

[4] Cf. Watson, M./Lambert, C. (2008), p. 4.

[5] Cf. IATA (2007a).

[6] ATAG (2008).

[7] Cf. Wennberg, L. (2007) and Schiphol Group (2007)

[8] Cf. Sausen et al., p. 556.

[9] 1 kg of fuel burned results in 3.156kg of CO_2, cf. Schaefer (2006), p. 2.

[10] Cf. Energy Information Administration (2008).

[11] Cf. McLean, D. (2006), p. 33.

[12] Cf. IATA (2007b).

[13] Short-/Medium-range aircraft with their entry into service: Comet 4 (1959), DC-9 (1965), B737-200 (1967), MD-80 (1980), B737-300 (1984), A320 (1988) B 737NG (1997)

[14] Airbus claims that the A380 consumes “less than three litres per 100 seat kilometres” (Airbus 2008, p. 5), which would translate into about 3.5 litres per 100 passenger kilometres at typical load factors of 85% on many long-haul markets. The Boeing 747-400 consumes slightly less than 4 litres per 100 passenger kilometres (Cf. Lufthansa 2008).

[15] Cf. Boeing (2008).

[16] Cf. Norris, G. (2006).

[17] Cf. Kjelgaard, C. (2006).

[18] Cf. Kingsley-Jones, M. (2008).

[19] Cf. Gmelin, T. C./Hüttig, G./Lehmann, O. (2008), p. 8.

[20] Cf. Gmelin, T. C./Hüttig, G./Lehmann, O. (2008), p. 52.

[21] Cf. VROM (n.d.)

[22] Cf. IEA (2008).

[23] The German Energy Agency dena estimates the yield of the BtL fuel production process at about 4000 litres per hectare (cf. Deutsche Energie Agentur (2006)), which would result in a requirement of 715,000 km^2 to achieve a yield of 286 million litres of fuel currently used for air transport.

[24] Cf. Daggett, D. L. et al. (2008), p. 3.

[25] Cf. Anon. (2008).

[26] Cf. McLean, D. (2006).

[27] Cf. EUROCONTROL (2008), p. 68.

[28] Cf. EUROCONTROL (2008), p. 69.

[29] Cf. Anon. (2007), p. 18.

[30] Cf. Wit, R. et al. (2005), p. 13.

[31] Cf. EUROCONTROL (2004), p. C-5.

[32] Cf. Airbus (2006), p. 84f.

[33] Not available are utilisation statistics for Soviet/Russian/Ukrainian and Chinese aircraft. Excluded from the modelling approach herein are also all aircraft with less than 100 seats.

[34] Cf. Airbus (2006), p.98.

[35] Cf. Dixon (2007), p. 7.

[36] Cf. Daimler (2007), p. 14 and Brauer, S. et al. (2007), p. 4. The Dutch ministry of Housing, Spatial Planning and the Environment states that:” Further development of biofuels could lead to biofuels that reduce CO_2 by about 90%” (VROM, n.d.)

[37] E.g. IATA expects an increase in fuel efficiency by 1.3% per year; cf. IATA (2004), p. 27.

[38] Cf. European Parliament (2008).

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