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CO_2 HEDGING FOR AIRLINES

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Essays on methods to reduce the risk exposure
of the emission trading for aviation

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For once you have tasted flight
you will walk the earth with your eyes turned skywards,
for there you have been and there you will long to return.

— Leonardo da Vinci

Es gibt alte Piloten und es gibt kühne Piloten,
aber es gibt keine alten, kühnen Piloten.

— André Kostolany

Für wen, wenn nicht für Dich?

ABSTRACT

The inclusion of aviation into the Emission Trading Scheme (ETS) of the European Union (EU) poses new risks for the airline industry. Three different ways to mitigate the risk exposure of the ETS are examined.

First, a combined kerosene and Carbon Dioxide (CO_2) surcharge that allows airlines to optimally calculate surcharge levels depending on the price elasticities of travellers is analyzed. The proposed solution performs about five percent better than the current industry practice. Furthermore, the proposed policy outperforms the base policy even more in more adverse environment such as one where kerosene prices increase steeper.

Second, the question is answered whether biofuels, that are credited with zero emissions in the ETS, can be used to overcome the costs of CO_2. Biofuels are more expensive than kerosene. By giving a price to the CO_2 emissions of kerosene, the ETS can reduce this price differential and help to promote the adoption of biofuels. Different scenarios for the pricing of CO_2 and also the benefits of a state support are analyzed. The ETS brings forward the point of price parity for biofuels by about three years and the cummulative biofuel volumes are about 30 percent higher with the implemented ETS. A limited state support scenario can advance cost parity by another two years.

Third, the impact of CO_2 costs when evaluating new and more kerosene efficient airplanes is analyzed in two scenarios: First, a deterministic (no uncertainty about kerosene and CO_2 costs) present value scenario for a short- and long-haul airplane. Second, the impact on purchase option valuation for short and long-haul planes under uncertainty for kerosene and CO_2. The value of CO_2 costs is about 4 million Euro over the lifetime of long-haul plane and about 1 million for a short-haul plane. For the option pricing, the value of CO_2 is only about 0.4 million Euro for the long-haul plane and only a modest value for the short-haul plane.

ZUSAMMENFASSUNG

Die Einbindung des Luftverkehrs in das Emissionshandelssystem (ETS) der EU stellt neue Risiken für die Luftfahrtindustrie dar. Im folgenden sollen drei verschiedene Wege, mit denen Fluggesellschaften die Auswirkungen dieser Risiken reduzieren können, untersucht werden.

Als erste Methode wird die Möglichkeit eines kombinierten Kerosin- und CO_2-Preiszuschlages untersucht. Mit der vorgeschlagenen Methode können Fluggesellschaften die Höhe von Zuschlägen je nach Preiselastizität der Passagiere optimieren. Die vorgeschlagene Lösung liefert Ergebnisse, die in etwa fünf Prozent besser sind als die gegenwärtig vorherrschende Industriepraxis. Unter schwierigeren Bedingungen, in etwa bei stark steigenden Kerosinpreisen, ist die Überlegenheit der vorgeschlagenen Lösung sogar höher.

Als zweite Methode wird untersucht, ob Biokraftstoffe (biofuels) als Mittel gegen CO_2-Kosten verwendbar sind. Diese werden als emissionsneutral im ETS behandelt, sind aber deutlich teurer als Kerosin. Durch die Bepreisung der CO_2-Emissionen wird der Preisabstand geringer und die Verwendung von Biokraftstoffen sollte ansteigen. Unterschiedliche Szenarien der CO_2-Bepreisung und die Auswirkungen einer Staatssubvention werden untersucht. Die Ergebnisse zeigen, dass das ETS den Punkt der Kostengleichheit zwischen Biokraftstoffen und Kerosin um etwa drei Jahre nach vorne bringen kann und dass kumulative Biokraftstoffvolumen etwa 30 Prozent höher liegt. Eine überschaubare Staatssubvention könnte den Punkt der Kostengleichheit um zwei weitere Jahre vorverlegen.

Die letzte untersuchte Methode ist die Beschaffung von neuen, effizienteren Flugzeugen. Es wird der Einfluss der CO_2-Kosten auf die Bewertung von neuen Flugzeugen untersucht: Zum einen ein deterministisches (keine Unsicherheit über die Entwicklung von Kerosin- und CO_2-Preisen) Barwertmodel für Kurz- und Langstreckenflugzeuge. Zum anderen den Einfluss

der CO_2-Kosten auf die Bewertung von Beschaffungsoptionen unter unsicheren Kerosin- und CO_2-Preisen. In der Barwertbetrachtung wirken sich CO_2-Kosten über die Lebensdauer mit etwa 4 Millionen Euro für das Langstreckenflugzeug und mit etwa 1 Million Euro für das Kurzstreckenflugzeug aus. Für die Optionsbewertung ergibt sich ein Wert des CO_2-Einflusses von etwa 0,4 Millionen Euro für das Langstreckenflugzeug und nur ein sehr geringer Wert für das Kurzstreckenflugzeug.

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My thanks go to my family for their continous love, support and help. And this being a very uncommon statement for our family, I changed it over and over again, but left it here in the end. It is simply true.

The last thanks go to Caro. Even with no gossip inside, I hope this one is for you.

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ACRONYMS

AAU	Assigned Amount Unit
AEA	Association of European Airlines
AG	Aktiengesellschaft
ASTM	American Society for Testing and Materials
ATM	Air Traffic Management
BtL	Biomass-to-Liquid
BWB	Blended Wing Body
CER	Certified Emission Reductions
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
DEHSt	Deutsche Emissionshandelsstelle
ECX	European Carbon Exchange
EEX	European Energy Exchange
EIA	Energy Information Administration
ERU	Emission Reduction Unit
ETS	Emission Trading Scheme
EU	European Union
EUA	EU-Allowance
EU-ETS	European Union Emission Trading Scheme
EUAA	EU-Aviation Allowance
F-T	Fischer-Tropsch

HRJ	Hydrotreated Renewable Jetfuel
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
kg	Kilogramm
LH	long-haul
LCC	Low Cost Carrier
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer
ppm	parts per million
RED	Renewable Energy Directive
RPK	Revenue Passenger Kilometer
RTK	Revenue Tonne Kilometer
SES	Single European Sky
SH	short-haul
UHC	Unburnt Hydro-Carbons
UK	United Kingdom
US	United States
USA	United States of America
USD	United States Dollar
UN	United Nations
WTI	West Texas Intermediate

1 INTRODUCTION

1.1 AVIATION AND THE ENVIRONMENT

Since the rise of aviation as a means of mass transport, the effects of aviation on the environment have become visible to a broad audience. Contrails against the blue sky remind everyone of the immediate impact aviation has on the atmosphere. Locally, other effects such as noise and land usage of airports can contribute to the image of aviation as an environmental hazard. With its global and visible environmental footprint, aviation is therefore at the center of attention of many environmental agencies. This, in turn, has raised the pressure on governments to act on the increasing emissions of airlines.

When talking about the environmental impact of aviation, it is important to understand which type of impact is being addressed. Aviation influences the environment in a number of ways. In addition to the emission of noise, gaseous emissions from the combustion of the traditional aviation fuel kerosene are at the core of aviation's environmental footprint [Upham, 2003]. The combustion of kerosene results in different emissions, and these emissions influence the atmosphere in distinct ways (e.g., climate warming, contrails) [Lee et al., 2010]. One tonne of kerosene typically emits 3.15 tonnes of CO_2, 1.25 tonnes of water, 14 Kilogramm (kg) of Nitrogen Oxides (NOx), and a number of other elements such as Unburnt Hydro-Carbons (UHC). The focus of attention has shifted over time from particulate matter to ozone (a byproduct of NOx and UHC), and from there to today's focal topic, CO_2 emissions [Lee et al., 2009].

The most comprehensive review on the topic of aviation's impact on the environment was done by the Intergovernmental Panel on Climate Change (IPCC) [1999]. It was the first general report to assess the different influences aviation has on the en-

vironment, with a clear focus on CO_2 emissions. Based on the initial IPCC report, a number of authors have updated scenarios [e.g., Sausen et al., 2005, Lohmann and Feichter, 2005]. In its most recent form, the IPCC report [2007b] on climate change again discusses comprehensively aviation's CO_2 emissions.

Aviation contributes to global anthropogenic CO_2 emissions about 3 percent [IPCC, 2007b]. The transport sector in total accounts for about 20 percent of manmade CO_2 emission, about half of the CO_2 emissions generated by sector power generation (see also Figure 1). Within the transport sector, road transport clearly is the main contributor, producing about three-quarters of all transport-related CO_2 emissions. International and domestic aviation accounts for 13 percent of the transport sector. This means CO_2 emissions of about 832,000,000 tonnes per year from aviation, comparable to a medium-sized industrialized country such as the United Kingdom (UK).

To make matters worse, CO_2 emissions from aviation are considered to be more harmful to the atmosphere, as they are emitted at higher altitudes [Sausen et al., 2005]. Excluding the effect of cirrus cloud enhancements, the radiative effects of CO_2 from airplanes is almost twice as great as those of ground-based CO_2 emissions [Lee et al., 2009]. With large uncertainties, a generally accepted estimate for the effect of cirrus cloud formation is about 40 percent of the initial CO_2 emissions [Burkhardt et al., 2010]. As the uncertainties around the various effects are still considerable, in most statistics (and in the ETS discussed in Section 1.2.2), only direct CO_2 emissions (i.e., those without any additional radiative effects) are counted.

What makes aviation a key focus topic of agencies and governments is its rapid growth in recent years [Bows et al., 2009b]. Air traffic (measured in Revenue Passenger Kilometer (RPK)) has been growing at a rate of 4.4 percent in the past decade worldwide [Boeing Commercial Airplanes, 2010a]. There are two main contributing factors for this growth: first, the rise of airlines operating under a Low Cost Carrier (LCC) model in all parts of the world, and second, a strong growth in traffic demand in developing countries [Airbus S.A.S., 2009]. Efficiency improvements, measured in the reduction of kerosene

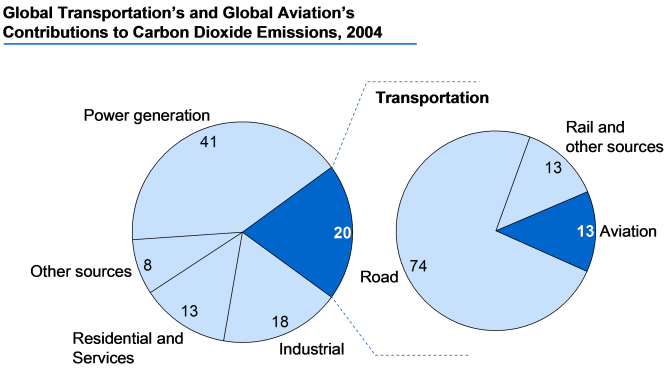

Figure 1: Global CO_2 emissions by sector [IPCC, 2007b]

consumption per RPK, have not sufficed to counter the growth in traffic [Lee, 2009]. Annual efficiency improvements are assumed to be around 1 percent per year [Lee et al., 2001]. This means that, after efficiency improvements, aviation's CO_2 emissions have grown at an annual growth rate of about 3 percent per year.

There are a number of forecasts, and the report by IPCC [2007b] summarizes most of them. The estimates of increases over the year 2010 until the year 2050 range between a moderate 50 percent and a 5-fold increase. The most likely scenario expects that emissions will triple by the year 2050. Even on shorter time horizons, Macintosh and Wallace [2009] expect an increase between 60 and 100 percent in 2025 over that of 2010.

Looking into the future, aviation faces a serious problem: Other sectors are forecast to become less CO_2 intensive, while aviation traffic overall will continue to grow faster than the development of efficiency improvements [Bows et al., 2009a]. Making aviation less CO_2 intensive is as difficult a task as, for example, substituting electricity generated from coal with wind energy. There are only a few fuels with a high-energy intensity per kg, a key requirement for the propulsion of planes, and almost all of them are from fossil fuels. This means that

the share of emissions from aviation will likely increase in the next decades. Bows and Anderson [2007] expect the share under a business-as-usual scenario to account for almost all of the UK's emission, with a 450 parts per million (ppm) target[1]. The authors claim that their results are transferable from the UK to the rest of the EU.

Business-as-usual means that no additional mitigation options are pursued. The International Energy Agency (IEA) has developed a reference scenario in which all likely available technological mitigation options are used. Including these mitigation options for aviation (such as a certain share of biofuels and new engine technologies), aviation will account for almost 11 percent of global CO_2 emissions in 2050, almost a fourfold increase over the current share [IEA, 2009].

1.2 EMISSION TRADING FOR AIRLINES

One of the measures taken to reduce the emission growth of airlines is emission trading, which assigns emission rights a cost by limiting the total volume of emission rights. The added costs of emission rights, in turn, should lower demand for air travel and thus limit the future emission growth. The International Air Transport Association (IATA) endorses emission trading as one possible mitigation strategy in its four-pillar strategy for CO_2-neutral growth under the terms of a "market-based approach" [IATA, 2009].

First, a general introduction and literature overview for emission trading is given in section 1.2.1, and section 1.2.2 highlights the special case of the inclusion of aviation into the European Union Emission Trading Scheme (EU-ETS).

1 450 ppm means 450 parts CO_2 per million parts of atmospheric volume. This is generally considered a scenario in which catastrophic effects of climate change could be contained [Jones et al., 2010]. Currently, this value stands at about 400 ppm in 2050.

1.2.1 *The principle of emission trading*

The basic idea of emission trading goes back to a concept developed by Dales [1968]. He proposed that the best policy implementation would be to establish a market for policy implementation. Dales built his work on the foundations of economic efficiency from the allocation under externalities defined earlier by Coase [1960].

The problem of climate change is the failure of the market to recognize the atmosphere as a sink for anthropogenic greenhouse gases (most importantly, CO_2) [Ellerman et al., 2010]. The scarcity of the atmosphere's CO_2 absorption abilities is not reflected in a market price, and therefore there is no incentive to reduce greenhouse gas emissions. There are two ways to establish such a price: first, by introducing an emission tax per emission unit and, second, by establishing a market for emission allowances.

In an emission market, an overall cap of emissions per period of time is set. Adherence to the cap, of course, is monitored by the authorities. Initially, the cap is broken down to individual polluters (CO_2 emitters), and these polluters are assigned emission allowances. By doing so, emission allowances are assigned property rights. As long as polluters can cover their emissions with enough emission allowances, their behavior is completely legal. If they want to emit more than their initial allowance allocation, they are required to buy allowances from emitters who have not exhausted their allocation. These transactions establish a market price for CO_2 emissions [Perman et al., 1999]. This market price is an incentive for emitters to reduce their emissions and sell their surplus emissions on the CO_2-market or emission trading scheme. The combination of capping total emissions and the incentive to trade surplus emissions defined by property rights is the reason why ETSs are often called cap-and-trade systems [Stern, 2007].

In theory, an ETS provides a cost-efficient way of reaching an emission goal [Tietenberg, 2006]. Emission trading provides an incentive for those who can reduce their emission at the least costs to reduce their emissions most. The result

is that the overall burden on the economy of reaching the cap is likely achieved at or close to the minimum cost [Ellerman et al., 2010]. The reduction of greenhouse gases is especially suitable to emission trading, as the danger of local overpollution is not a problem for greenhouse gases.

The main implication of an ETS is that there is not a fixed price for emission rights, as would have been the case with an emission tax. Emission rights are traded based on supply and demand. Thus, they exhibit considerable uncertainty similar to other commodities traded on markets. Supply in an ETS is defined by the cap set by the regulator and is therefore easy to understand. However, as the decision on the actual size of the cap is driven by political decisions, it can affect the market price of emission unexpectedly [Alberola et al., 2008].

Demand, in contrast, is driven by three main factors [Convery and Redmond, 2007]: first, the initial allowance allocation, second, the cost of their CO_2 reduction options, and third, by the development of the CO_2 emission levels during the trading period. The latter two drivers are particularly affected by multiple factors. Emission costs for utilities, for example, vary with the prices of natural gas and coal prices [Benz and Trück, 2009]. Under low gas prices and high emission costs, it is more profitable to operate gas-powered plants and vice verse. The development of the emission levels is driven, among other factors, by economic growth. With lower outputs than expected in the EU, CO_2 prices are currently trading near record lows [Declercq et al., 2011].

The adoption of emission trading has been promoted by the Kyoto protocol, in which most industrialized countries committed to significant emission reduction over the 1990 baseline up to the year 2012 [OECD and IEA, 2001]. The Kyoto protocol allows emission reductions trough three measures: first, Joint Implementation (JI), which are emission reductions within industrialized countries; second, Clean Development Mechanism (CDM), which are emission reductions in developing countries that are credited to an emission reduction target for industrialized countries; and lastly, Assigned Amount Unit (AAU), which is "grandfathered" to nations and is trad-

able among emitters. All of these emission allowances are only tradable between states. These emissions are converted via national registries into tradable emission allowances for local emission trading schemes [Lefevere, 2004].

The largest emission trading scheme is currently the European ETS for stationary emitters [Neuhoff et al., 2006]. In the EU-ETS the EU-wide cap is set to 2.04 billion emission allowance for the sectors covered by the ETS in 2013 and is decreasing by 1.74 percent per year until the year 2020 [European Parliament and Council, 2009b]. The sectors covered in the EU are mainly utilities with large power plants and CO_2-intensive industrial sites such as concrete or steel plants.

Figure 2 shows the relationship between the different emission allowances under the Kyoto protocol and the EU-ETS. AAUs are only tradable among states and are traded for the purpose of the EU-ETS converted into an EU-Allowance (EUA). Emission Reduction Unit (ERU) is an emission allowance coming from a JI in industrialized countries and are therefore backed by AAUs. A Certified Emission Reductions (CER) is the EU-ETS equivalence to emission reductions coming from international CDMs. The usage of CDMs or CERs is limited to a certain share of total emissions for an emitter (currently, around 13 percent for stationary emitters). In the EU, there is an additional allowance type created for the aviation sector, the EU-Aviation Allowance (EUAA). These are emission allowances that can only be used by airlines for emission compliance. The reason for this special allowance type is the incompatibility of international aviation with the Kyoto protocol. More details on this will be given in section 1.2.

All company-level emission units are traded on CO_2 exchanges such as the European Energy Exchange (EEX) or the European Carbon Exchange (ECX). Actual ownership or transfer of ownership is registered with national registries. In Germany, this task is performed by the Deutsche Emissionshandelsstelle (DEHSt).

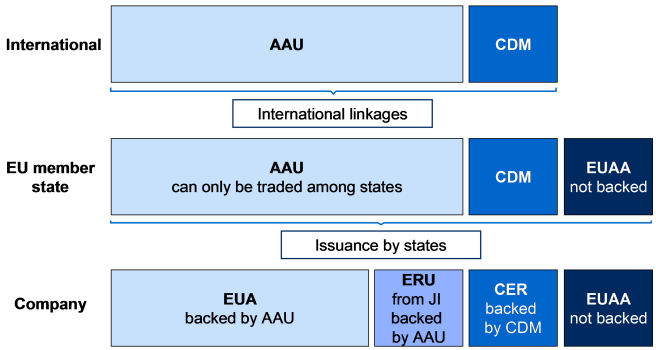

Figure 2: EU-ETS and Kyoto units

1.2.2 *Emission trading for airlines in the EU*

To curb the growing emissions from airlines and internalize the emission costs, the EU has decided to include aviation in the ETS. The European Council and the European Parliament decided upon the implementing directive [European Parliament and Council, 2008] in 2008, which came into effect in 2009. As aviation is not part of the international Kyoto protocol, the EU has created separate emission allowances for the aviation sector, called EUAAs. Only airlines can use these EUAAs for their emission compliance. Thus, the total emission cap defined by the Kyoto protocol for the EU does not increase.

Almost all commercial airlines operating in and out of European airports are affected by the aviation-ETS. There are only limited exemptions granted for very small airlines and non-commercial flights, such as military or rescue flights. Foreign airlines are assigned to an administering country. This country monitors compliance and the reporting process and supervises the benchmarking process for the free allocation.

The inclusion of non-European airlines into the ETS has attracted some controversy. It has been argued that the inclusion conflicts with the Chicago convention in civil aviation, which forbids levying duties on international air travel. Discussions have taken place both at the International Civil Aviation Or-

ganisation (ICAO) and on bilateral levels, culminating in a declaration of the ICAO stating opposition to the ETS [ICAO, 2011c]. This declaration was later enhanced by some member states to suggest retaliatory action, such as revoking landing rights. In a recent attempt, the United States (US) Congress has drafted a bill prohibiting US airlines from participating in the scheme. Other nations such as China and Russia are considering similar moves [Surgenor, 2011]. China has even decided to block an aircraft order worth several billion Euros of Chinese airlines with the European airplane manufacturer Airbus as a protest against the aviation-ETS [Walker, 2012].

The EU Commission believes that the inclusion of all airlines is in accordance with international law and that the inclusion of non-EU carriers demonstrates avoidance of competitive distortions in the international aviation market. This view is supported by legal experts [Petersen, 2008] and was recently confirmed by the European court of justice in 2011 [Court of Justice of the European Union, 2011].

The following paragraphs shortly summarize the main parameters of the benchmarking allocation that influences airlines with respect to the financial impact:

- In the first year, the total quantity of allowances is equivalent to 97% of the historical aviation emissions. Historical aviation emissions are calculated on the basis of the average total emissions reported for the years 2004-2006. This figure has been available to the public since July 20, 2011, and was fixed to an average value of 221,420,279 tonnes per year, which is the cap for the cap-and-trade system [EEA Joint Committee, 2011]

- In 2012, 85% of allowances are allocated at no cost, the remainder being auctioned off. The allocation for aviation is the same for all member countries [Anger and Köhler, 2010]. The EU has learned from overly generous free allocations of member countries from the stationary ETS and unified the free allocation process for aviation. The share of auctioning is likely to increase with future revisions of the directive. The EU plans to auction off most al-

lowances in the ETS for stationary emitters by 2013 (when the next phase of emission trading will start in the EU) and plans to reduce the exemptions granted to energy and competition-intensive industries in the further process. A similar development for the airline industry, at least in future trading periods, therefore seems highly likely.

- Free allocation of EUAAs is based on a benchmark, and the benchmark is calculated as follows. From the historical emissions the sum of the cap reduction, the auctioned share and a special reserve for new and fast-growing airlines is subtracted. The result is then divided by the sum of verified tonne-kilometer data of all participating operators in 2010. The initial free allocation for an individual airline is calculated by multiplying the benchmark with the transport activity of 2010 of the respective airline. The reason behind the benchmark is to incentivize efficient behavior. Efficiency in this context means transporting a fixed mass over a kilometer with the least possible emissions. This benchmarking process favors LCCs and cargo airlines as their airplanes typically see very high load factors. Network carriers, which have low utilized feeder flights and offer premium seats (first and business class), have naturally lower payloads and are therefore penalized by the benchmarking process.

- Airlines can also buy EUA from the market for stationary emitters, which have been part of the ETS since 2005. Abatement costs for airlines are a lot higher than for other sectors [Morris et al., 2009]. The Commission Of The European Communities [2006] has estimated the costs for a closed ETS for aviation (with no possibility to purchase from other sectors) to be between 115 and 325 Euros per tonne in 2020. This would be about eight times higher than in an open scheme. The price for these EUAs is a lot lower, standing currently at about 8 Euros per tonne. Additionally, airlines can buy CER up to 15% of their total allowances. Banking of allowances is allowed

from 2012 to the third trading period of the EU-ETS starting in 2013, so surplus allowances of 2012 can be used up to the year 2020.

Anger and Köhler [2010] give an overview on the state of research on the aviation-ETS. The main research direction so far has been toward the assessment of the financial impact of the ETS and the implications of the ETS on airlines.

A number of papers and reports have tried to assess the financial implications of the ETS. A lot of these reports were created before finalization of the ETS design and therefore focused on the implications of the design parameters [e.g., Wit, 2005, Morrell, 2007, Scheelhaase and Grimme, 2007]. There are two peer-reviewed articles written after the finalization of the scheme: One is by Scheelhaase et al. [2010] , and the authors estimate that, at full cost pass through, price increases in the first years will be in the range of 3 to 13 Euros, depending on the length of the trip. The second study, by Vespermann and Wald [2010], arrives at a similar range of about three to seven Euros per trip. The total cost impact of the ETS, according to these studies, stands at about 3 billion Euros per year during the period of 2012 to 2020. It is likely that airlines will pass some of these costs on to customers. This, in turn, has implications on the demand for air travel. Vespermann and Wald [2010] estimate traffic to be about six percent lower compared with an unrestricted scenario in 2020. Anger [2010] estimates the impact to be above seven percent, with the reduction coming mainly from the supply side.

As has been mentioned, competitive distortion is a major concern for the ETS. Ernst & Young and York Aviation [2008] have assessed various scenarios that could distort competition. However, their findings should be considered with some bias, as the report was requested by the Association of European Airlines (AEA). The main argument for competitive distortions is that airlines are only required to pay for their emissions up to the first stop outside of the EU. Airlines with hubs just outside of the EU would therefore only have to pay for a small portion of the flight if passengers are connecting through the

hub. Albers et al. [2009] have addressed a similar question - whether the ETS will lead to network reconfigurations. Their conclusion is that, at current CO_2 prices the cost impacts are too low to instigate network reconfigurations. As both flights to and from the EU are covered by the ETS, competitive effects are significantly reduced.

If only flights from the EU (and therefore the fuel purchased in the EU) were covered, distortions would likely be bigger. On this topic, Cames [2007] has examined whether it makes sense for airlines to "tanker" fuel just outside of the EU under such a scheme. They conclude that it makes sense, depending on the relation of CO_2 and kerosene costs. If the relation of 2006 is assumed, tankering could be an option on city pairs with an intermediate stop option up to a distance of 4,000km.

Brueckner and Zhang [2010]have studied the effects on airfares, service offerings, and airplane design. Their results show that the inclusion of aviation into the ETS on the one hand raises fares, reduces flight frequency, increases load factors, and raises aircraft fuel efficiency. On the other hand, there is no effect on aircraft size. They conclude that these changes are efficient and bring society closer to a social optimum. Also regarding aircraft size, Morrell [2009a] estimates that the ETS is likely to upgauge aircraft sizes on short-haul routes, with limited impact on long-haul aircraft.

The research on the aviation-ETS so far has mainly focused implications of the inclusion in the ETS on an aggregated or industry-wide level. Managerial implications or actual counter strategies for individual airlines have been addressed only briefly. In the following parts, methods for airlines to actively react to the changes brought along by the ETS will be presented.

1.3 MITIGATION STRATEGIES AGAINST CO2 COSTS

Given the start of the aviation ETS, airlines have three main options to address the problem of fluctuating emission costs: They pass on the costs of CO_2 on to customer, they stabilize the costs of their CO_2 purchases on the market, or they reduce

their kerosene consumption and thus the amount of their CO_2 emissions. As follows, each of the mentioned options will be shortly presented.

Airlines can pass price changes on to passengers or air cargo customers with surcharges. The risk of price increases is that they induce demand reactions. These demand reactions depend on the price elasticity of travellers. Price elasticities vary significantly among the routes (and customers) airlines serve [Brons et al., 2002]. The key for airlines then is to determine the right level of surcharge for each route or even each passenger. Currently, few airlines have announced plans for imposing a separate CO_2 emission surcharge in addition to the widespread practice of implementing a kerosene surcharge. One of the airlines with a separate CO_2 surcharge is Delta Airlines, which levies a surcharge of three dollars one way to destinations affected by the aviation-ETS [Reuters, 2012].

The second option for airlines is to stabilize the purchase cost of CO_2 with financial instruments. The idea of hedging in CO_2 markets has been discussed for the market of stationary emitters [see e.g., Fan et al., 2010, Çetin, 2009, Daskalakis et al., 2009]. Airlines face the question of how much of their emission requirements they will cover with which emission allowances. CERs or JIs are trading at lower prices compared with EUAs, because their exact supply and demand are unknown [Mansanet-Bataller et al., 2011]. In contrast, only demand is uncertain for EUAs. Additionally, emitters are only allowed to use a certain share of CERs, limiting their flexibility. For aviation, this figure is set to 15 percent in 2012. Lastly, airlines receive EUAAs which they can only trade with other airlines. Managing the costs of CO_2 for an airline is therefore a task similar to portfolio management, even before the use of derivatives on the different emission allowances. Due to the only recent start of EUAAs in January 2012, the data basis for such an approach is currently very limited. It will be interesting to see how airlines cope with this complex task in the future.

An important factor in financial hedging is certainty about the amount of emissions for which the airline seeks protec-

tion in the market, the so-called basis risk [Giaccotto et al., 2001]. Quantity uncertainty stems from two sources in the EU-aviation-ETS: the amount of emissions that an airline has produced in a year and the free allocation an airline can expect from the benchmarking. The difference between actual emissions and free allocation yields the net quantity exposure of the airline.

The third and most long-term option for airlines is to reduce their kerosene consumption. This option can be broken down into four main areas: new airplane technologies, alternative fuels, changes in infrastructure, and efficient operations.

- *New airplane technologies:* There are a number of ways new technologies can reduce the kerosene consumption of airplanes. Engine technology is one of these. In the past, engine efficiency has been improved by increasing the bypass ratio (the part of air moved by the fan that does not move through the hot engine core) of gas turbine engines [Lee, 2003]. One possible next step is to introduce geared turbofans, which let the fan and the engine core run at their optimal speeds. The first of these geared turbofans, the Prat & Whitney PurePower, will burn about 15 percent less kerosene than current engines when it enters service around 2015 [Prat & Whitney, 2012]. Another possibility is the open rotor engine, promising fuel burn reductions of more than 20 percent [Sieber, 2009]. The technological readiness of open rotor engines, however, is not expected before the mid-2020s. Next to engine technologies, new materials used for the construction of airplanes are under development. For example, the next generation of long-haul airplanes by Airbus and Boeing will use larger shares of carbon fibre composites than any other previous airplane. A higher share of carbon fibre composites enables airplane constructions to be lighter than planes constructed from aluminium and thus save on weight and kerosene [Soutis, 2005]. Lastly, another area of research involves airplane concepts beyond the current tube-and-wing concept. One

of the options is a so-called Blended Wing Body (BWB), where wings and passenger compartment are merged. This increases aerodynamic efficiency greatly and consequently reduces fuel burned per passenger by as much as 30 percent [Liebeck, 2004]. Given that only the first model-scale test runs for BWBs are conducted, an entry into service before the year 2030 is generally considered unlikely [Bows et al., 2009b].

- *Alternative fuels:* Another possible solution is to replace kerosene with alternative fuels. In the EU-ETS, biofuels are credited as CO_2 neutral for airlines. The biofuels most explored so far are of the drop-in type. This means that they can be used with no changes in the current infrastructure (e.g., aircraft engines and fuelling infrastructure). Second-generation biofuels are derived from feedstock which is not in direct competition with human food crops or grown on areas suitable for human food crops. They have addressed many of the sustainability concerns raised regarding first-generation biofuels (generated from human food crops such as corn). Typical feedstock currently considered are jatropha curcas, camelina sativa, and bio waste [Blakey et al., 2011]. These feedstocks can be converted into kerosene through different refining techniques. The two most commonly used to generate kerosene are a gasification process with a subsequent Fischer-Tropsch (F-T) reaction and the hydrotreatment of oil seeds [SWAFEA, 2011]. Third-generation biofuels, generated from algae feedstock, create a promising path due to the potential for very high oil yields. However, generally no widespread adoption of these fuels is expected before 2030 due to their current prohibitively high cost [Sun et al., 2011]. There are two major drawbacks to aviation biofuels that currently hinder their widespread adoption: first, the technological uncertainty around the prevailing feedstock and refining technology, and second, their high prices compared to kerosene. Again,

the inclusion of aviation into the ETS can give an incentive to promote the adoption of this technology.

- *Changes in infrastructure:* This option is mainly about Air Traffic Management (ATM). IATA [2009] brings forth Single European Sky (SES) as a possible infrastructure measure. Eliminating unnecessary deviations from the ideal route due to national ATM could reduce the emissions for intra-European flights by as much as 5 percent [Peeters et al., 2009]. In the US, a next-generation ATM is expected to reduce emissions by about 12 percent [Dillingham, 2009]. Similarly, advanced ATM such as SES would enable airplanes to perform continuous decent approaches to airports. With continuous decents, the aircraft's engine remains idle from cruise altitude until shortly before touchdown. This, however, requires more advanced ATM procedures. SES and similar measures in other parts of the world are held back by the significant investments required in ATM technology and a slow political process necessary for the European implementation. Eurocontrol, the European organisation for the safety of air navigation, expects a first trial period between 2012 and 2014.

- *Efficient operations:* The report by IPCC [1999] identified inefficiency in airline operations to account for about six percent. Among those options, most of which are already implemented where possible, are single-engine taxiing, regular engine washing, and limited use of the auxiliary power unit (a small engine for electricity in the back of the plane). More difficult to implement are slower cruise speeds [IPCC, 2007b] or electrical powered taxiing [Lee, 2003]. Weight reductions also fall in this category. Airlines have shown some creativity in reducing the weights of planes: Measures range from lowering fuel reserves, reducing the amount of water carried for toilettes, replacing in-flight shopping magazines with electronic versions in the in-flight entertainment, and re-

placing beverage carts with lighter versions [Aviation Week, 2006].

To conclude, airlines have a number of options to reduce their CO_2 costs. What is worth note is that not all of these options are cost-effective under CO_2 costs. Some are cost-effective when including both CO_2 and kerosene costs for airlines, and some are, at least currently, not cost-effective. By giving CO_2 emissions a price, the ETS can give incentives that promote the advancement of these technologies.

1.4 QUESTIONS FOR RESEARCH

Based on the background developed in the previous chapters, questions for research are defined. These questions guide more detailed deep dives into three research subjects that will be presented from Chapter 2 to 6.

- The first research question is concerned with the effects of a CO_2 surcharge, and the results are given in Chapter 2 . The question is how airlines can optimize their profits under a fluctuating CO_2 and kerosene prices by passing price changes on to customers. As has been laid out, the ETS poses a new risk for the input factor CO_2 for airlines. Similarly to the approach by airlines to kerosene prices, where surcharges are used to counter price increases of kerosene, a CO_2 surcharge could be one possible solution against the risk of a fluctuating CO_2 price. Surcharges for airlines have not been addressed explicitly in the academic literature. The pricing of airline tickets has focused on the technique of revenue management [see e.g., Chiang et al., 2007]. In this deep dive, a new perspective on the pricing for airlines is presented: ticket pricing under the fluctuating kerosene and CO_2 prices taking into account demand reactions of price changes. Thereby, the existing literature both on revenue management and the managerial implications of the aviation-ETS is extended.

- The second research question is concerned with the impacts of the aviation-ETS on the adoption of biofuels, and the results are given in Chapter 4. The question is whether the introduction of the ETS influences the adoption of biofuels. Biofuels are currently not cost competitive with kerosene. The additional cost of CO_2 introduced by the ETS can be an incentive to adopt these biofuels earlier. Chapter 4 assesses the impacts the ETS has on the adoption of biofuels with the actual cost impacts of the ETS. Previous studies have assumed a fixed CO_2 price, not taking into account the actual cost impacts of the ETS, which are softened by free allocation of emission allowances. By comparing different scenarios, the influence of the free allocation is determined. Thus, the existing literature is extended by incorporating the actual cost impact of the ETS in the assessment of the adoption of biofuels.

- The third research question is concerned with the implications of the aviation-ETS on the financial evaluation of new, more efficient airplanes, and results are given in Chapter 6. The question is how big the financial impact of CO_2 costs is on the evaluation of more efficient airplanes, in settings both with and without uncertainty. The CO_2 costs introduced by the ETS affect the evaluation of new and more efficient airplanes. First, the question is answered regarding how great the influence of CO_2 costs over the lifetime of an aircraft are in terms of present values. Second, the influence of the valuation of purchase options under fluctuating CO_2 and kerosene costs is assessed. The literature so far has failed to incorporate actual CO_2 costs in the deterministic valuation of new airplanes and has not taken into account the influence of CO_2 at all for the valuation of purchase options.

2

SURCHARGE MANAGEMENT OF KEROSENE AND CO_2 COSTS FOR AIRLINES UNDER THE EU'S EMISSION TRADING

2.1 INTRODUCTION

According to estimates by the IPCC [2007a], international aviation contributes about three percent to anthropogenic global warming. Despite efficiency improvements by airlines and airplane manufacturers, aviation emissions worldwide will likely triple by the year 2050 [IPCC, 2007b].

To curb the increase in CO_2 emissions, the European Union (EU) has decided to include airlines in the EU's ETS as of January 2012. With only limited exemptions, the ETS will affect almost all airlines flying in and out of European airports via Directive 2008/101/EC [European Parliament and Council, 2008]. As international aviation is not part of the current Kyoto protocol, airlines will receive EUAA. These EUAAs can only be used by airlines to achieve emission compliance. Airlines are also allowed to buy and sell EUA for stationary emitters, which have been part of the ETS since 2005. The directive therefore links aviation to the risks of a fluctuating CO_2 price and airlines will face new challenges when it comes to hedging the risks from the ETS.

Traditionally, airlines have used two instruments to protect against input factor price increases: financial hedging of input factors and surcharges to pass input factor price increases on to customers. As financial hedging in emission markets is still in its infancy, we turn our attention to the airline's ability to pass changes of input factor prices on to customers with surcharges. This type of hedging, however, introduces the risk component of demand reactions due to price increases. We address this problem in our model for pricing decisions under a joint CO_2 and kerosene input factor risk.

Despite its recent start, the inclusion of aviation into the EU-ETS has already found some interest in the academic literature. Anger and Köhler [2010] give a good overview of the current state of research on this topic, which has thus far focused on the financial and operational implications of the ETS for airlines. Addressing the financial implications, Scheelhaase et al. [2010] estimate the cost incurred for two airlines and show that at full cost pass through, price increases will range between 3 and 13 Euros depending on the trip length. Along with the work by [Vespermann and Wald, 2010], a study by Scheelhaase et al., is among the few peer-reviewed papers next to a number of technical reports to assess the financial impact and the influence of various design parameters before finalization of the ETS [e.g., Wit, 2005, Morrell, 2007, Scheelhaase and Grimme, 2007]. Other authors have addressed the operational implications of the aviation ETS, such as network reconfigurations [Albers et al., 2009], effects on airfares, service offerings and airplane design [Brueckner and Zhang, 2010], or aircraft assignment [Morrell, 2009a]. Morrell [2009b] has highlighted some of the considerations that apply to a potential CO_2 surcharge. However, no author to date has addressed the specifics of the inclusion of aviation into the EU-ETS when it comes to both the challenges of hedging the risks of price fluctuation of the CO_2-Price and a possible solution to the problem. Kerosene hedging has been addressed by a number of authors. There are articles by Rao [1999a,b], Morrell and Swan [2006] and Loudon [2004] detailing actual hedging practices, while Carter et al. [2006] research if hedging makes economic sense in the airline industry.

Since changes in end customer prices will affect demand, our research also has relations to revenue management. Revenue management is the process of segmenting demand and charging the maximum price possible of each segment [Talluri and Ryzin, 2005]. Revenue management in the airline industry has been discussed extensively [see e.g., Chiang et al., 2007, McGill and Ryzin, 1999]. The airline industry is one of the primary examples for the application of revenue management because of its ability to segment demand and its fixed cost-

driven cost structure. Surcharge management has not been addressed specifically for the airline industry. The current literature has extensively addressed the selling or market side of the airline industry, which is a fair assumption as long as airline services are considered a fixed cost heavy industry. In contrast, we consider the joint pricing decision linked both to the market side (different routes with different demand patterns) and two input factor prices (kerosene and CO_2). Therefore, we extend the current literature by linking external and internal factors in determining the optimal pricing decision.

2.2 THE INCLUSION OF AVIATION IN THE EU-ETS

The European Council and the European Parliament decided upon the implementing directive [European Parliament and Council, 2008] in 2008; it became effective in 2009. Scheelhaase et al. [2010] provides a summary of the design parameters including the benchmarking process for free allocation. Several states, including the US, China and Russia, have opposed the inclusion of aviation in the EU-ETS. The proposed measures range from making participation in the ETS illegal to the suspension of orders with the European aircraft manufacturer Airbus [Surgenor, 2012a]. On a global level, various organizations support a global ETS for aviation; however, the support of governments so far has been weak [ICAO, 2011b].

Using the benchmark value calculated by Scheelhaase et al. [2010], we calculate the impact for an European airline group of the ETS. The additional cost burden can have severe consequences in the airline industry, where margins are notoriously low [Morrison and Winston, 1995]. We analyze the impact on the Lufthansa Group and base our estimation on their 2009 annual report (Group, 2010) as well as their sustainability report (2010), to assess the impact of flights under the ETS (i.e., we exclude the share of SWISS long haul flights). Our estimate shows that the Lufthansa Group will incur costs of about 476 million Euros in 2012, with about 178 million Euros for allowances in excess of the free allocation. This figure may rise to roughly 1 billion Euros by 2020, with about 695 million Eu-

ros for allowances in excess of the free allocation. To put these numbers into perspective, Lufthansa Group has had an average net profit of about 350 million Euros over the past 10 years. Even if Lufthansa succeeded in passing 50 percent of the auctioned costs on to customers, its long-term profit would be fully consumed by 2020.

These figures depend on a number of assumptions. The most sensitive cost drivers are the price per allowance and the increase in the auctioning share of allowances (see Table 1). This highlights our motivation to include the price of CO_2 in our model.

Therefore, airlines have three main options to address the problem of CO_2 emission and kerosene costs: reducing CO_2 emissions, stabilizing CO_2 costs with financial hedging, or finding a suitable way to pass on CO_2 costs to customers.

One possible way to reduce CO_2 emissions and kerosene consumptions is to purchase newer, more efficient planes [see e.g., Morrell and Dray, 2009]. While this option simultaneously reduces kerosene and CO_2 emissions, it is clearly a long-term solution. The major airplane producers have an order backlog of several years and financing the replacement for only a part of the fleet of a major airline group can be a challenging task. We therefore include no explicit decisions on capital investment in our model.

It is already a widespread industry practice to protect against price spikes and profit from low prices with various financial instruments, which can be used to stabilize the purchase cost of input factors [Morrell and Swan, 2006]. However, in the long run, airlines will have to pay market prices. Therefore, we indirectly include the uncertainties of financial hedging. In the long run, every airline will ultimately pay the market price for input factors.

Finally, airlines can seek a suitable method to pass costs on to customers. Price elasticities vary significantly among the routes and customers that an airline serves [Brons et al., 2002]. For example, business travelers tend to be less price elastic than other travelers and long haul travel is less elastic than short haul (where other modes of transport are able to

Assumptions	Value in base case in 2020	Source	Cost for auctioned allowances	Increase if assumption is increased by 30%
Price per allowance (Euro per ton)	35	Mid ranges found in Anger and Köhler, 2010	695 million Euros	208 million Euros
Efficiency gains (percent per year)	1 %	Morrell, 2007, Scheelhaase et al., 2010		- 25 million Euros
Traffic growth (percent per year)	4 %	Airbus S.A.S., 2009, Boeing Commercial Airplanes, 2010a		95 million Euros
Cap reduction (vs. 2004-2006)	10 %	Own assumption derived from European Parliament and Council, 2008		12 million Euros
Auctioning share	50 %	European Parliament and Council [Minimum for stationary emitters from 2013 as found in 2009b]		108 million Euros

Table 1: Impact assessment and assumptions for Lufthansa Group

substitute). The key for airlines is to determine the right level of surcharge for each route. We directly address this question in our proposed solution.

2.3 REVENUE MANAGEMENT AND SURCHARGE MANAGEMENT

Our research focuses on the ability to pass changes in input factor prices on to customers in the airline industry. To better understand the proposed changes and the motivations for the model, we briefly discuss current revenue management practices in the airline industry. Overall, classical revenue management has focused exclusively on the selling side, as airline service is considered a fixed-cost heavy business. Instead, we explicitly incorporate input factor costs into our model and derive an optimal pricing decision under input factor price changes. Currently, these input factor changes are incorporated into the pricing decision with surcharges.

Traditionally, airlines have used revenue management to optimize their profits. Revenue management in the airline industry aims to allocate the right capacity to the right customer at the right time for the right price [Smith et al., 1992]. Revenue management has become popular in airline industry for several reasons [Ingold et al., 2000]. First, airlines can segment demand by defining fare rules for the same service, i.e., transport from A to B. For example, by requiring a weekend stop over during a round trip, they typically can segment business travelers (less price sensitive) from vacation travelers (more price sensitive). By doing so, they are trying to extract the maximum willingness to pay for a service from each segment. Another reason is the property of a perishable good. A seat on a departed flight cannot be sold later; thus, an airline cannot build up an inventory of unused seats. Third, airline services are considered a fixed cost driven business. Indeed, leasing fees for airplanes, crew costs and management overhead are largely fixed. However, one of the main challenges of airlines in recent years, kerosene costs, is typically considered activity related [Belobaba et al., 2009]. Kerosene consumption can also

be viewed as dependent on the payload carried. We reflect this view on kerosene consumption in our model.

Revenue management has been a very successful business practice for airlines, but it does not consider the increase in input factor prices, i.e. the shift from fixed costs to activity related or variable costs. Over the past years, oil (and thus kerosene) prices have risen significantly. Figure 3 shows the development of aircraft operating costs compared to indirect operating costs [ATA, 2010]. Fuel costs have risen sharply in the last few years and now constitute about one-quarter of total costs. For longer flights, this figure is even higher, as kerosene consumption grows faster than other large cost buckets (such as crewing cost). Another reason why this cost bucket will increase, at least for airlines operating to and from Europe, is the ETS. CO_2 emissions are directly proportional to kerosene consumption (3.15 tonnes of CO_2 are emitted for each tonne of kerosene). Luckily for airlines, one tonne of CO_2 is much cheaper than one tonne of kerosene (about 8 Euros per tonne vs. 770 Euros per tonne as of March 2012). Currently, most emission allowances are allocated for free, but this will be reduced in the future. Additionally, CO_2 prices will likely increase, further supporting an increase in non-fixed costs. We therefore turn our attention to the problem of incorporating input factor price changes in pricing decisions.

This paper presents a new perspective on the pricing of airline services. We specifically include the uncertainties of input factor prices when deciding upon prices for different routes in an airline's network. Due to rising non-fixed costs, we turn away from the traditional revenue management approach dominated by the selling side and start to incorporate the input factor risks. Similar to traditional revenue management, we include in our model the fact that airlines can segment between different demand profiles. Although we apply this for illustrative purposes only on a route level, our concept can easily be transferred to segmentation within a specific route or flight. It is not our intention to reject the validity of revenue management, as traditional revenue management includes more than pricing decisions (e.g. inventory control

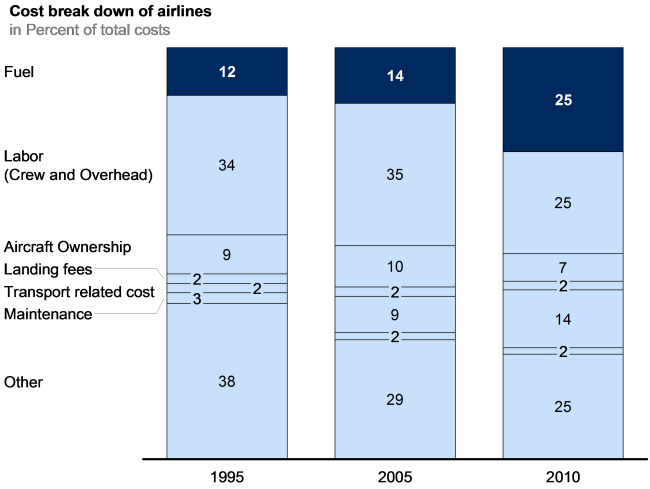

Figure 3: Cost composition development for airlines [ATA, 2010]

over time and forecasting). However, the merits of incorporating input factor price uncertainties are valuable, especially in an environment with rising fuel costs.

2.4 MODEL DEVELOPMENT

We solve our model using dynamic programming, a methodology originally developed by Bellman et al. [1955]. The key idea of dynamic programming is to break down a large problem into smaller sub-problems (in our case, individual time periods). The decision that we want to optimize is the prices for different airline routes under the uncertainty of two changing input factors: kerosene and CO_2. Instead of setting optimal prices for all periods at the same time, we can break down this large problem into smaller sub-problems and make a decision in each period after we have observed the prices for kerosene and CO_2. This is called a closed loop system [Bertsekas, 2007], meaning that we make our decision after we have observed the realizations of random outcomes. We can do this as long as

the formulation is additive over time and we can separate the decision problem over time, the key difficulty in formulating the problem. These optimal decisions are then also optimal for the whole problem, which is the so called *principle of optimality* [Bertsekas, 2007]. The goal of our model is to calculate the percentage of price changes in kerosene and CO_2 passed on to customers in each period.

To focus on the key aspects of surcharge management, we conduct our analysis in a simplified environment. We assume a single airline network with no direct competition. A model with perfect or limited competition can only be analyzed with much more complicated game-theoretical models. Our analysis is a multi-period model, where each period is indexed with $t = 1, \ldots, T$ and each route with $r = 1, \ldots, R$. To keep the notation simple, we separate both indexes with a comma only where confusions may arise.

We build a simplified airline profit equation that includes revenues given by ticket prices p_{tr} (in Euros per passenger ticket), quantities of tickets sold (given by a linear demand function $a_r - b_r * p_{tr}$) and costs as determined by kerosene c^K, CO_2 costs c^C and kerosene quantities calculated with a distant dependent kerosene consumption factor $k_r(d_r)$. Equations 2 to 6 show the profit formulation in full. The core of the profit function is equation 2 and we break each component out of this formulation in separate equations to make them easier to understand. It would be possible (and we have done so to calculate the optimality conditions) to merge all equations into one profit equation.

We explain each component of the profit equation in the following paragraphs. We start with the costs per tonne for kerosene and CO_2, then the kerosene consumption factor necessary for the kerosene quantities (which can be easily transformed into CO_2 quantities with an emission factor) and lastly explain the modeling of ticket prices and the resulting passenger quantities.

Input factor costs for kerosene c_t^K and CO_2 c_t^C: On the cost side, we focus on two variable input factors for the production of airline services. These factors are kerosene c^K (super indexed

with a K) and CO_2 emission rights c^C (super indexed with a C). Prices for kerosene c_t^K (in Euros per tonne kerosene) and CO_2 emission rights c_t^C (in Euros per tonne CO_2) are a result of the previous period's prices and a random change in prices (in percent) or mathematically $c_t^K = c_{t-1}^K \left(1 + \Delta_{t-1}^K\right)$. Therefore, the price of kerosene c_t^K is a result of the market price of the former period $c_{t-1}^K$and a random realization Δ_{t-1}^K (with Δ_{t-1}^K being non-stationary and iid-distributed), denoting the change in value between two periods for kerosene (see Equation 3). The price of CO_2 c^K is determined in the same way as can be seen in Equation 4.

Quantities for kerosene $k_r\left(d_r\right)$: Quantities of kerosene and CO_2 are determined by Equation 5, shown separately in Equation 1.

$$k_r\left(d_r\right) = \left(k^{TO} \times d^{TO} + k^F \times \left(d_r - d^{TO}\right)\right)\left(1 + k^{lh}\frac{d_r}{d^{lh}}\right)e_r^{BC} \tag{1}$$

We model kerosene consumption dependent on the number of passengers and the distance flown. To calculate total kerosene consumption, we multiply $k_r\left(d_r\right)$ by the passenger quantities as determined by the demand function. Kerosene costs are generally considered as activity based. However, we assume that kerosene and CO_2 quantities are dependent on the number of passengers. The kerosene consumption calculation consists of four parts: consumption for the takeoff phase, consumption for the cruise phase, consumption penalty for very long flights, and a component to account for the share of business class seats.

The takeoff distance component of our model is calculated as follows. Short haul flights have drastically higher kerosene consumption per kilometer as the energy intensive takeoff and climb phase constitute a major part of the total flight. For longer flights, the climb out proportion decreases along with the kerosene consumption per kilometer (total consumption still increases due to the longer distance traveled). We use an approach similar to that used by CompenCO2 [2011], a company offering CO_2-offsets for airlines, to determine kerosene consumption per economy seat per route. We do not take into account freight explicitly in the calculations but assume that

calculations on a per seat basis reflect a typical share of air freight.

Actual consumption is determined by kerosene consumption during takeoff and climb out k^{TO} (in tonnes kerosene per passenger per kilometer traveled during takeoff) and the respective distance traveled in kilometer during that phase d^{TO}. We assume no flights shorter than this phase (250 km in the numerical example). During cruise flight (the remainder of the flight distance $d - d^{TO}$) a different consumption factor of k^F (in tonnes kerosene per passenger kilometer) is applied.

To account for the additional kerosene consumption of long haul flights, we multiply the kerosene consumption by a long haul penalty. It is calculated by dividing the total kilometer distance d by the long haul factor d^{lh} and multiplying this by an additional consumption factor of k^{lh}. This means that the kerosene consumption (as determined by the cruise and takeoff portion) increases by the factor d_r/d^{lh} multiplied by the long haul factor k^{lh}. For example, if k^{lh} is set to 3 percent and $d_r = 8000$ and $d^{lh} = 1000$, then the kerosene consumption increases by 24 percent (8000km/1000km*3 percent). Cross-checking our calculation method with kerosene consumption values found in Lufthansa Group [2010b] for short, medium and long haul routes confirms the validity of our method.

In addition to the distance, kerosene consumption per passenger is dependent on the relation of economy seats versus premium seats (first and business class seats) as we base our calculations on economy seats. Premium seats take up more space (and are heavier), therefore the kerosene consumption per seat is higher. To include this in our model, we assume a share of business class seats in a plane BC and a share of of economy seats $1 - BC$. As business class seats take up more space and therefore contribute more to kerosene consumption per seat, the business class seats are multiplied with a emission factor e^C. We set this emission factor to 2 in the numerical example for twice the emission of a premium seat over an economy seat. To simplify notation, we contract these parameters to a route specific emission factor of e_r^{BC} with the formula $e_r^{BC} = (1 - BC)(BC * e_r^C)$.

Quantities of CO_2*:* As the quantity of CO_2 emission is dependent on the consumption of kerosene, we multiply the amount of kerosene by a fixed emission factor e with the value 3.15 (in tonnes CO_2/tonne kerosene).

Ticket prices p_{tr}*:* Airline revenues are driven by prices p_{tr} that passengers are willing to pay for a ticket for route r. The airline can adjust the prices for its service with a surcharge that it levies on its passengers to counter changes in input factor prices. To simplify matters, we do not distinguish between price and surcharge but rather show a new price for each period. The resulting surcharge would be the price change between periods. The airline must determine in terms of u_{tr} what percentage of the changes in the prices of input factors kerosene and CO_2 (also percentage changes) it wants to pass on to customers. To reflect the differences in both quantity and price of input factors, we weight the price changes with the respective prices and quantities (a multiplication with the emission factor $e = 3.15$ for CO_2). For example, for a kerosene price c^K of 700 Euros per tonne (and a price change Δ^K of 5 percent) and a CO_2 price c^C of 8 Euros per tonne (and a price change Δ^C of 10 percent), the weighted price change would be only 5.17 percent (700/(700+3.15*8)*0.05+8/(700+3.15*8)*3.15*0.1). The weighting of the input factor price change is reflected in the brackets before the control rule $u_{t-1,r}$ in Equation 6.

Passenger quantities: We model demand for the airlines service indirectly with a linear demand function $D_{tr} = a_r - b_r * p_{tr}$. Airlines tend to understand the markets they serve (and therefore the demand function) quite well due to the revenue management techniques applied. Thus, this is not a too restrictive assumption.

Putting all of the pieces discussed together, the total profit function for one period can then be denoted by Equations 2 to 6:

$$\pi_t = \sum_{r=1}^{R} \left[p_{tr}\left(u_{tr}\right) - k_r\left(d_r\right) \left(c_t^K \left(\Delta_t^K \right) + e c_t^C \left(\Delta_t^C \right) \right) \right] \left(a_r - b_r \times p_{tr}\right) + \frac{1}{1+r} E\left[\pi_{t+1}\right] \quad (2)$$

s.t.

$$c_t^K = c_{t-1}^K \left(1 + \Delta_{t-1}^K\right) \quad (3)$$

$$c_t^C = c_{t-1}^C \left(1 + \Delta_{t-1}^C\right) \quad (4)$$

$$k_r\left(d_r\right) = \left(k^{TO} \times d^{TO} + k^F \times \left(d_r - d^{TO}\right)\right) \left(1 + k^{lh} \frac{d_r}{d^{lh}}\right) e_r^{BC} \quad (5)$$

$$p_{tr} = p_{t-1,r}(1 + \left(\frac{c_t^K}{c_t^K + e c_t^C} \Delta_{t-1}^K + \frac{c_t^C}{c_t^K + e c_t^C} e \Delta_{t-1}^C \right) u_{t-1,r}) \quad (6)$$

For dynamic programming to work, the problem formulation must be additive over time. This means that all periods after the current period can be added to the current period. As future periods include uncertainties about the future prices of kerosene and CO_2, we have to work with an expected value operator $E\left[\pi_{t+1}\right]$. For each period, there is a decision to be made for the current period that also takes into account the coming periods which are summarized by the expected value. These coming periods, in turn, depend on the decisions made in the following periods. To account for time differences in the decisions, we discount the expected value with $\frac{1}{1+r}$ where r is the intertemporal interest rate.

2.5 SOLUTION TO THE FORMULATED PROBLEM AND INTERPRETATION

In this section, we present the optimal solution to the problem formulation of the previous section. For a detailed description of the solution steps for the control rule, please see the A.

We have formulated a problem in the form of the profit equation for an airline to determine the optimal level of prices given uncertain costs for kerosene and CO_2. Solving the stated problem formulation for its optimal solution yields a control rule that can be determined by solving the formulated problem analytically. The control rule allows us to make optimal

decisions given the parameters of a route. It is therefore not necessary to recalculate the decision for all periods in order to find a solution. It is sufficient to plug the relevant parameters into the control rule in each period and obtain the optimal decision (the level of pass-through of the price changes of kerosene and CO_2).

Equation 7 shows the control rule in its analytical form.

$$u_{tr} = \frac{w\left(a_r d^{LH} + b_r w e_r^{BC}\left(d^{LH} + d_r k^{LH}\right)\left(d_r k^F + d^{TO}\left(k^{TO} - k^F\right) - 2b_r d^{LH} p_{tr}\right)\right)}{2b_r d^{LH}\left(c_t^K \Delta_t^K\left(1+\Delta_t^K\right) + c_t^C \Delta_t^C\left(1+\Delta_t^C\right) e\right) p_{tr}} \quad (7)$$

with

$$w = c_t^K\left(1+\Delta_t^K\right) + c_t^C\left(1+\Delta_t^C\right) e$$

Clearly, the control rule is influenced by all parameters defined in the previous section and therefore is rather complex. Thus, we provide some interpretations of the control rule to facilitate understanding of the results calculated in Section 2.6.

Based on the assumptions defined above (specifically, no competition and therefore a monopolistic price setting), we expect the results of p_{tr} to follow the markup rule (Samuelson and Marks, 2003), which states that prices in a monopoly follow equation 8.

$$\frac{p_{tr} - MC_{tr}}{p_{tr}} = \frac{1}{\eta_{tr}} \quad (8)$$

MC stands for the marginal cost of serving a customer and η for the price elasticity of demand. Because kerosene and CO_2 consumption are dependent on the number of passengers, marginal costs are easy to derive. We can substitute the definition of marginal costs from our problem formulation into equation 8 and prove that our solution follows the markup rule. We substitute MC_{tr} with the marginal costs. Similarly, we substitute the price elasticity η_{tr} with the formulation of the demand function using the expression $\eta = \frac{b_r \times p_{tr}}{a_r + b_r p_{tr}}$ and show that it is the exact same formula that can be derived when substituting the control rule from equation 7 in the definition of p_{tr} of equation 2 in the problem formulation. Therefore, prices (a result of the optimal pricing of the control rule u_{tr}) follow the mark up rule of monopolistic pricing.

What does this mean for the pricing scheme calculated with our control rule? First, routes with lower price elasticities will, ceteris paribus, have higher prices as routes with higher price elasticities (as the demand reaction to price increases is bigger). Second, a higher marginal cost (in our case, kerosene and CO_2 consumption) means, ceteris paribus, higher prices. This factor particularly affects long haul flights, where marginal costs constitute a larger proportion of total costs.

To explore how different parameters in the control rule affect the results of the control rule (see B for details), we take the partial derivatives of the control rule for the parameter under scrutiny. If the partial derivative is negative, then the influence of this parameter on the control rule (i.e., the level of pass-through of price changes) is decreasing. In contrast, a positive value has an increasing impact on the level of pass-through. These relationships are true only ceteris paribus.

We find a positive influence for the intersection of the demand function a_r, the price of kerosene c^K, the kerosene consumption during flight k^F and the distance per route d_r. We find a negative influence on the control rule for the price p_r and the slope of the demand function b_r and the change of the price of kerosene Δ^K.

Important to understand is what we mean by a price change. If the parameter in question has a positive impact on the control rule and the price change is positive, the value of the control rule will increase (larger cost pass through). In most derivatives, there is a term that determines whether the changes of kerosene and CO_2 trigger a positive or negative price change. To be precise, it is the term $c_t^K \Delta_t^K \left(1 + \Delta_t^K\right) + c_t^C \Delta_t^C \left(1 + \Delta_t^C\right) e$. The straightforward interpretation of this expression derives from the weighted price change defined in the problem formulation. The result is that the direction of the input factor price change with the higher absolute value determines the direction of the change of the control rule. This is true for all partial derivatives except for c_t^K and Δ_t^K. We will explain the influence of this factor on these variables when we discuss these two factors.

Initial price p_r: An increase in price has, ceteris paribus, a negative impact on the value of u_{tr}. With higher initial prices (and a linear demand function) demand is going to be in a less elastic area of the demand function for a positive price change (and vice verse for negative price changes).

Parameters of the demand function a_r and b_r: Similarly, the parameters of the demand function a_r and b_r do have an impact on u_{tr}. We find a positive impact of a_r, which stands for the constant in the demand function. A larger a_r means lower price elasticity at the same price and same slope b_r and therefore a better ability to pass on cost to customers. For b_r, the opposite can be said: with positive price changes, u_{tr} decreases. Again, price elasticity lies behind the interpretation, as a higher slope of the demand curve for a given price leads to higher price elasticities.

Price change of kerosene Δ^K: As an example, we look at the price change of kerosene Δ_t^K (similar considerations apply to the input factor CO_2). The change in kerosene prices Δ^K is analytically complex but easy to understand when taking into account the results of the markup rule derived above. When close to the optimum as defined by the markup rule, larger price changes result in a smaller control rule (thus having a negative impact on the change of the control rule). The control rule tries to maintain the position defined by the markup rule and therefore curbs larger price changes. The price change is not affected by the sign change mentioned earlier. Instead, the weighting is squared; thus, the negative impact stays negative for both a positive and negative price change.

Cost of kerosene c^K: In contrast, parameter c^K has a positive influence on the control rule. Increasing c^K implies a higher marginal cost for serving a customer and therefore a higher price to the customer and a higher pass-through rate. The cost of kerosene is not affected by the direction of the price change.

Kerosene consumption during flight k^F: The kerosene consumption during flight illustrates how a reduction in fuel burn (e.g., from using newer airplanes) helps to influence the control rule. The influence of the kerosene consumption during flight is positive. It is easy to see the reasons for this: Increas-

ing kerosene consumption leads to higher marginal costs and therefore higher cost pass-through rates.

Route distance d_r: Because distance is a heavy contributor to kerosene consumption, we expect a positive influence on the control rule, as marginal costs increase with longer distances. Indeed, this turns out to be true.

To sum up the influences of different parameters on the control rule, two main drivers affect the control rule: price elasticity and marginal cost. Some of the parameters are clearly linked to marginal costs (such as $k^F$and d_r), others to the price elasticity (such as a_r and b_r) and the last group to both.

2.6 NUMERICAL EXAMPLE

We apply our developed methodology to a short numerical example. Assuming no direct competition, we model eight routes in the numerical example to show the effects of surcharge management in an airline's network, which depend on route length and route characteristics. We set the number of periods T to 120 (where one period is one month) to show how the developed control rule works. Section 2.6.1 lays out the data collection process to determine the parameters and Section 2.6.2 presents the computational results. In Section 2.6.3 we compare our derived policy with the current industry practice, where price increases are passed on to customers with less flexible surcharges.

2.6.1 *Data Collection*

First, we collect data for parameters that are not dependent on the route. Table 2 presents the value of some key parameters that are not dependent on r. We take the value for c^K from the US Energy Information Administration (EIA) as of February 2012. Similarly, we use data from the ECX for daily futures to derive values for c^C. Figures for the calculation of the kerosene consumption are taken from CompenCO2 [2011] and the emission factor e from IPCC [2007a]. As they do not

	c^C	c^K	k^{TO}	k^F	k^{lh}	d^{TO}	d^{lh}
Value	8	700	0.000076	0.000025	3%	250	1000
Unit	Euro per tonne CO_2	Euro per tonne kerosene	Tonne kerosene per RPK	Tonne kerosene per RPK	unit less	km	km
Source	ECX	EIA	CompenCO$_2$				

Table 2: Route independent parameters

influence the decisions made we do not include fixed costs in the numerical solution and thus give values for profit as raw margin (revenues minus variable cost for kerosene and CO_2).

Table 3 presents the uncertainty parameters. These are the changes in kerosene prices Δ^K and in CO_2 prices Δ^C. Data are taken from the EIA for kerosene, spanning the date range from January 2000 to February 2012. For CO_2 prices, we take data from the ECX, a large trading platform of CO_2 emissions, from May 2008 through February 2012; this spans the second phase of CO_2 trading in the EU-ETS, where prices show less extreme behavior. Correlation between kerosene/oil and CO_2 prices has been very low [Daskalakis et al., 2009]. We therefore do not include a specific measure of correlation for the two input factors. As noted earlier, we assume iid-distributed returns for both input factors; i.e. returns are non-stationary.

In addition to these route independent and uncertain values, we introduce a number of parameters with route dependency. We model routes for short, medium and long haul travel. Great circle distances d_r can be found in Table 4. Initial payloads are chosen such that the aircraft type used typically could carry more payload to perform the route in the case that the control rule determines a price reduction (and therefore a passenger increase). For the demand functions, we use basic pricing theory and the summary of elasticities presented

	$\triangle^K$	$\triangle^C$
Mean value	1.42%	-0.76%
Standard deviation	9.47%	15.40%
Source	EIA	ECX

Table 3: Uncertainty parameters

by Brons et al. [2002]. We assume a given demand (i.e., for air transport in terms of passengers) for a current price. For example, Route 1 assumes 180 passengers paying an average initial one-way fare of 300 Euros. Combining this with the meta-analysis of Brons et al. gives the parameters a_r and b_r of the linear demand function per route [Shy, 2008].

We list the prices p_r and the price elasticities η_r for each route used to construct the demand functions in Table 4 . Prices are derived from the average yield per passenger kilometer as listed in Lufthansa Group [2010a]. We adjust short, medium and long haul trips as well as business/leisure intensity with suitable markups to derive yields per passenger for each route. For each route length, elasticities are chosen to represent a vacation destination (high price elasticity), a mixed destination (mid-price elasticity) and a business destination (low price elasticity); they are also adjusted for trip length (longer routes have lower elasticities). As mentioned, data for elasticities are from a meta analysis of price elasticities conducted by Brons et al. [2002]. We also include a starting value for the algorithm that is different than the price used to construct the demand function. This is because, in the first period, the algorithm moves prices to the range defined by the markup rule and adjusts prices to the changes of the input factor prices. For some routes, the movement of the first component can be quite significant (and thus would distort the representation of our data); consequently, we define starting prices p_{0r} close to the optimum given by the markup rule.

Our main research goal here is to show the workings of our solution; thus, we focus on the effects of the price changes of input factors. Finally, we give relevant shares of business class seats to calculate a suitable emission factor e^{BC} with the methodology applied by CompenCO2 [2011]. We assume for every business class seat twice the emissions of an economy seat.

2.6.2 *Results*

We calculate results in Mathematica with the given starting values and route dependent values as shown in the previous chapter. Repeatedly applying the control rule to all parameters, we gather results for 7,500 iterations of random parameters over 120 periods (10 years). For most figures we use nominal values, i.e., we do not discount with the discount rate r to better illustrate our findings.

Figure 4 presents the average relative price developments. We set the price of the first period to 100 percent and show the relative development over time, to account for the differences in prices of the different routes. The overall tendency is to increase prices over time, because we set a positive drift rate for the price of kerosene (the dominant input factor). Furthermore, there are different levels of cost pass-through in the different routes. Long haul routes see much higher price increases than short haul routes. For example, long haul Routes 7 and 8 see increases of about 45 and 35 percent, respectively, relative to their initial starting prices; short haul Routes 1 and 3, about 19 and 11 percent, respectively. Price increases are also differentiated among the price elasticities, with higher price increases for routes with lower price elasticities. The relative price development shown in Figure 4 seems to present the contrary. However, on a relative development the initial price, which is higher for less elastic routes, distorts the picture. In absolute terms, the price increases are a lot higher for low elasticity routes than for high elasticity routes. Taking again routes 7 and 8, the absolute price change is about 480 Euro for route 7 and 740 Euro for route 8.

Table 4: Route dependent parameters

Route	Description	Route Example	d_r	x_{0r}	p_r	η_r	a	b	p_{0r}	BC_r	e^{BC}
1	Vacation short-haul	Madrid - Palma de Majorca	548 km	180	300	-1.8%	504	1.08	245	10%	1.15
2	Mixed short-haul	Munich - Rome	719 km	180	400	-1.5%	450	0.675	350	15%	1.23
3	Business short-haul	Frankfurt - London City	621 km	180	500	-1.2%	396	0.432	475	20%	1.30
4	Vacation medium-haul	Vienna - Faro	2.346 km	200	600	-1.3%	500	0.500	525	10%	1.15
5	Mixed medium-haul	Barcelona - Istanbul	2.236 km	200	700	-1.0%	440	0.343	675	15%	1.23
6	Business medium-haul	London - Istanbul	2.519 km	200	800	-0.7%	380	0.225	875	20%	1.30
7	Vacation long-haul	Frankfurt - Cancun	8.618 km	350	900	-0.9%	700	0.389	1050	10%	1.15
8	Business long-haul	Frankfurt - Singapore	10.285 km	450	1600	-0.7%	810	0.240	2150	30%	1.45

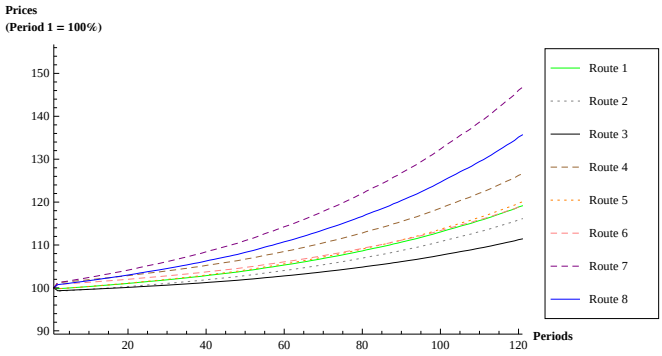

Figure 4: Price development for all routes (indexed at period 1)

Let us take a look at what that means in terms of the control rule. We find the highest values for the control rule for Route 7. Here, marginal costs are highest in relation to the price per ticket. Also, the inverse of the price elasticity is lower for this route. Therefore, the algorithm tries to pass on more of the price changes to the price than for the other routes. We find the second heaviest reactions for Route 8, again a long haul route with high marginal costs. On the lower end of the changes is Route 3, the short haul business route. Here, the relation of price and marginal costs and the inverse of the price elasticity is significantly higher. The control rule basically tries to maintain a "sweet spot" given by the markup rule. What helps in the case of airlines is that marginal costs are quite low. For example, for the most affected route (vacation long haul), the relation of price to marginal cost is about 25 percent. Figure 5 shows actual price changes (the value of control rule multiplied by the price changes of input factor prices). Price changes in each period are quite low but add up to significant increases as shown previously for the relative price development. Again, the routes with the highest marginal costs have the greatest price changes.

What do these cost pass-through rates (and therefore prices) mean for the demand on each route? As mentioned, price increases induce demand reaction. We apply the calculated

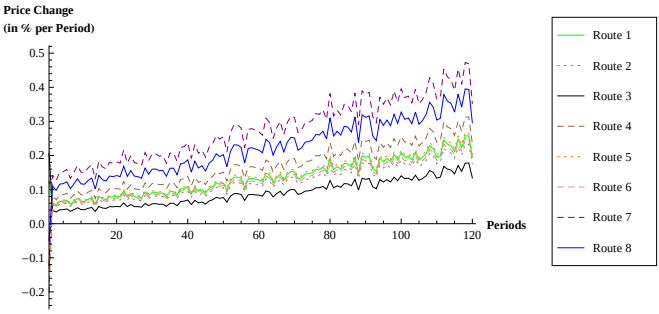

Figure 5: Price changes per period

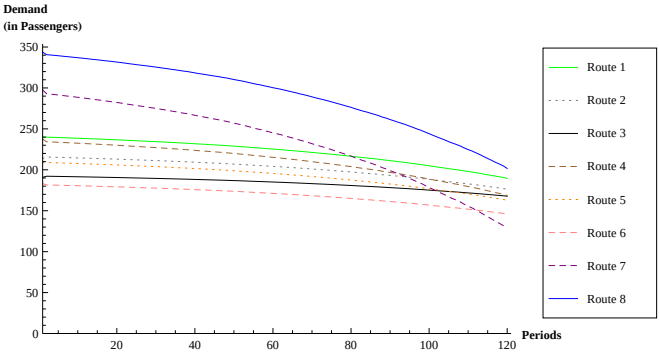

Figure 6: Demand development

prices to the demand functions and calculate values for the demand in each period on each route. Figure 6 shows the results. Short haul routes with low marginal costs and low pass-through rates are quite stable in terms of demand (Routes 1 to 3). For the longer routes, demand reactions are more pronounced: Route 8 sees a reduction from 340 to roughly 230 passengers due to the price increases; Route 7 sees demand fall by about 150 passengers. Here, the higher marginal cost in relation to the price and greater price elasticity lead to a greater demand reduction.

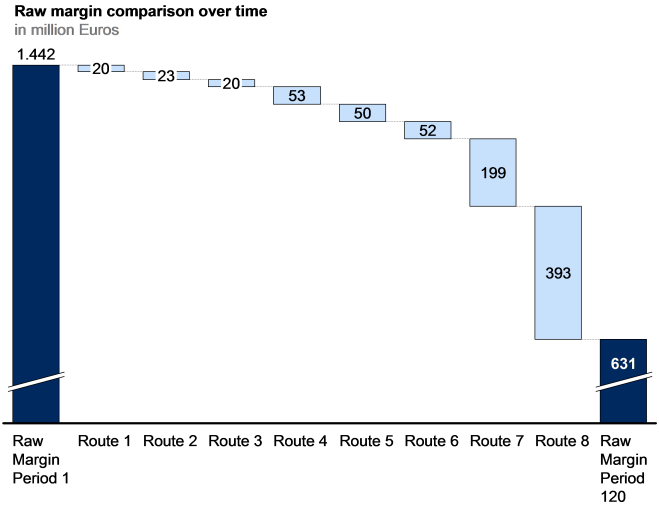

Figure 7: Raw margin development

Comparing the undiscounted raw margins (i.e., revenues minus variable costs) over time, we see a decrease of about 56 percent over the full length of the simulation due to the stark increases in kerosene costs. Further reductions are triggered by reduced revenues due to the reduced number of passengers. As with the demand development, Figure 7 shows the largest decreases for the long haul Routes 7 and 8: raw margins decrease considerably by 81 and 65 percent, respectively. In contrast, decreases for short haul routes are rather small (e.g., 23 percent on Route 3).

To determine how different developments of kerosene and CO_2 prices influence the pricing, we adjust the drift rates (the average price change per period for each input factor) with a scaling factor(see Figure 8). We take 50, 100 and 200 percent of the original drift rate. Since the drift rate for kerosene is positive, doubling the kerosene drift rate raises the price increases. In contrast, since the drift rate for CO_2 is negative, doubling should lower price increases. The different plots for CO_2 are hardly discernible; therefore, a change in the CO_2 drift

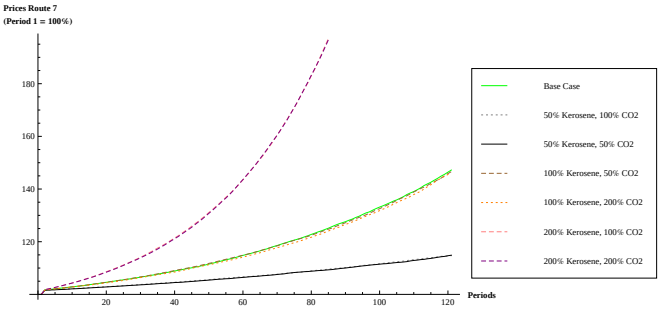

Figure 8: Price development under different kerosene and CO_2 prices

rate has only a limited impact on the pricing decision. However, the drift rate of kerosene has a large impact on the price adjustments.

Lastly, we examine sensitivities of the standard deviation on the numerical results of the control rule. We examine a range of different standard deviation starting from 0 to 300 percent of the standard deviation increasing in steps of 20 percent. We analyze sensitivities for joint CO_2 and kerosene changes, kerosene alone and CO_2 alone (we fix standard deviation for the other factor to the values given in Table 3). As we expected from our analytical derivation, we find a decreasing slope, meaning higher standard deviations yield a smaller control rule and therefore a smaller cost pass-through. With higher deviations from the mean value, and therefore higher uncertainty, the control rule decreases on average. For the CO_2-only test of sensitivities, the results are a rather flat slope with increasing levels of standard deviation. Here, the increased uncertainty of the input factor CO_2 does not have a large enough impact on the control rule to stimulate a significant change in the control rule.

2.6.3 *Comparison with base policy*

To show the improvement potential of our optimal policy, we compare our results with current industry practice. Currently,

airlines define a base price for the transport service and then add surcharges to counter increases in kerosene prices. Surcharges typically are calculated by increasing the charge with increases in kerosene or heating oil prices. We assume a base price for kerosene of 700 Euros per tonne. For this price, we do not calculate a surcharge, and prices are as defined for p_{0r} in Table 4. The surcharge increases are as follows: For every increase of 50 Euros per tonne of kerosene, we increase prices by five Euros on short and medium haul routes and 15 Euros on long haul routes. For example, at a kerosene price of 770 Euros per tonne and a base price of 300 Euros, a short haul route would have a selling price of 310 Euros (a surcharge of 10 Euros). The review period for price adjustments is every three months. This means that in the base policy, airlines have a less continuous reviewing policy as in our proposed solution applying the developed control rule. In the proposed solution price changes are possible every month. Note that we do not include the price risk of CO_2 emissions in the surcharge.

There are four main differences between the base policy and our proposed solution. First, our solution includes the price changes of CO_2 and kerosene, whereas the base policy is only concerned with the latter. Second, the review frequency for the surcharges is higher in the proposed solution (monthly versus once every three months). Third, the proposed solution differentiates price increases between route lengths and can adjust the price increases continuously. The base policy, in contrast, differentiates only between short and long haul routes and with fixed price increases (5 Euros for short haul and 15 Euro for long haul) for each incremental steps over the base price. Lastly, the base policy does not differentiate between different price elasticities, whereas the proposed solution does.

Prices, especially for short haul routes (Route 1), increase sharply with the traditional surcharge. The base policy coarsely differentiates among the routes as opposed to including a fully variable price change in the optimal model. If the surcharge were based on marginal costs, the increases for short haul routes would be much smaller. Also, the non-continuous price

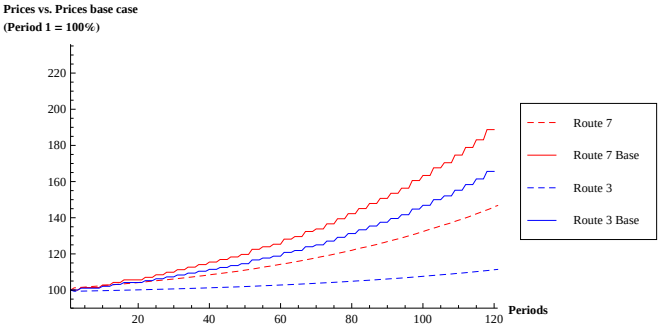

Figure 9: Direct comparison base policy with proposed solution

change interval of three months leads to a jagged, staircase-like pattern of price increases.

To highlight the differences, we show a direct comparison between the base policy (solid lines) and our proposed solution (dashed lines) in Figure 9. We have chosen Routes 3 and 7 to represent a short haul business route and a price sensitive long haul route. Price increases for both routes are much higher with the base policy than with our proposed solution. For Route 3, the base policy increases prices by about 60 percent due to the changes in kerosene cost. Our solution increases the price for Route 3 only moderately, reflecting the low marginal costs of kerosene for the short haul route. Price increases for the long haul Route 7 are more significant (about 50 percent over the base price) but not as sharp as the price increases for the base policy (where price increases by about 90 percent). Our proposed solution strikes a better balance between the high marginal costs for the long haul route and the high price elasticity of the vacation route.

Price changes, of course, do have an impact on the demand on each route. Figure 10 shows the demand development of the different routes in the base policy. Comparing Figures 10 and 6 shows a far more drastic reduction for the short haul Route 1 and the long haul Route 7 (in fact, demand drops to zero for the former). Both routes are price sensitive leisure

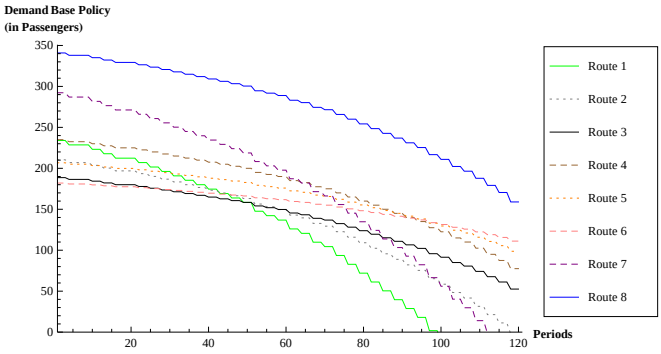

Figure 10: Demand development in base case

routes for which the undifferentiated price increases of the base policy raises prices much more than with the proposed solution. This triggers sharper demand reactions and thus makes some of the routes no longer viable with zero demand. Business heavy routes such as Routes 6 and 8 fare better but still see more drastic demand reactions than with our proposed solution.

Finally, we calculate the raw margins of each route and the differences to the optimal scenario. Figure 11 shows the cumulative raw margin for the base case on the left and the differences for each route and the total raw margin for the optimal scenario on the right. Overall, the optimal model gives about 6.3 million Euro more raw margin over the considered time frame, an increase of about 5.6 percent. For Routes 1 and 7, the solution of the proposed model yields significantly better results. The main reason is that our model increases prices more modestly for these routes, since it can allocate price increases more flexibly. Therefore, demand reactions are not as drastic, and raw margins for these routes are significantly better.

We now add extensions to the base policy that allow the base policy to capture the main differences to our proposed solution. We begin with the monitoring horizon that was set in the base policy to a three month review horizon. More

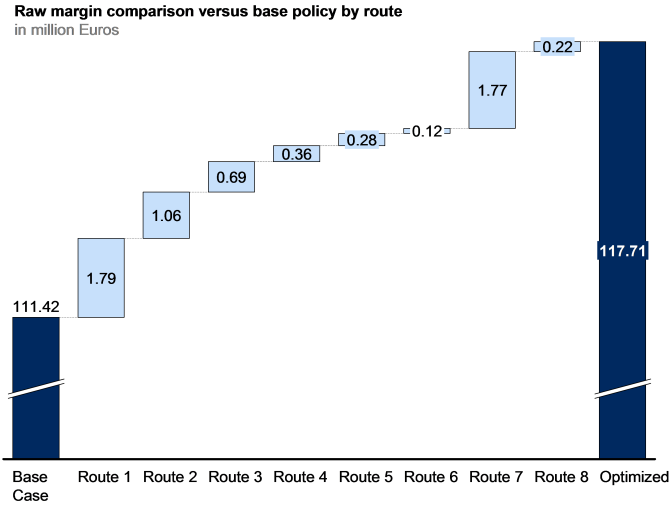

Figure 11: Raw margin comparison base case and optimal

frequent price changes allow the new price levels to better reflect the changes in input factors. We set the review horizon to one period; this matches the continuous reviewing policy that our proposed solution achieves. We find that the increase in reviewing frequency gains an additional 0.38 million Euro or about 6 percent of the gap to the proposed solution

As a second step, we allow for more continuous price changes. In our initial base policy, we had fixed price increases of 5 Euros per short haul route and 15 Euros per long haul route for each 50 Euro increment over the base price of kerosene, which broadly reflects current industry practice. We now reduce the price increment bracket from 50 to 1 Euro and adjust the price increases of the surcharge to 0.1 Euros for short haul and 0.3 Euro for long haul flights. Since no airline has a continuous surcharge policy at the moment, we use these levels to broadly reflect the marginal costs of kerosene for the route types. In combination with the shortened review horizon, we find that this gives a further gain of about 0.67 million Euro or about 11 percent of the total gap.

Next, we allow the base policy to differentiate between different price elasticities. As airlines do not differentiate their surcharges among their passengers, we assume a surcharge increase of 30 percent for routes heavily used by business travelers (Routes 3, 6 and 8). In contrast, the surcharge is reduced by 30 percent for leisure routes (Routes 1, 4 and 6). On mixed routes (Routes 2 and 5), the usual surcharge is levied. We find that this gives an additional gain of about 1.69 million Euro or about 27 percent.

The last bucket is a residual that we calculate by taking the total gap between the optimized solution and the base policy and then subtracting the sum of the extensions incorporated. Taking together all three effects (continuous adjustments, continuous review and differentiation among price elasticities), a gap of 3.55 million Euro (56 percent) remains. The main components of this bucket are the benefit from incorporating the costs of CO_2 in the optimized policy and adjusting the surcharge more flexibly to price elasticities. We treat these two effects as a residual since it is difficult or impossible to adjust the base policy to match our proposed solution. There is no standard industry practice for incorporating CO_2 prices into a surcharge. Similarly, to our knowledge, the way we have incorporated the different price elasticities of the routes has not been done by an airline nor is it as refined as in our proposed solution. Our proposed solution has a lot more flexibility to exploit the differences in price elasticities of travelers. While review horizon and increment steps can be broadly matched with our solution, the price elasticities cannot be built into the base model without developing a model similar to the one proposed.

Figure 12 shows the contribution of the different levers starting from our initial base policy. Clearly, the adjustment for different price elasticities and the residual of CO_2 and elasticities are the main contributors to the optimal solution.

Note that our policy performs better than the base policy with steeper price increases of the input factor prices. We scale the drift rates as defined previously with values ranging from 50 to 150 percent of the initial rates (Figure 13). The

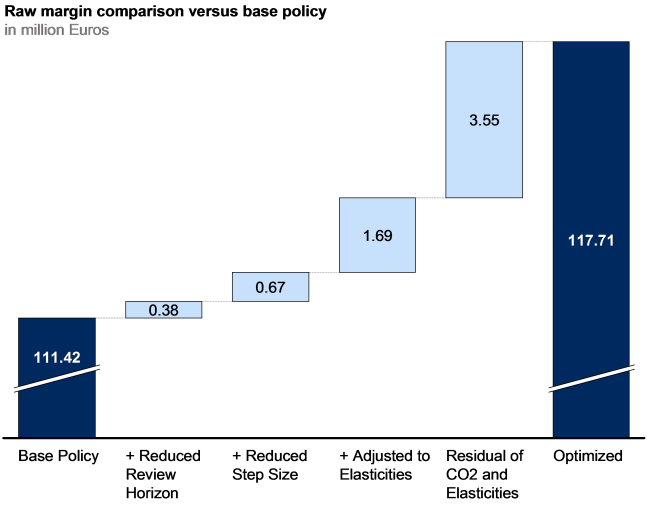

Figure 12: Breakdown of levers versus base policy

line chart with the axis on the left-hand side shows the benefit in raw margins of our proposed solution against the base policy in percentages. On the right-hand axis, the figure shows the value of the raw margins. The lighter bar charts depict raw margins of the base policy in absolute values, and the darker charts depict the benefit of the optimal solution. Clearly, with reduced drift rates for the input factors (i.e., slower cost growth), the benefit is minimal as shown by the small dark bars to the left of the chart. The faster input factor prices are rising, the better our solution performs. Our proposed solution can balance price increases much more differentiated among different route lengths and price elasticities and therefore can profit from more adverse conditions as given by higher kerosene prices. Of course, overall profits (as measured in raw margins) deteriorate due to the increases in input factor costs as shown in the decreasing bar heights for profit margins going from left to the right.

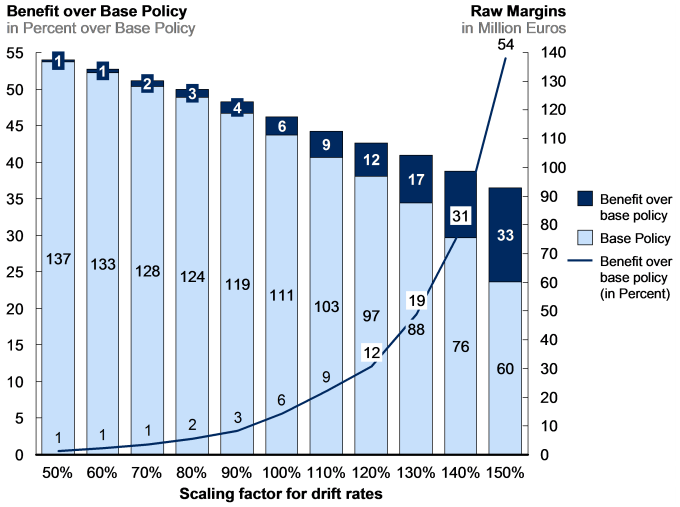

Figure 13: Comparison with base policy over different input prices

2.6.4 *Managerial Implications*

There are two managerial implications of our approach: the disruption to revenue management operations and the differentiation of surcharges. Airlines have used route or passenger specific pricing for years. In contrast to revenue management, we propose the incorporation of input factor risks. Doing so would abandon many of the experiences gained over the last year in the use of revenue management. In practice, only a few airlines have so far announced separate CO_2 surcharges; most others will simply increase existing kerosene surcharges. This seems to be a practical approach, as the quantity component of the CO_2 costs scales linearly with the kerosene component. For ticket sales targeted at very price sensitive customers, this could make it difficult to maintain certain price points that are important for the price perception of an airline. We have shown that our solution can yield significant benefits over the base policy. There are multiple ways to incorporate parts of our solution into the current industry practice. One would be

to reduce the review horizon and the adjustment size. Currently, most airlines use a trailing surcharge that curbs both cost increases and decreases, similar to the three-month revision policy defined in our base case policy. This helps to prevent price sensitive customers from shying away with too sudden price changes and allows airlines to recapture some of the losses incurred when costs are falling again. As we calculated our policy with a monthly revision, the dampening effect would certainly diminish. Airline managers must determine whether a more frequent review of price with smaller adjustments can provide better results that outweigh demand losses triggered by sudden price increases. In our example, moving from the base policy as defined above to a policy with a monthly price revision and smaller price changes yields about 1 percent better raw margins. Some cargo airlines already apply a more frequent surcharge revision policy. For cargo airlines, where short term bookings and a continuous customer base are common, this could translate into better yields. For airlines where certain price points and high advance booking levels are dominant, it may be difficult to implement such a surcharge policy. More significant, however, would be a surcharge that differentiates among the price elasticities of travelers. With a very crude differentiation as applied to our base policy, a further 1.5 percent margin could be gained and, with a more refined approach, a significant part of the remaining residual bucket. With more adverse development of input factor costs in the future, this could be an important learning for airlines.

2.7 CONCLUSION

We propose a new airfare pricing model that explicitly incorporates input factor uncertainty. Input factor costs for airlines will increase because of rising kerosene costs and the introduction of the European ETS for aviation. We have shown that cost impacts on airlines without cost pass-through can be serious, as profit margins in the airline industry are traditionally low. As a possible solution, we present a dynamic optimization

model which explicitly includes the risk of two input factors for airlines: kerosene and CO_2 emissions. The optimum price determined in each period follows the markup rule of monopolistic pricing. Applying our results to an illustrative airline network with different route characteristics (length, prices and demand patterns), the results are especially meaningful for routes where marginal costs are high (typically long haul routes). For these routes, changes in input factor prices can severely affect profitability. Comparing our model to current industry practice, our results are about 5 to 6 percent better in raw margins. This value increases with more steeper price trajectories, as the benefit of a more flexible and continuous price adaption is more beneficial in such an environment.

There are some limitations of this perspective which offer potential for future research. First, our assumption of a variable cost for each passenger can be challenged. It can be argued that a few additional passenger do not cause relevant additional costs, as a few additional passengers do not matter in relation to the kerosene and CO_2 required to move the airplane itself. While not much can be said against this, it is true that for long haul routes, where our model gives the most notable results, airlines aim to eliminate any additional (non-paying) weight because of its influence on kerosene consumption [Lee et al., 2001]. Thus, it is fair to treat paying weight (cargo or passengers) in the same way.

The second limitation is our assumption of a monopolistic setting. We do not take into account competitive effects and reactions in our pricing decision. Competition in the airline industry can be fierce or non-existent. In a strict sense, our model is only valid for the latter. However, it is possible to model the effects of competition into the parameters of the demand function. To fully include the effects of competition (including, for example, feedback from competitor prices on the control rule) would be a valuable extension of our model. The third limitation is the use of a linear demand function and therefore a variable price elasticity. Some routes have highly (in)elastic demand and therefore would be better suited to a fixed elasticity. Generally, however, fixed price elasticities

are not very common for goods; thus, we capture the main characteristics with the demand function parameters. A dynamic modeling of the demand functions could be an extension. Over time, travelers may get used to higher price levels and readjust their demand so that the initial price elasticities would again hold true.

Lastly, there are some practical concerns for the application of our model. Ticket sales sometimes have a very long lead time (up to one year). Prices therefore need to account for price changes that occur after the actual sale of the ticket. Given the fact that this is not possible for any forward selling pricing policy (and our model yields better results for late ticket sales where adjustments are still possible), it is not a very limiting factor. To conclude, this paper contributes analytical rigor incorporating cost factors for airline ticket sales. While traditional revenue management has its merits, our model could be used as a second opinion when determining ticket prices of highly discounted tickets or to calculate surcharge levels. As we have shown, a differentiated surcharge can have significant benefits.

3

BIOFUELS AS AN ALTERNATIVE MITIGATION STRATEGY

In the previous chapter a surcharge as a possible mitigation strategy against the risks of CO_2 was discussed. As shown, an optimal surcharge can pass on the cost increases of input factors to the customers finely differentiated. This helps to minimize demand reactions, which could lead to much lower overall profits.

In contrast to surcharges, that pass on cost increases to customers, there is also the possibility to eliminate the cost risk of CO_2. The aviation-ETS allows airlines to replace the traditional aviation fuel kerosene with fuel derived from renewable sources, so called biofuels. The CO_2 emissions generated from these biofuels are credited with zero emissions in the aviation-ETS as the burning of biofuels, in an ideal world, emitts only the amount of CO_2 that was absorbed when the sources of biofuel were grown. In reality, the production, logistics and the refining of biofuels also uses energy and therefore biofuels are not strictly CO_2 neutral.

There is, however, one major drawback to this: Biofuels are significantly more expensive than kerosene. The costs of CO_2 can be an incentive to use biofuels: With costs for CO_2 the full costs (i.e., including the costs for CO_2 emissions) of one tonne kerosene is higher. This higher price, in turn, reduces the cost difference to biofuels and can therefore make their adoption more likely. The main research question of Chapter 3 is whether the costs for CO_2 promote the adoption of biofuels by lowering the price differential between biofuels and kerosene. To derive the results for this question, one has to calculate the adoption of biofuels with a cost for CO_2 emissions and the adoptions of biofuels without CO_2 costs.

The ETS can promote the adoption of biofuels in a second way: By redistributing the proceeds from the ETS back to the

aviation sector via a state intervention, the high prices of biofuels could be lowered and therefore the adoption again increase. We will show the benefits of such a state intervention in the following part.

4

DOES THE AVIATION ETS PROMOTE BIOFUEL USAGE? AN ASSESSMENT OF THE EU-AVIATION-ETS FOR COSTS OF CO_2 AND ITS IMPLICATION FOR THE USAGE OF BIOFUELS

4.1 INTRODUCTION

According to estimates by the IPCC [IPCC, 2007a] international aviation contributes about 3 % to anthropogenic global warming. Despite efficiency improvements by airlines and airplane manufacturers, aviation's emissions worldwide will likely triple by the year 2050 [IPCC, 2007b] if current industry practices do not change fundamentally.

To curb the increase in CO_2 emissions, the EU has decided to include airlines in the EU's ETS, starting in January 2012. With only limited exemptions granted, the ETS will affect almost all airlines flying in and out of European airports via the Directive 2008/101/EC [European Parliament and Council, 2008]. As international aviation is not part of the current Kyoto protocol for CO_2 emissions, the EU has created an aviation ETS through which airlines can trade among them in EUAA. This means that, in addition to the traditional ETS for stationary emitters, there will also be a newly created market for aviation allowances. These EUAAs can only be used by airlines to achieve emission compliance. As abatement costs are a lot higher for airlines than for other sectors and to alleviate the financial impact of the ETS, airlines are allowed to buy and sell EU allowances (EUA) from the traditional ETS for stationary emitters that started in 2005.

One measure to achieve carbon neutral growth in aviation, starting in the year 2020, as postulated by the IATA is the usage of biofuels [IATA, 2009]. Their actual usage or market adoption, in turn, depends both on future cost reduction (bio-

fuels for aviation are currently not cost-competitive with the traditional aviation fuel kerosene) and the combined price development of kerosene and CO_2.

Despite its start in the year 2012, the aviation ETS has already elicited some interest in the academic literature. Anger and Köhler [2010] give an overview of the current state of research on this topic. The main research so far on the aviation ETS has focused on the implications of the ETS for airlines, both financial and operational. For the financial implications of the ETS, Scheelhaase et al. [2010] estimate the cost incurred for two airlines. Their research shows that, at full cost pass through, price increases in the first years will be in the range of 3 to 13 Euros, depending on trip length. Next to the work by [Vespermann and Wald, 2010] and by Scheelhaase et al. there are number of additional technical reports to assess the financial impact and the influence of various design parameters before finalization of the ETS [e.g., Wit, 2005, Morrell, 2007, Scheelhaase and Grimme, 2007].

Biofuels for aviation have been covered by recent research, despite the fact that, also in this area, a lot of literature stems from the gray literature conducted by consultancies, agencies and government bodies [e.g., Hileman et al., 2009, Caldecott and Tooze, 2009, EQ2, 2010, Darzins et al., 2010, IATA, 2010a,b, Graham et al., 2011, IEA, 2011]. Schade et al. [2011] give a comprehensive overview in terms of feedstock, technical specifications, sustainability discussion and production volumes. A number of authors have addressed specific subtopics, such as sustainability [Rye et al., 2010], technical interchangeability [Blakey et al., 2011] and the impact of peak oil on aviation biofuels [Nygren et al., 2009].

Research on biofuels in general (i.e., not specifically for aviation) is relevant to our work for two reasons: First, experience curves estimated for other biofuels and renewable energy technologies are relevant for the estimation of the future cost of biofuels in the aviation industry [e.g., Neij, 1997, van den Wall Bake et al., 2009, Weiss et al., 2010, de Wit et al., 2010], and second, adoption rates seen for other (biofuel) technologies are necessary for our modeling approach [Geroski, 2000,

Jacobsson and Johnson, 2000, Lund, 2006], which will be explained later on.

Our research goal is to examine the impact the ETS has on the adoption of biofuels. The ETS can support this adoption in two ways: First, by reducing the difference between biofuels and kerosene plus CO_2, and second, by redistributing proceeds from the ETS back to the industry with state aid. For the former, research so far has failed to address the actual cost impact of the aviation ETS when estimating future biofuel usage. So far, biofuel usage was mostly calculated with a fixed CO_2 price that did not take into account free allocations as provisioned in the aviation ETS. Next to the risk assessment of the aviation ETS, we specifically address the question of whether the aviation ETS does boost adoption of biofuels. Our research contribution therefore is fourfold:

- We examine whether the aviation ETS has a positive influence on the adoption of biofuels in the airline industry in the EU, give estimates for the biofuel volumes stimulated by the introduction of the ETS and estimate points of cost parity for the implemented CO_2 price, full CO_2 price and no CO_2 price.
- We show the impact of different state support scenarios on the adoption of biofuels should proceeds from the aviation-ETS auctions be redistributed. Specifically, we examine the impact of financial support for a bio refinery.
- We calculate actual CO_2 costs for airlines based on CO_2 market prices and free allocation of allowances and assess uncertainties, both in terms of quantities and costs, related to the aviation-ETS

The remainder of the paper is organized as follows: After the introduction, section 4.2 lays out the setup of the aviation ETS, presents possible challenges for hedging and lists possible hedging options. Section 4.3 gives a short overview of biofuels for the aviation industry and current challenges. Section

4.4 develops the model used to estimate quantity and cost-uncertainties details as well as biofuel usage by explaining the independent and dependent model variables and the data collection process. Section 4.5 provides results for the required CO_2 quantities and costs under the ETS with and without biofuel usage, gives results regarding whether the ETS boosts adoption of biofuels both in terms of reduced price differentials and possible state support scenarios. Section 4.6 summarizes this paper and gives an outlook for further research.

4.2 THE AVIATION ETS - SETUP AND CHALLENGES FOR HEDGING

The European Council and the European Parliament decided upon the implementing directive [European Parliament and Council, 2008] in 2008 and it became effective in 2009. A summary of the design parameter can be found in Scheelhaase et al. [2010]. Here we shortly summarize the main parameters of the benchmarking allocation that influences airlines with respect to the financial impact:

- In the first year, the total quantity of allowances to be allocated to aircraft operators will be equivalent to 97 % of the historical aviation emissions. The historical aviation emissions will be calculated on the basis of the average total emissions reported for the years 2004-2006. This figure has been available to the public since July 20, 2011, and was fixed to an average value of 221,420,279 tonnes per year, which is the cap for the cap-and-trade system [EEA Joint Committee, 2011]

- In 2012, 85 % of allowances will be allocated at no cost, the remainder being auctioned off. The share of auctioning is likely to increase with future revisions of the directive. For comparison, the EU plans to auction off most allowances in the ETS for stationary emitters by 2013 (when the next phase of emission trading will start in the EU) and plans to reduce the exemptions granted to energy and competition-intensive industries in the further pro-

cess. A similar development for the airline industry, at least in future trading periods, therefore seems highly likely.

- Free allocation is based on a benchmark, and the benchmark is calculated as follows. From the historical emissions the sum of the cap reduction, the auctioned share and a special reserve for new airlines and fast-growing operators is subtracted. The result is then divided by the sum of verified tonne-kilometer data of all participating operators in 2010. The initial free allocation for an individual airline is calculated by multiplying the benchmark with the transport activity of 2010 of the respective airline.

- Currently, only the figure for historic emissions is available publicly since July 2011 (published with a delay of about six months). Airlines will know their actual allocation for the year 2012 by February 2012 (currently planned to be postponed by two months). In a recent attempt, U.S. Congress has drafted a bill prohibiting U.S. airlines from participating in the scheme. Other nations such as China and Russia are considering similar moves [Surgenor, 2011].

Given the start of the aviation ETS, airlines have three main options to address the problem of emission (and kerosene) costs:

- They find a suitable method to pass costs on to customers. Price elasticities vary significantly among the routes (and customers) an airlines serve [Brons et al., 2002]. The key for airlines then will be to determine the right level of surcharge for each route. Currently, airlines have not announced any plans on a separate CO_2 emission surcharge in addition to the widespread practice of a kerosene surcharge.

- They stabilize the purchase cost of their input factors with financial instruments. An important factor in financial hedging is knowing the amount of emissions from

which the airline seeks protection in the market. Uncertainty for this quantity in the EU-aviation-ETS stems from two sources: the amount of emissions that an airline has produced in a given year and the free allocation an airline can expect in the EU-aviation-ETS. The difference between actual emissions and free allocation yields the net quantity exposure of the airline. Uncertainty in this term is known as quantity risk and plays a significant role in the design of the aviation ETS. We will give an estimate for the value of this uncertainty in chapter 4.5.1.

- They reduce their CO_2 emissions (and kerosene consumptions). One possible solution is to replace kerosene with alternative fuels that do not require the purchase of emission allowances. In the EU-ETS, biofuels are credited as CO_2-neutral for airlines. However, biofuels currently are not cost-competitive, making their widespread adoption dependent on the future kerosene price development, actual CO_2-costs for airlines and the development of the price of biofuels. We will show the results of this analysis in chapter 4.5.2.

The aviation ETS market is a special market artificially created for the desired purpose to commit airlines to their CO_2-emissions by the European Commission. While similar considerations also apply to the ETS for stationary emitters (e.g., Abadie and Chamorro [2008]), this leads to a number of challenges, derived from both the market design and the aviation industry it targets. The main challenges are illiquidity of the EUAA market, basis risk when hedging via proxy markets and quantity risk.

The announcement of an individual airline allowance allocation for the year 2012 and 2013 will be made by February 2012. Therefore, airlines face uncertainty about their net quantity exposure until two months into the start of the EU-aviation-ETS. Airlines typically hedge their fuel risk one year ahead [Carter et al., 2006], and therefore a similar approach will not be feasible for the hedging of allowances.

We specifically examine the monetary impact of the quantity uncertainty, as we believe this is the key starting point for any other hedging activity, whether with financial or non-financial instruments. Building on these figures, which in fact determine the actual cost impact of the EU-aviation-ETS, we estimate the impact of the EU-aviation-ETS on the adoption of biofuels as an operational hedging measure.

4.3 BIOFUELS IN THE AVIATION INDUSTRY AND THE INFLUENCE OF THE ETS

Biofuels are fuels generated from biomass. Biofuels for aviation can be generated from a number of raw materials or feedstock with different refining techniques. Here we provide a short summary of these feedstock and the refining techniques and highlight operational implications of using biofuels. Our focus is on drop-in fuels that can be used with full compatibility with the existing infrastructure.

So-called second-generation biofuels, derived from feedstock which is not in direct competition with human food crops or grown on areas suitable for human food crops, have addressed many of the sustainability concerns raised regarding first-generation biofuels (generated from human food crops such as corn). Typical feedstock currently considered for the use in the airline industry are jatropha curcas, camelina sativa and bio waste [Blakey et al., 2011]. These feedstocks can be converted into kerosene through different refining techniques. The two most commonly used to generate kerosene are a gasification process with a subsequent F-T reaction and the hydrotreatment of oil seeds. The former is mainly used to generate biofuels from wood waste or plants with high cellulosic content, where it is known as Biomass-to-Liquid (BtL) or XtL if other feedstocks are used. Hydrotreated Renewable Jetfuel (HRJ), in contrast, is generated by extracting the content of oil-rich seeds and the subsequent hydrotreatment of this extract. Figure 14 gives an overview of potential pathways for the production of biofuels [adapted from SWAFEA, 2011].

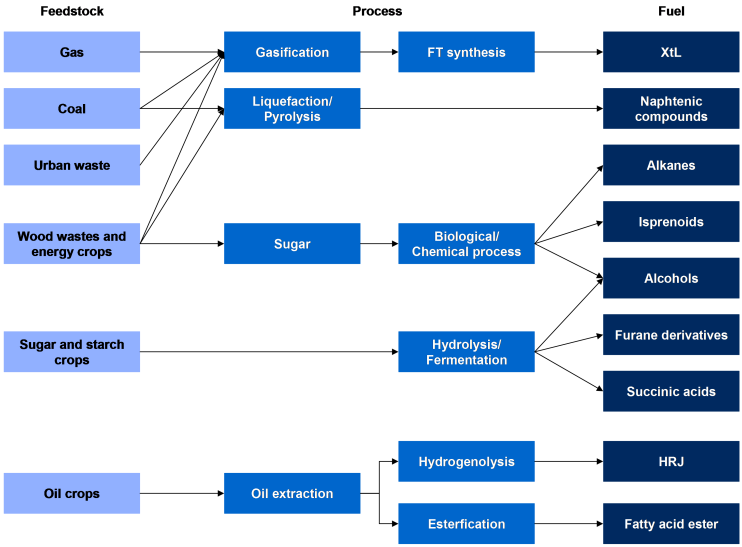

Figure 14: Pathways for aviation biofuel production

Third-generation biofuels, generated from algae feedstock, create a promising path due to the potential for very high oil yields. However, we assume no widespread adoption of these fuels before 2030 due to the current prohibitive cost levels as they are in the early stages of experimental production [Sun et al., 2011].

In our biofuel adaption model for the influence of the ETS, we do not model one specific technology. Currently, there is too much controversy regarding whether F-T or the hydrotreatment of oil seeds (or another technology/feedstock) will dominate the kerosene replacement market. While F-T is technologically more advanced and can utilize inexpensive feedstock, its refining technology is more capital intensive. HRJ, on the other hand, requires more expensive feedstock but is said to have more learning potential both in the refining process and the growing of feedstock and requires less capital intensive processing plants [IATA, 2010b, IEA, 2011]. The IATA does not see a clear winner and therefore suggests the support of all likely

technologies. In our model, we follow a similar approach and do not model one specific alternative fuel, but assign values both to initial costs and the suggested learning rate, matching both technologies. On the commercial application, there seems to be slight favor for HRJ in recent announcements for pilot projects [ICAO, 2011a].

In addition to technological and feedstock considerations, there are more practical problems encountered with the introduction of biofuels. One important step was the certification of both types of biofuels for the use in civil aviation, which has been granted in July 2011, for blends of up to 50 % with kerosene by the American Society for Testing and Materials (ASTM), a certifying body for aviation fuel [ASTM, 2011].

Lack of infrastructure and the development of a large scale supply chain is another concern. Given the early stages of the supply chain on one hand and the high demand of airlines for experimental flights, there is a significant shortage of biofuels on the world market leading to higher prices. A lack of dedicated biokerosene refineries presents a significant problem. Switching from biodiesel for automobiles to biokerosene currently causes significant downtime in the refineries, adding to the cost of biokerosene. Fuel tanking infrastructure is another problem, especially for carbon accounting; currently, only one infrastructure exists for the fueling of kerosene at most airports. As the amount of fuel tanked is used to calculate CO_2 emissions for the ETS, it is currently not straightforward to get credit for the usage of biofuels in the ETS. For current test flights, a separate fueling vehicle is used in contrast to underground fueling facilities on most European airports used for traditional kerosene. A current workaround for this problem is to deduct the amount of biofuel from the amount of kerosene purchased. However, this requires a verified report ("book and claim") by the fuel supplier [Roetger, 2011], and it adds significant cost.

In contrast to these problems of biofuel, there are a number of benefits. Biofuels have a higher energetic content [Blakey et al., 2011] and scheduled test flights have confirmed a better fuel burn. Further positive outcomes of scheduled test flights

are that demixing of biofuels does not occur in real life application and the fear of bacterial growth in biofuels was baseless.

Diffusion of new technologies such as biofuels can be supported in a number of ways by governments [e.g., Stoneman and David, 1986, Stoneman and Diederen, 1994, OECD, 1997, Blackman, 1999]. The most important levers are the following:

- Policy setting: New technologies can be become mandatory (or old technologies forbidden). In the realm of transport biofuels in the EU, the Renewable Energy Directive (RED) stipulates a mandatory share of 10 % of biofuel usage in the transport sector by 2020 [European Parliament and Council, 2009a]. There are no specific targets for aviation fuels, but aviation biofuels are credited towards the mandated quota.

- Financial support: Governments can directly support new technologies with subsidies through, for example, grants and loans or tax benefits.

- Awareness building and information dissemination: These measures enhance the flow of information of a new technology as information about new technologies is often imperfect [Stoneman and Diederen, 1994]. Possible ways to do this are information campaigns or pilot projects, proofing the technical viability of the new technology in question.

- Infrastructure: Providing the right infrastructure can be essential for technology diffusion. For biofuels, logistic infrastructure upstream of the refinery (i.e., improving road linkages to refineries from nearby feedstock fields) and distribution infrastructure at airports are possible measures.

There are two levers by which the aviation ETS can promote the usage of biofuels in the aviation industry: First, it lowers the price differential between the full cost of kerosene (kerosene plus a respective CO_2 price) and biofuels. Second, the proceeds from the ETS could be used by states to support the

deployment of biofuels financially. Airlines have lobbied for government support for biofuels. Their primary argument is as follows: Instead of draining the airline industry of financial resources for emission compliance, proceeds from the aviation ETS should be invested by the state into key technologies reducing aviation emissions [World Economic Forum, 2011]. With fiscal tightening in most European states currently under way, the outlook for such a subsidy looks bleak. Nevertheless, we want to show the benefits a subsidy could have on the introduction of biofuels. Therefore, we limit our analysis to a straightforward example of a subsidy (financial support for pilot bio refineries). Other designs for state support (e.g., direct fuel subsidy or tax benefits for biofuel usage) are certainly possible.

As we have shown, there are several ways of promoting the diffusion of biofuels. Consequently, we follow a two-pronged approach: First, we believe a certain share of government support for biofuels is either channeled into the general national budget or distributed undirected, such as for information campaigns, basic research or infrastructure measures. The impact of these measures is hard to quantify, and we therefore do not include it in our model. Second, the remaining funds are used for a specific policy intervention. In our model we choose to evaluate state help to build initial refining capacities for F-T-types of fuel in Europe up to the year 2020.

The reasoning for this specific intervention is that feedstocks for F-T pathways are far more likely to be grown in Europe than sun intensive oilseed, and they are also by far easier to transport over longer distances [Richard, 2010]. As our modeled support is paid out by European states, we assume that politicians want to keep as much as possible of the value chain within the states of Europe and therefore (in contrast to the rest of the paper, where we explicitly model an unspecific technology) choose F-T fuels as an object of state aid. Furthermore, F-T refineries are capital intensive, and this makes them a high risk investment for a single private investor, given the uncertainties of the new technology. For other biofuel production

pathways, it must be said, however, that similar consideration can apply for oilseed (or other technologies).

One point to note is that a state subsidy would, in fact, be counterproductive to the idea of an emission trading scheme, which allows participants to trade their allowances to reach a given emission reduction. However, there are ample examples of further policy instruments interacting with emission trading schemes, and Sorrell and Sijm [2003] find that, despite increasing overall abatement costs, market failures can justify a government intervention. In this article, we take this perspective of a market failure due to underinvestment for the modeling of state aid.

4.4 MODELING COST UNCERTAINTIES OF THE ETS AND THE IMPACT ON BIOFUEL ADOPTION

To assess the actual cost impact of the EU-aviation-ETS and the resulting use of biofuel usage in the airline industry, we employ a simulation model. The setup of the aviation ETS follows the implementing EU directive [European Parliament and Council, 2008] and the published figures thus far for the historical emissions, which other authors had to estimate. Our model includes input variables and dependent variables (which are dependent on the input variables). Figure 15 gives a schematic overview of the dependencies. In section 4.4.1 we will shortly explain the different scenarios we are examining: the influence of the aviation ETS on biofuel adoption and the benefits of state aid for the adoption of biofuels. Afterwards we introduce the independent variables in section 4.4.2, the dependent variables for different CO_2 pricing scenarios in section 4.4.3 and in section 4.4.4 the variables for the different support scenarios.

4.4.1 *Development of scenarios*

We generate three scenarios: The first is the base case, in which we model the aviation-ETS without biofuel usage. In the second scenario, biofuels are introduced and we compare the bio-

fuel usage under the implemented ETS against two other CO_2 pricing alternatives: A full CO_2 price (without free allocation) and no CO_2 price (the business-as-usual scenario). The third scenario is concerned with the question of whether proceeds from the ETS should be redistributed to the aviation sector via some kind of state aid. For this, we model a special case of state aid (financial support for bio refining capacity) under three support options: no support, moderate support and high support.

There are five main outputs of the model: (1) The net quantity of CO_2-allowances required by airlines, meaning required allowances minus free allocated allowances; (2) the cost of these allowances; (3) the biofuel usage with the actual CO_2 costs (taking into account free allocation as granted by the ETS); (4) The biofuel usage without and with full CO_2 costs for airlines; and (5) The biofuel usage with different levels of state aid. Outputs (1) and (2) are subdivided into two periods: 2012-2020 and 2021-2030. Subtracting (3) from (4) (i.e., comparing the scenario with the ETS as implemented and the other two CO_2 pricing scenarios) is the effect of additional biofuel usage promoted by the ETS (or the shortfall due to the full free allocation, respectively). The difference between (3) and (5) is the additional biofuel usage that could be promoted with state aid from the revenues of the ETS.

As we incorporate uncertainties in some of the input variables in our model we use a simulation model incorporating risk analysis software. In our study, all costs are given as real 2010 values.

We use the index y for variables dependent on the specific year. The base year for our analysis is 2010. If not otherwise stated, we discount the results of our financial estimates with an interest rate of 3.5% per year. We distinguish three different adoption rates, indexed with the index a. For no adoption the index takes the value 0, for the lowest adoption rate 1, for the moderate adoption it is 2 and for the high scenario 3. In our assessment, we use the index c to distinguish three scenarios for certain variables regarding whether the EU-Aviation-ETS does promote biofuel usage: The number 1 for the scenario with a

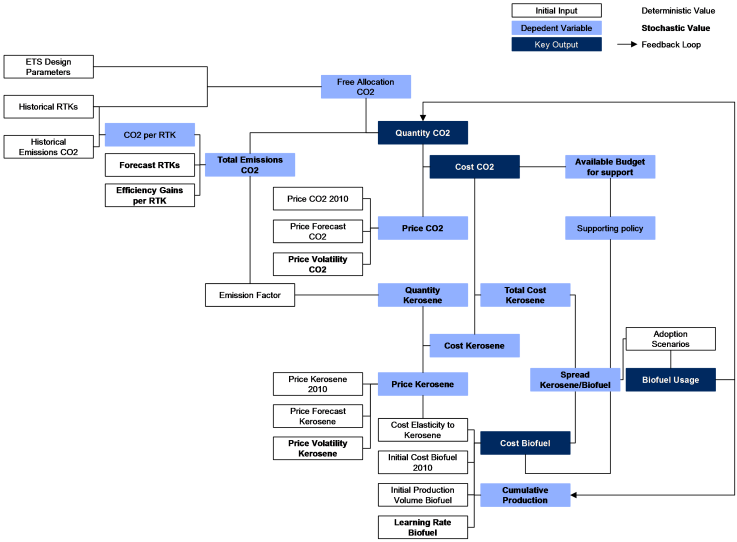

Figure 15: Independent and dependent variables

full CO_2 price (i.e., no free allocation as provisioned in the implementing directive), the number 2 for the scenario modeling the implemented ETS and the number 3 for no carbon dioxide price at all. We establish these scenarios to highlight whether a more stringent implementation would have promoted biofuel adoption and to show the effect of the current ETS versus a business-as-usual scenario. In section 4.4.4 we compare biofuel adoption with different support scenarios, should proceeds from the aviation ETS be redistributed to the aviation sector. We discern three scenarios with the index s: 1 for no support, 2 for moderate state aid and 3 for high support. Table 5 gives a summary of the indecies used.

4.4.2 *Input variables and data sources*

Variables in this section are introduced in alphabetical order.

Index	y	a	c	s
Meaning	Time	Adoption scenarios	CO_2 pricing scenario	State support scenario
Range of Values	2010-2030	0,1,2,3	1,2,3	1,2,3

Table 5: Indecies used

Adoption rates ($adop\_rate_{ya}$): We take values for adoption rates for three different scenarios (low, moderate and high) from a report for the United Kingdom's Committee on Climate Change [Bauen et al., 2009] and adjust the values for the 2020 time frame with the values we gathered from industry interviews. The values for adoption in each scenario are 0.2 % in 2020 and 1.4 % in 2030 for the low scenario, 5 % and 12 % in the moderate scenario and 10 % and 33 % in the high scenario. For values between these data points we use a logistic diffusion (also known as s-curve) function, a common model used for energy technologies [Grübler et al., 1999, Lund, 2006]. We fit a standard s-curve model to the given data by assuming the starting year 2010 and using the two data points given for each scenario. The formula used for the s-curve is shown in equation 9:

$$adop\_rate_{ya} = \frac{1}{1 + e^{\alpha_a (y - T_a)}} \tag{9}$$

Where α_a is a scenario specific scaling factor and T_a stands for the time in which 100 % market penetration is reached. Given equations 10 and 11 we determine α_a and T_a as follows:

$$\alpha_a = \frac{\ln\left(\frac{1}{adop\_rate_{2020a}} - 1\right) - \ln\left(\frac{1}{adop\_rate_{2030a}} - 1\right)}{2030 - 2020} \tag{10}$$

$$T_a = \frac{\ln\left(\frac{1}{adop\_rate_{2020a}} - 1\right)}{\alpha_a} + 2020 \tag{11}$$

Allowance prices (awp_y): We take current CO_2 prices from the European Energy Exchange (a value of about 14 Euros in 2011) and assume a normal distributed growth trend according to a forecast to 20 Euros per tonne in 2020 and to 38 Euros per tonne in 2030 [Schlesinger et al., 2011]. We estimate volatility from the period 2008 to 2011 (the second, more stable trading period for stationary emitters).

Cap reduction (cap_y), Auctioning share (auc_y) and Special reserve (spr_y): For the period 2012-2020 we set these values as demanded in the directive. This means a cap reduction of 3 % for 2012 (5 % for 2013 and the following years), a special reserve of 0 % for 2012 (3 % for 2013) and an auctioning share of 15 % for 2012 and 2013. In the directive, a review of these figures is postulated once the ETS is up and running. For the rest of the period until 2020, we assume no changes to these values, given the current turmoil around the ETS. For the year 2021, we assume no change to the special reserve, a cap reduction of 21 % compared to 2005 and an increase in the auctioning share to 50 %. The cap reduction would in this case be similar to the cap reduction for stationary emitters, and the auctioning share is comparable to competitive industries in the third trading period of stationary emitters, starting in 2013. Given aviation's global and competitive nature, we do not believe that free allocation will be reduced further.

Capital expenditure for bio refinery (capex_ref): Government support for the construction of a bio refinery is set to 200 million Euros. Investment costs for F-T bio refineries with a capacity of about 200,000 tonnes per year range between 250 and 400 million Euros [Anex et al., 2010, SAFN, 2011], thus, the required contribution from private investors would still be sizable.

Cost elasticity of biofuels (cost_ela): We assume the price of biofuels to be dependent on the price of crude oil to a certain extent. Research has shown that, especially for biofuel that can easy substitute traditional fuels (such as oil from rape seeds for the blending with diesel), there is a market dependency between renewables and crude oil [International Energy Agency, 2009]. The reason for this is that a higher crude price

triggers a higher demand for alternative fuels, thus increasing the costs for alternative fuels. For the two fuel types we are assuming in our model, the dependency on the crude oil price has been weak so far (but so have been production volumes). The IEA assumes two influences on the production costs of biofuels: One is the general increase in costs due to increases in input factor costs excluding feedstock: e.g., in processing energy costs. The second is an increase in feedstock costs. The effect of feedstock price due to rising crude oil prices is assumed to be moderate for F-T fuels and HRJ. We incorporate both factors with a factor capturing 5 % of the price changes of crude oil.

Crude oil prices (cop_y): Historical crude oil prices for West Texas Intermediate (WTI) until 2010 are taken from the IEA. We assume a normally distributed growth trend from 2010 prices (about 80 US Dollar per barrel) according to two forecasts: One for the year 2020 (at 105 US dollar per barrel) and one for 2030 (at 120 US dollar per barrel). These forecasts are the mid values of a recent forecast of Natural Resources Canada [2010]. These values provide the growth rates for the Brownian motion we are assuming for crude oil prices. We estimate volatility for the stochastic growth trend from a time series of the years 1990 to 2010, taken from the IEA.

Efficiency gains (eg_y): We assume airline fuel efficiency gains to be normally distributed and fluctuating around 1 % per year with a standard deviation of 2%, estimated from fuel burn figures time series per Revenue Tonne Kilometer (RTK) provided in the sustainability report of Lufthansa [Lufthansa Group, 2010b]. This means that future fuel burn per RTK is determined by a Brownian motion. The figure of 1% improvement is often cited in the literature [Wit, 2005, Vespermann and Wald, 2010]. Previous studies [e.g., Lee et al., 2001] estimated this figure to be higher, but they also showed diminishing values in recent years as airplane technology seems to mature. As a major advancement in aircraft technology is not expected before the mid-2020s and the time frame of our simulation ends in 2030, we leave the expected value at 1 % per year. We also intentionally set the value to the lower end of es-

timates, as we explicitly exclude biofuels from these efficiency gains (i.e., efficiency gains stem from e.g., new airplane technology, air traffic control or operational procedures).

Emission factor (efactor): Set to 3.15 tonnes CO_2 per tonne kerosene as defined in the EU Directive 2009/339/EC [European Parliament and Council, 2009b].

Exchange rate United States Dollar (USD)-EUR (exr_y): We assume a normal distributed exchange rate between US dollars and the Euro, having a mean value of 1.33 US dollars per Euro. This is the mean value for the year 2010, taken from a time series of the European Central Bank. We estimate the standard deviation of this stochastic parameter from the same source over a time frame of 20 years. The exchange rate is used where market prices are predominantly quoted in US dollars. This is the case for crude oil (and thus kerosene) and biofuel feedstock prices. To simplify notation, we do not show the exchange rate in the further process, but simply convert all prices to Euros where applicable.

Historical emissions (he_y): Historical emissions for the EU-27 were published by the EU Commission on March 7, 2011. The values are 209,123,385 for 2004, 220,703,342 for 2005 and 228,602,103 for 2006. The average therefore for the years 2004-2006 is 219,476,343 tonnes of CO_2 [Comission of the European Communities, 2011]. On July 20, a revised average figure for the European Free Trade Area (EU-27 plus Norway and Iceland) was published, setting the yearly average to 221,420,279 [EEA Joint Committee, 2011]. We adjust the figure for the emissions in 2006 of the EU-27 slightly by adding 0.88 % (the addition by the newly published average compared with the old average).

Initial Biofuel costs (init_bfc): We assume initial biofuel costs to be about 1400 Euros per tonne (or 1.13 Euros per liter). Currently, there is no transparent market for biofuel prices. We therefore estimate current prices from two data points: one from publicly announced statements and industry sources reflecting current market prices, the other from technical reports, mostly relying on bottom-up cost estimates. Our price is at the lower end of the first sources and at the upper end of the sec-

ond sources. For the first, we take a value from a statement from Lufthansa about their first regular biofuel test flights, where the price of the used biofuel is said to "be closer to 2,000 Euros per tonne than to 3,000 Euros" [Gourlay et al., 2011]. Similar values for early production volumes were given by our industry experts. It has to be noted, though, that these prices are driven up in part by production shortages. As the production cost of biofuel is treated as confidential by producers and consumers at the moment, we rely also on a second set of sources. For example, our value falls in line with a recent study conducted by the IATA [IATA, 2010b], which shows that the BtL and HRJ stand on average at about 1.2 Euros per liter. Similar values are found by other sources [e.g., Caldecott and Tooze, 2009, IEA, 2011, Graham et al., 2011]. Note that this value fits both Fischer-Tropsch types of fuels and HRJ fuels. To put this value into perspective, kerosene cost per tonne was about 550 Euros in 2010.

Initial production volume biofuels (init_vol_bf): As produced volumes so far are very low, compared to traditional fuels, there is no official monitoring of production volumes. We take the following approach: First, we limit our research to two main feedstock types currently in the discussion for aviation biofuels: jatropha and camelina. Where available, we collect direct production volumes (for camelina we take production volumes from the state of Montana, the leading producer of camelina). Additionally, where these figures are unavailable we collect acreage figures and convert them with typical oil yields [for jatropha: GEXSI, 2008, Reinhardt et al., 2008] into production volumes, accounting also for about 15% volume loss during the refining process. Taking all these figures together, we estimate the cumulative initial production volume to be about 82,000 tonnes of bio jet fuel in 2010.

Level of support ($level_s$): For our different scenarios of state aid, we assume three different levels of support: No state aid, the use of 50% of the available budget after unspecific measures for the support of bio refineries for the moderate support and 100% of the available budget after unspecific measures for the high support scenario.

Progress rate biofuel costs (pr_bfc_y): Progress ratio (PR) represents the cost reductions, if cumulative output doubles [Yelle, 1979]. A PR of 10 % means, should cumulative output double, a cost reduction of 10 % . PRs for biofuels and other renewable technologies have been assessed by a number of authors [Neij, 1997, de Wit et al., 2010, Weiss et al., 2010]. We assume a normally distributed PR of 6 % fluctuating with a standard deviation of 3%, accounting for variability in the progress ratio.

Reduction of biofuel price with state aid (red_aid): State aid should trigger a reduction in biofuel costs. As capital costs for an F-T type of refinery are among the most significant cost drivers, we assume a cost reduction of the current level by 15 %. This is reflects the share of capital expenditures for F-T fuels and the level of state support [SWAFEA, 2011].

Refining Capacity (ref_capa): Refining capacity of the state aid refineries is set to 200,000 tonnes of output per year. This reflects an industrial size F-T plant [Maniatis et al., 2011] as currently envisioned.

Revenue tonne kilometer (rtk_y): We take data from Boeing Commercial Airplanes [2010a] for RPK for civil commercial aviation from the Europe segment and data from the AEA for civil (scheduled and chartered) cargo aviation for RTK. RPKs are converted into RTKs by using a fixed weight of 100 kg per passenger (including baggage), an industry standard value and also provisioned in the directive. Exemptions granted by the ETS are taken into account by subtracting a share of 3 %. To account for deviations from the great circle distance, we add 6 % to the RTK figure. This yields a value of about 297 billion RTK in 2010, the benchmarking base year for the period 2012-2020. We take forecasts for the mean of market growth from Boeing Commercial Airplanes [2010a], the passenger forecast, and Boeing Commercial Airplanes [2010b], the cargo forecast. For passenger traffic, this means an annual growth rate of about 2.5 % per year; for cargo traffic the figure is 4.7 % for traffic to and from Europe. These figures are matched broadly by a similar source from Airbus S.A.S. [2009]. We model market growth as randomly distributed with the above means and

variance estimated from historical RTK figures. To account for a significant correlation (correlation coefficients of 0.92 and 0.84 for passenger and freight growth, respectively) between crude oil price changes and market growth, we correlate the growth rates with a correlation matrix.

Spread kerosene-crude oil (skc_y): We assume the refining spread between kerosene and crude oil to be normally distributed around 123 % and a standard deviation of about 9 %. Data is taken from the IEA time series of crude oil and kerosene from the years 1990 to 2010.

Unspecific state aid (unsp): We reduce the budget generated from the auctioned-off allowance by an unspecific state aid. This can be thought of either as unspecific policy measures such as basic research and information campaigns or as a reduction of state aid. This would imply that proceeds from the auctioning are used in the general fiscal policy. We set this share to 50 %.

Upper and lower bounds for adoption rates ($ubound_a$ and $lbound_a$): To distinguish between the different adoption rate scenarios, we introduce upper and lower bounds for each scenario. These bounds relate to the spread $spread\_bf_{yc}$ between traditional kerosene plus the respective price of CO_2 and the cost of biofuel. For spreads below 0 % (i.e., biofuel cost that is the same as the full cost of kerosene) we assume a high adoption scenario, for equal or less than 20 %, but above 0 % the scenario is moderate and between 150 % and 20 % spread, adoption is low. For spreads above 150 %, we assume no biofuel adoption at all, as this seems to be the cut off, where limited testing begins as demonstrated by recent regular test flights [Learmount, 2011].

4.4.3 *Dependent variables for CO2 pricing scenarios*

Variables in this section are introduced in the order in which their calculation is required to reach our final result – the adoption of biofuels. We therefore explain the calculation for each required dependent variable and simply refer to previous intermediate steps in later stages of the calculation.

VARIABLE	2012	2013-2020	2021-2030	COMMENT
cap_y	3%	5%	21%	In line with reduction planned for IV. EU-ETS-phase
auc_y	15%	15%	50%	In line with share for competitive industries in III. EU-ETS-phase
spr_y	0%	3%	3%	No increase for special reserve

Table 6: Auctioning share, special reserve and cap reduction

Benchmarking value (b_{yc}): We calculate the benchmark, used for free allocation, as stipulated in the directive. The calculation is shown in formula 12

$$b_{yc} = \frac{\frac{1}{3}\sum_{y=2004}^{Y=2006} he_y \left(1 - cap_y\right)\left(1 - auc_y\right)\left(1 - spr_y\right)}{RTK_b} \tag{12}$$

RTK_b is the number of RTKs in the respective benchmarking year. For the periods 2012 and 2013-2020 this is the year 2010. We assume a similar process for the period post 2020 and therefore set RTK_b for the period 2021-2030 to 2019. Values for cap_y, auc_y and spr_y are assumed as shown in Table 6.

Total emissions (em_y): Total emissions are calculated in the following way: We divide the historical emission (he_{2006}) by the total number of RTKs in the respective year (RTK_{2006}). This gives a figure of CO_2 emissions per RTK. We then subtract yearly efficiency gains from this historical figure to update this value for each year in the future. We then multiply this value with the RTKs of the respective year to calculate the total emissions for this year.

$$em_y = \frac{he_{2006}}{RTK_{2006}}(1 - eg_y)^{y-2006} \times RTK_y \tag{13}$$

Emissions after biofuel usage (em_bf_{yc}): We calculate total emissions for all airlines after the usage of biofuel (under the assumption - as provisioned in the directive - that biofuels do not count towards CO_2 emissions) by subtracting the share of biofuel usage from the total emissions:

$$em\_bf_{yc} = em_y \left(1 - bf\_share_{yc}\right) \tag{14}$$

Free allocation (fa_{yc}): Free allocation is simply the respective benchmarking value multiplied by the number of RTKs of an individual airline. As we are concerned with an overall industry perspective, we multiply with industry-wide RTKs (basically, eliminating the value of RTK_b):

$$fa_{yc} = \frac{1}{3} \sum_{y=2004}^{Y=2006} he_y \left(1 - cap_y\right) \left(1 - auc_y\right) \left(1 - spr_y\right) \tag{15}$$

Net exposure (exp_{yc}): Net exposure is defined as emissions after biofuel usage in a given year minus the free allocation, giving the actual allowances, which need to be bought in addition to the free allocation. Thus, $exp_{yc} = em\_bf_{yc} - fa_{yc}$.

Actual allowance prices (ac_awp_{yc}): We weight the allowance price awp_y with $\frac{exp_{yc}}{em_y}$, the proportion of allowances required to be bought on the market. This means that the average allowance price is reduced by the freely allocated portion. Obviously, for the scenario n with no price for CO_2, we set $ac\_awp_{yc} = 0$.

$$ac\_awp_{yc} = awp_y \frac{exp_{yc}}{em\_bf_{yc}} \tag{16}$$

Kerosene costs (ker_y): Kerosene costs are a result of the crude price and the refining spread between crude and kerosene, thus $ker_y = cop_y \times skc_y$.

Total kerosene costs ($total\_ker_{yc}$): Actual kerosene costs are determined by kerosene costs and actual allowances costs multiplied with the emission factor: $total\_ker_{yc} = ker_y + efactor \times ac\_awp_{yc}$

Spread traditional fuel versus biofuel ($spread\_bf_{yc}$): The speed of our adoption is based on the spread between the cost of biofuel and the costs of kerosene plus cost of CO_2 multiplied

with the emission factor. This compares the costs of biofuel with the full cost of kerosene, accounting for the CO_2 emissions. We express the spread as a percentage compared to kerosene.

$$spread\_bf_{yc} = bfc_{yc} / total\_ker_{yc} - 1 \tag{17}$$

Biofuel costs (bfc_{yc}): Biofuel costs are assumed to follow a cost decrease in the cumulative production volume given by the PR and the cumulative production in relation to the initial production volume. The initial biofuel cost $init\_bfc$ decreases with additional cumulative production. We use a version of the experience curve [Hax and Majluf, 1982] that accounts for initial cumulative volumes. In addition, we incorporate the dependency on the price change of crude oil with the cost elasticity $cost\_ela$ and the change in crude oil prices compared to the base year ($cop_y / cop_{2010} - 1$). Thus, biofuel costs evolve according to equation 18

$$\begin{aligned} bfc_{yc} \quad = \quad & init\_bfc \left(\frac{cum\_vol\_bf_{yc}}{init\_vol\_bf} \right)^{\left(\frac{\lg(1-PR_y)}{\lg 2} \right)} \times \\ & \left(1 + cost\_ela \times \left(\frac{cop_y}{cop_{2010}} - 1 \right) \right) \end{aligned} \tag{18}$$

Volume biofuels (vol_bf_{yc}): Volumes for biofuels are the total kerosene demand in tonnes (derived over CO_2 emissions) multiplied by the respective share of biofuels: $vol\_bf_{yc} = \frac{em_y}{efactor} \times bf\_share_{yc}$

Cumulative volume biofuels ($cum\_vol\_bf_{yc}$): Cumulative volumes of biofuels are added up for each year. It is assumed that consumed volumes equal produced volumes in the long term. For the base year 2010, $cum\_vol\_bf_{2010c} = init\_vol\_bf$.

$$cum\_vol\_bf_{yc} = \sum_{y=2010}^{Y} vol\_bf_{yc} \tag{19}$$

Share of biofuel usage (bf_share_{yc}): As the scenarios of biofuel adoption introduced previously are defined for large bounds, we adjust the original adoption rates $adop\_rate_{ya}$ within the given bounds to make them more susceptible to price changes. With the proposed adjustments, the full adoption rate is only achieved when the lower bound of the given scenario is reached

(where, in turn, another scaling happens for the more progressive scenario).

$$bf\_share_{yc} = adop\_rate_{ya} - \frac{spread\_bf_{yc} - ubound_a}{lbound_a - ubound_a}\left(adop\_rate_{ya} - adop\_rate_{ya-1}\right) \tag{20}$$

4.4.4 *Dependent variables for state aid scenarios*

We are also concerned with the question of whether the ETS can open up funds for state aid for the biofuels industry. We answer this question under the implemented CO_2 price. Consequently, index c is dropped for these results and replaced with index s, where applicable. For the sake of brevity, we do not explain all dependent variables again but rather highlight significant differences in this section. Again, variables are introduced in their order of calculation.

Support budget (sup_budget): The potential budget for state aid is derived from the auctioning of EUAAs. Therefore, it is calculated by subtracting both the cap reduction cap_y and the special reserve spr_y (we assume a full allocation of the special reserve and therefore no auctioning of surplus allowances in the special reserve) from the historical emissions. This value is then multiplied with the current CO_2 price awp_y. Differences between auctioned allowances and allowances traded on the secondary market are negligible for EUAs (below 1 %) and we assume a similar development for EUAAs. Furthermore, the support budget is determined by the share of unspecific use of funds (such as basic research) and the chosen level of support (no support, 50% and 100%):

$$sup\_budget_y = \left(\frac{1}{3}\sum_{y=2004}^{Y=2006} he_y\left(1-cap_y\right)\left(1-spr_y\right)\times auc_y\left(1-unsp\right)level\_sup_s\right)awp_y \tag{21}$$

Available budget (av_budget): The available budget is determined by the proceeds from the support budget, the costs of

refineries built and the carryover budget from the previous period. For the first two years (2010 and 2011) there is of course no budget carried over, as auctioning of allowances starts in 2012.

$$av\_budget_{ys} = av\_budget_{y-1} + sup\_budget_{y} - no\_ref_{y} \times capex\_ref \tag{22}$$

Number of refineries (no_ref): The number of refineries to be constructed is dependent on the cost of a refinery and the available budget. We assume that, if there is not enough budget for a full refinery the available funds are carried over to the next year and only integer number of refineries will be built (thus the use of the floor function in Equation 23). We assume a time lag of two years for a refinery to be fully operational.

$$no\_ref_{ys} = \begin{cases} \left\lfloor \frac{av\_budget_{y-2}}{capex\_ref} \right\rfloor & for\ av\_budget_{y-2} \geq capex\_ref \\ 0 & for\ av\_budget_{y-2} < capex\_ref \end{cases} \tag{23}$$

Available refining capacity (cum_cap_{ys}): Available refining capacity is the sum of all refineries built up to the current year multiplied by the capacity of a refinery. As refineries have an economic life of around 20 years, we assume no refinery shut downs in our time frame from 2012-2030.

$$cum\_cap_{ys} = \sum_{y=2010}^{y} no\_ref_{ys} \times ref\_capa \tag{24}$$

Biofuel costs (bfc_{ys}) and biofuel costs after subsidy (bfc_sup_{ys}): Biofuel costs develop similarly to the previous section.

$$bfc_{ys} = init\_bfc \left(\frac{cum\_vol\_bf_{ys}}{init\_vol\_bf} \right)^{\left(\frac{\lg(1-PR_y)}{\lg 2} \right)} \times \left(1 + cost\_ela \times \left(\frac{cop_y}{cop_{2010}} - 1 \right) \right) \tag{25}$$

If installed refining capacity is greater or equal to biofuel demand, the cost of biofuel is reduced by the reduction factor of the state aid *red_aid*. If refining biofuel demand exceeds

installed capacities, volumes up to the refining capacity are produced at reduced prices and volumes exceeding it are produced at unsubsidized prices. Thus, biofuel costs evolve according to equation 26.

$$bfc\_sup_{ys} = \begin{cases} cum\_cap_{ys} bfc_{ys} \, (1 - red\_aid) + bfc_{ys} \\ \left(\frac{em_{ys}}{efactor} \times bf\_share_{ys} - cum\_cap_{ys} \right) \\ \text{for } cum\_cap_{ys} < vol\_bf_{ys} \\ bfc_{ys} \times (1 - red\_aid) \\ \text{for } cum\_cap_{ys} \geq vol\_bf_{ys} \end{cases} \tag{26}$$

4.5 RESULTS

In this section we present the results of our simulation model. There are three main result sections: First, results for CO_2 quantities and its associated costs without biofuel usage are given. We stress the importance of quantity risk associated with the aviation-ETS and the resulting risk profile without biofuel use. Second, we show results for the usage of biofuels. Here we show whether the ETS does significantly influence the adoption of biofuels in the aviation industry and how its usage transforms the risk profile. Third, we compare the finding of section 4.5.2 with two different scenarios: One is a scenario in which the full CO_2 price is required to be paid and the other is a scenario without a CO_2 price. By comparing these scenarios, we find out whether the ETS promotes biofuel usage and by how much it falls short of a more stringent implementation (without free allocation). Lastly, we compare different state aid scenarios: A scenario with no support, a scenario with moderate support and a scenario with high support from the proceedings of the aviation ETS.

4.5.1 *Results for CO2 quantities and CO2 costs without biofuel usage*

Our resulting benchmark value for the free allocation of allowances for the year 2012 is about 0.62 kgCO_2/RTK and for 2013 about 0.59 kgCO_2/RTK[1]. For the third period starting in 2021, we find a value of about 0.21 kgCO_2/RTK. The stark decrease in the benchmarking value is driven by three main factors: First, the increase in the reduction cap. Second, the increase in the auctioning share (both factors bringing the aviation ETS in line with the ETS for stationary emitters) and third, the forecast increase in RTKs up to 2019.

The mean net exposure (exp_{yc}) for CO_2 emissions is about 96 million tonnes CO_2 per year for the period 2012-2020. In the period 2021-2030, the figure rises to about 254 million tonnes CO_2 per year. Over time, emissions increase due to the assumed growth in air traffic and thus the share of the free allocation of the ETS decreases (see Figure 16). There are two jumps in the free allocation (the lighter shade): The first, from 2012 to 2013, is triggered by the further cap reduction to 95 % of historical emissions and the introduction of the special reserve of 3 %. There is another jump for the period starting 2021, as we assume a further cap reduction and an increase in the auctioning share for this period. Costs for these CO_2 emissions are, on average, about 1.3 billion Euros per year for the period 2012-2020 and a considerable 3.9 billion Euros per year for the period 2021-2030. This stark increase in emission costs is driven by the reduced free allocation and an increase in the CO_2 price per tonne. For comparison, IATA forecasts a worldwide profit for airlines of about 2.8 billion Euros in 2011 (most of which in the less-affected Asian region) [IATA, 2011a], highlighting the urgency for airlines to adapt to carbon costs in an industry with low profit margins [Oum and Yu, 1998].

1 Scheelhaase et al. [2010] find a values between 0.58 and 0.61 and Vespermann and Wald [2010] find a value of 0.68

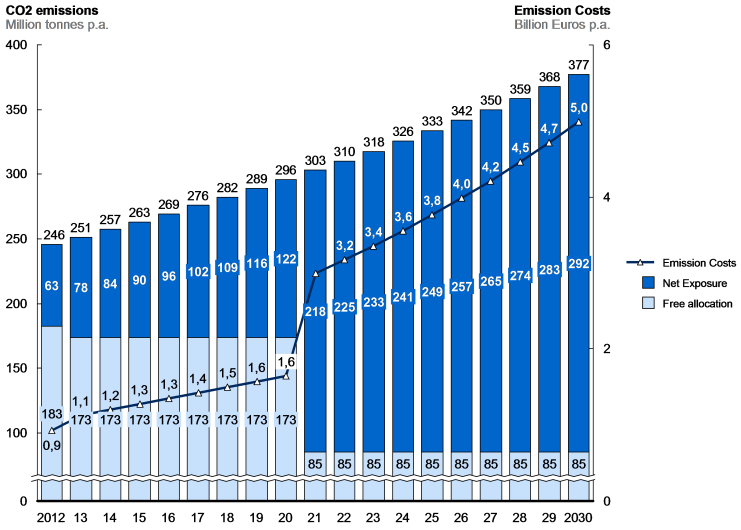

Figure 16: CO_2 emissions and free allocation

We briefly note the uncertainties associated with the CO_2 emission cost[2]. Therefore, we show risk profiles for average costs and net exposures of CO_2 in Figure 17 for each period. These risk profiles show the results of our simulation model both in the probability density function (the dark bars) and the cumulative probability function (the ascending line). Due to the assumed uncertainties in the input variables, the required allowances fluctuate around the previously stated mean of 95.6 million tonnes CO_2 (253.7 for 2021-2030) and the costs around 1.3 billion Euros (3.9 for 2021-2030). Figure 17 shows on the left-hand graphs that 90 % of the results for required allowances range between 54 and 136 million tonnes in the period 2012-2020 (179-337 million for 2021-2030). The actual CO_2 costs for these allowances does show a lot more uncertainty.

2 We believe a sound knowledge about CO_2 quantities and CO_2 costs is the main starting point for a financial hedging strategy. As this is clearly out of the scope of this article we only report the results we recorded in the process of determining our main research goal, the adoption of biofuels.

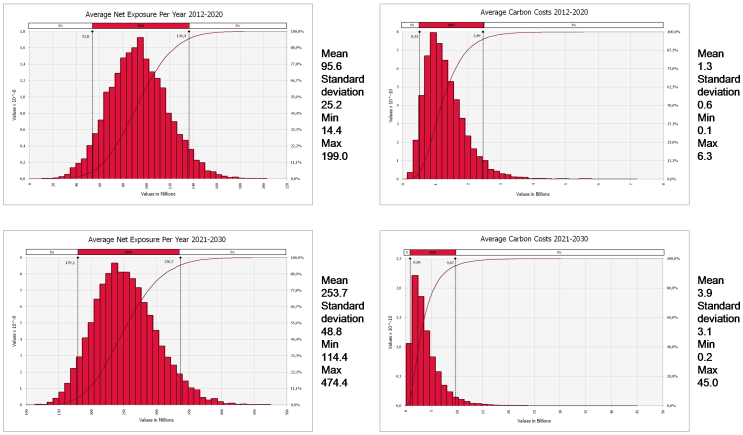

Figure 17: Risk profile net exposure and CO_2 costs

Figure 17 shows on the right-hand graphs that 90 % of the results for CO_2 costs range between 0.6 and 2.5 billion Euros for the period 2012-2020 (0.9 - 9.7 billion for 2021-2030).

The main drivers for the net exposure are found in the growth rates for passenger and cargo transport, a result also confirmed by Vespermann and Wald [2010]. For the actual costs of the required emissions, the allowance price shows the largest influence (along with the transport growth rates as stated above). This helps to explain the large variability that can be seen in the results: Our volatility assumption for the CO_2 price is, at about 20 %, rather high and thus significantly drives the risk profile of CO_2 costs.

In the next section we will analyze whether biofuel usage is promoted by the aviation-ETS and whether biofuel usage is a possible mitigation strategy for carbon cost uncertainties.

4.5.2 *Results for the usage of biofuels induced by the ETS*

Biofuels are counted with a zero-emission factor in the aviation-ETS. For CO_2-emission, we are assuming an ETS-logic of counting CO_2-emissions (which is the relevant logic when assessing financial impacts and, consequently, its implications for biofuel usage). These CO_2-emissions may be lower than actual CO_2-emission due to full life cycle emissions of biofuels.

Figure 18 shows the CO_2 emissions with biofuel usage as triggered by the aviation-ETS. The net exposure after free allocation (medium shade) shows a significant emissions reduction compared to the business-as-usual scenario without biofuel usage (dark shade). Indeed, our model shows a carbon-neutral growth for aviation in the EU from the year 2026 onwards with the usage of biofuels. This is a couple of more years than the goal set out by IATA for carbon neutral growth from 2020 onwards [IATA, 2009]. Around the year 2028, our model shows a significant reduction in CO_2-emissions of airlines due to widespread adoption of biofuels once cost parity has been reached. In the final year of our simulation, biofuels have reached a 33 % share, reaching the full high scenario introduced above. Over the simulated time frame, about 169 million tonnes of biofuels are used, resulting in a cumulative CO_2 reduction of about 531 million tonnes (or roughly 9.1 % over the total time frame). Emission costs for CO_2 decrease accordingly: Total emission costs are reduced by about 8.5 billion Euro or about 17 % compared to the scenario without biofuels.

Worth to note, however, is that a reduction in CO_2 costs is "bought" with biofuels. Once biofuels have reached cost parity, it is unclear if the actual price will be lower than the total cost of traditional kerosene. Instead, producers of biofuels could price their products on par with kerosene. Pricing biofuels on par with traditional fuels plus the respective CO_2 price opens up additional profit margins for producers, if biofuel prices would fall below the price of traditional fuels. This, according to basic economic theory, would attract additional producers and bring down prices.

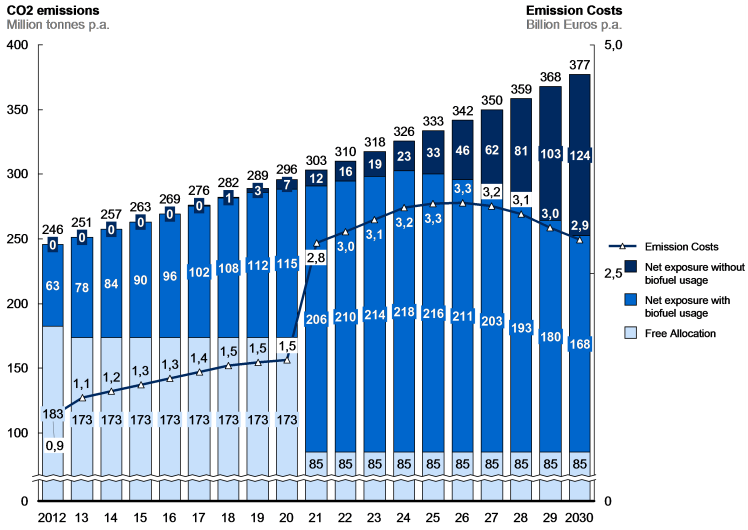

Figure 18: CO_2 emissions and free allocation with biofuel usage

We do not address this problem here explicitly, but state shortly the implications such a pricing tactic could have. As we assume in our model a moderate adoption of biofuels with biofuels prices higher than kerosene, in the end, airlines would pay more for their biofuel usage should prices of biofuels not fall below the total cost of kerosene $total\_ker_{yc}$. If this is indeed the case, airlines would pay 720 million Euros on average more per year for the early adoption of biofuels or 1.3 % of total fuel costs. Should prices fall below the price of kerosene and CO_2 (due the assumed learning rate) they could save about 620 million Euros (-1.1 % of total fuel costs) over both periods per year. In the remainder of the paper we follow the learning curve model that illustrates potential production cost decreases (i.e., biofuel prices can fall below the level of the full cost of kerosene).

As discussed in the context of emission volumes, the mean values do not give a measure for the uncertainty associated with the aviation ETS. We present risk profiles for the net ex-

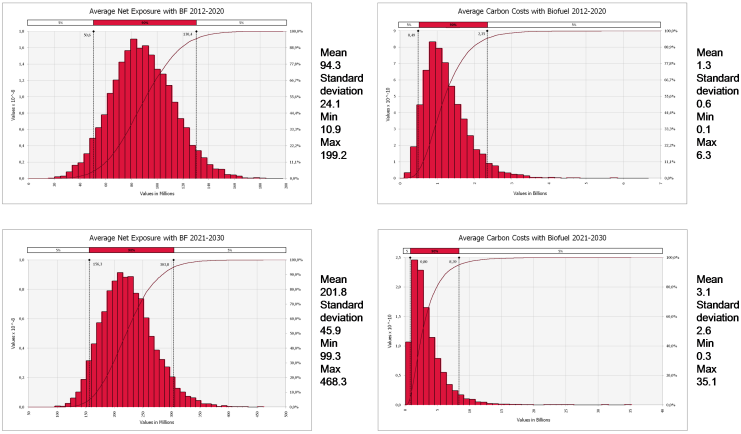

Figure 19: Risk profile net exposure and CO_2 costs with biofuel usage

posure and the CO_2 costs in Figure 19. In the first period until 2020, the impact of biofuels is rather limited. Consequently, the risk profile does not change by a meaningful measure. However, in the period 2021-2030, the net exposure decreases on average from 253 million tonnes to 202 million tonnes CO_2. Similarly, the 90 % range narrows down to 148 million tonnes (156-304) versus 158 without biofuel usage (337-179). As expected, the cost of the net exposure decreases in the mean from 3.9 to 3.1 billion Euros.

Cost parity with traditional kerosene plus the relevant CO_2-emission costs is the key for widespread adoption of biofuels. Cost development for traditional fuel is driven by two factors: First, kerosene prices increase with the assumed price growth of crude oil, and second, actual CO_2 prices are added to traditional kerosene. CO_2 prices are driven by free allocation (diluting the market price of CO_2) and assumed increases in the price of CO_2. Among the main drivers behind cumulative biofuel usage, the kerosene price and its growth trend are

the most important. Clearly, kerosene represents a far larger portion of total kerosene costs (about 550 Euros for kerosene versus about 48 Euros per tonne CO_2 per tonne kerosene in 2010). Biofuels, on the other hand, are driven by learning curve effects (triggered by increased cumulative production volumes) and partly driven up by the cost elasticity biofuels exhibit to the crude oil price change. According to our model, cost parity is reached around the year 2024. Consequently, widespread usage is reached after this point.

In the next section we will assess whether the implemented ETS does promoted biofuel usage compared with no CO_2 price and whether biofuel usage would have been higher with full CO_2 prices (no free allocation).

4.5.3 *Comparison with other CO2 pricing alternatives*

The question of whether the aviation-ETS does promote biofuel usage can only be answered when comparing the implemented scheme with different alternatives. As we are focusing our research on the aviation-ETS and thus the costs of CO_2, we propose two alternative scenarios: First, a scenario in which CO_2 would have no cost (as it was the case for airlines in the EU until the start of the aviation-ETS and will remain the norm for most of the world outside of the EU in the coming years), and second, a scenario with full CO_2 price as assumed above, but without the free allocation given by the ETS.

Our first comparison approaches the usage of biofuels under the three different scenarios. Figure 20 depicts the adoption curves. A full CO_2 price promotes biofuel usage, especially in the first years as compared to the implemented ETS. In contrast, biofuel usage under the scenario without a CO_2 price falls significantly and does not keep up with the other two scenarios. The cumulative usage over the simulated period biofuel under the base case, the scenario without a CO_2 price is about 126 million tonnes. This compares to 169 million tonnes for the actual CO_2 price and 195 million tonnes for the full CO_2 price. In terms of emissions reduction, the ETS does show a CO_2 reduction of about 33 %, and the full CO_2 price

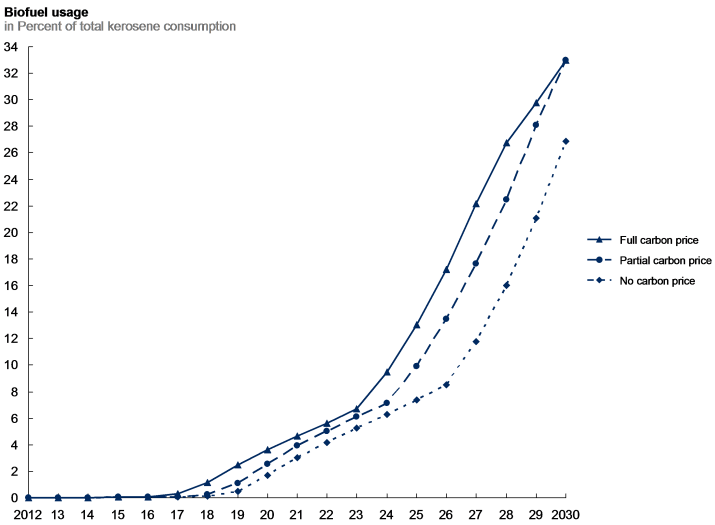

Figure 20: Adoption curves biofuels with CO_2 pricing alternatives

would have reduced emissions by a further 16 % compared to a world without CO_2 price.

There are two drivers for these results: First, a higher CO_2 price does reduce the premium paid for biofuels in comparison with kerosene. Second, a lower price differential promotes biofuel usage earlier on and, consequently, leads to faster cost reduction via learning effects. Figure 21 depicts the points of cost parity for the three scenarios. In the full CO_2 price scenario, the kerosene price is the highest of the three scenarios. As a consequence, more biofuel is used in early stages of the simulation, which leads to cost reductions and faster cost parity. For the scenario without CO_2 price, the opposite can be said. Cost parity with the full CO_2 price is reached around the year 2022, about one year before the scenario with the actual CO_2 price. Cost parity without a CO_2 price happens three years later, in 2026. To sum up, the aviation-ETS has positive influences on the adoption of biofuels. However, additional costs for CO_2, when compared with the costs for kerosene, do only

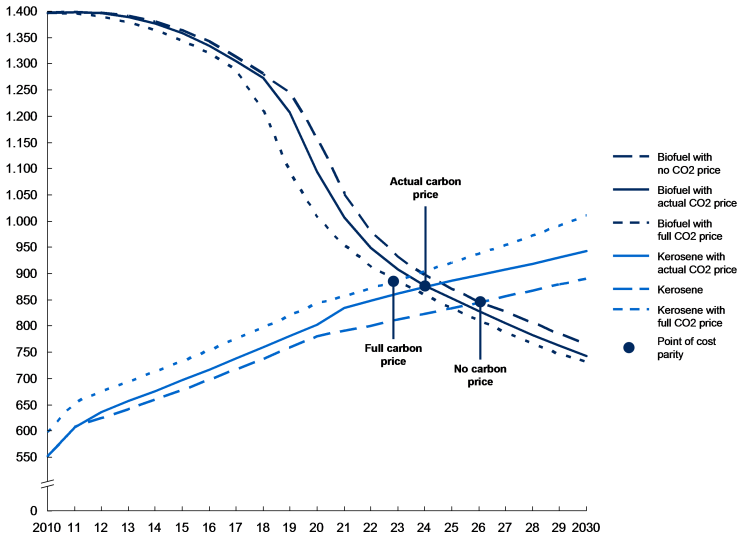

Figure 21: Points of cost parity with CO_2 pricing alternatives

have a limited influence on the decisions regarding biofuel adoption.

4.5.4 *Supporting the diffusion of biofuels with proceeds from the ETS*

Next to the effect of a reduced differential between traditional kerosene and biofuels, the ETS could have another effect on the promotion of biofuels: Funds generated from the ETS-auctions could be used by governments to support biofuel adoption.

We model one specific policy intervention in which the state supports constructions of capital intensive bio refineries, which constitute a significant cost proportion of F-T type of biofuels. Our model is based on the use of 50 % of ETS-auctioning revenues to be used as a stimulus for biofuels (the other 50 % can either be used for austerity measures or be used for undirected supporting measures). For the high support scenario, 100 %

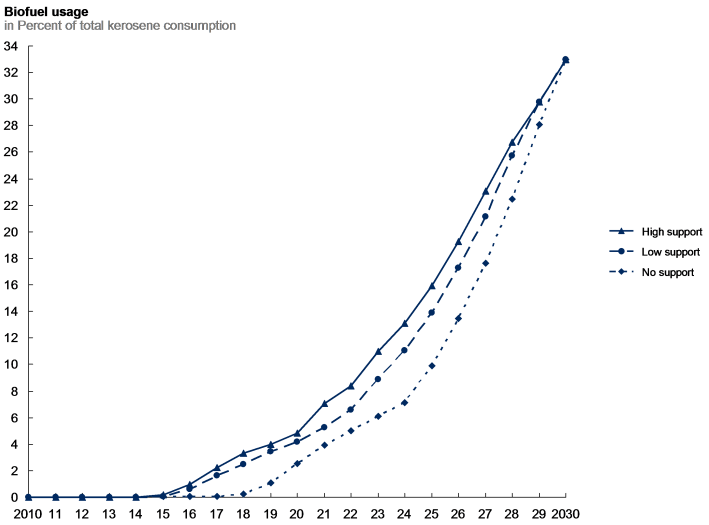

Figure 22: Adoption curves biofuels with state aid

of the remainder is used (50 % for the moderate scenario and 0 % for the "no support" scenario).

Adoption rates with state aid are consistently higher than with no support, as can be seen in Figure 22. Of note is that adoption rates with moderate support are almost as high as those for the high-support scenario. Government support can be key for the early adoption up to the year 2020, during which adoption with support lies between 4 and 5 %, while the curve with no support stands at half of the value. As we assume a fixed high uptake scenario of 33 % biofuel in 2030, the adoption rates of the different scenarios converge. Cumulative volumes over the modeled time frame are about 20 % and 31 % higher for the moderate- and high-support scenarios.

Price parity with high support is reached around the year 2020, with moderate support one year later and no support around 2024. Figure 23 shows the points of cost parity. With high support, about 12 refineries with a total capacity of around

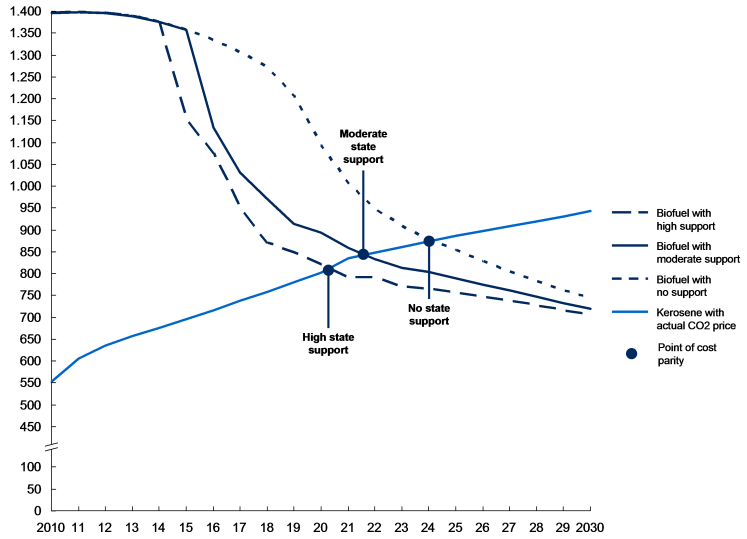

Figure 23: Points of cost parity with state aid

4.8 million tonnes are built up to the year 2022 (with no support after 2020, but a time lag for construction of two years). This figure goes down to 6 refineries and a refining capacity of 2.4 million tonnes p.a. for the moderate support scenario. Most significant for cost parity are the first refineries, which is reflected in the sharp dent in Figure 23 in 2014 (2015 respectively for moderate support). In early years, biofuel prices are high due to limited learning curve effects (therefore, our assumed reduction of 15 % has a larger impact), and full demand can be covered by the supported refineries. In later years, demand outstrips the capacities supported by the state and, consequently, price decreases due to the subsidy are no longer as significant.

What are the public costs of such a policy? In the high-support scenario, in which 12 refineries are built, the cost is 1.9 billion Euros (0.9 billion Euros for moderate support). Not included in this figure would be the 50 % share of undirected support, which could total 8.5 billion Euros for the full period

of 2012-2030 (or 1.9 billion up to 2020). At about 26 Euro per saved tonne CO_2 (35 Euro per tonne for the high scenario), the support is not competitive with current prices for CO_2. Still, this is a lot cheaper than other measures such as some renewable energy policies [Sorrell and Sijm, 2003].

4.5.5 *Limitations of the research*

In our simulation model we have used the most reliable sources and methods available to us. However, there are some parameters, such as the current costs for biofuel and learning rates, which are in most cases highly confidential for biofuel producers and thus have to be guessed from the outside by other authors. Furthermore, as with any major research undertaking that looks far out in the future, there is some uncertainty associated with the data collected. Among the parameters more susceptible to uncertainty are the design parameters of the aviation-ETS for the period after 2020. In our approach we modeled the main parameters closely to the third or fourth phase of the ETS for stationary emitters. As with any political decision, this is bound to be reviewed when an implementing bill comes to the European parliament and is thus hard to forecast. One of our key model assumptions is the rate of biofuel adoption. We collect data for this from a study [Bauen et al., 2009] that is broadly matched by other publications [see e.g., EQ2, 2010, SWAFEA, 2011]. Additionally, cut off values for the adoption scenarios are critical input. We made our best estimate for the cut off values for the adoption scenarios and confirmed these in selective interviews with experts from the biofuel industry. Lastly, we do not model a direct supply constraint in our adoption model for biofuels. To address this, we believe there is a lot of time left to ramp up supply (even in our highest case, the required acreage for biofuels (using jatropha) in 2030 would only be about 50 % higher than what is forecast for 2015 [GEXSI, 2008]). Finding suitable areas that truly meet all sustainability criteria, however, will be a challenge [Upham et al., 2009].

4.6 CONCLUSION AND OUTLOOK

As the uncertainties, given the long term perspective, in our simulation are considerable, we hope to encourage the discussion around biofuels and the economic incentives the ETS can create. Our research has shown that the ETS can promote biofuel usage: First, in the way it is currently conceived by giving CO_2 emission a cost. Cumulative production compared with a scenario without a CO_2 price is more than 30 % higher. It falls short of biofuel usage by about 16 % compared with a CO_2 price without free allocation. In terms of emissions, the ETS realizes an emissions reduction of about 9 %. For the second lever, the ETS could support the adoption of biofuels with modest amounts – compared to the revenues generated –channeled back to the aviation industry. Indeed, high upfront investment does currently prohibit its deployment and thus a temporary support could be helpful for the aviation biofuel industry. Without state support, airlines could themselves promote the development of an appropriate biofuel supply chain by forming joint biofuel cooperations that could guarantee minimum purchase quantities. Backed with these guarantees it would be a lot easier for biofuel producers to find investors or creditors.

One fact of note is that our research was only concerned with the effects of the EU-ETS on biofuels. By stimulating faster adoption for airlines affected by the EU-ETS, biofuel prices worldwide are likely to decrease due to better production economics and by overcoming initial operational hurdles. A potential worldwide aviation-ETS is not likely to be in the cards for at least another decade after talks at the last UN climate summit failed to include international bunker fuels. With a worldwide price for CO_2 emissions, biofuel usage could be promoted further.

Technological first-mover advantage is a further concern. Currently, the two major biofuels for aviation are BtL and HRJ. By the end of the next decade, algae biofuels are likely to become market ready. Similar to current technologies this fuel will not be cost competitive in the early stages. One risk of

the late market entry of algae biofuel could be that, despite the technological potential to reduce fuel costs with industrial scale production, current biofuels may have matured too far by then. This would make it very challenging for algae biofuels to move down the learning curve by reaching a cost-competitive scale. A similar development is feared in some circumstances for other biofuel technologies [de Wit et al., 2010].

As has been mentioned before, kerosene price constitute a far larger part of the total cost of kerosene (including the CO_2 price). Thus, price changes of kerosene will likely have a larger impact on biofuel usage than CO_2 prices. In this regard, biofuels can have an interesting additional effect. No matter where biofuels are used (in aviation or other transport industries), they can dampen further price increases for crude oil, as they are replacing demand for crude oil. Hileman et al. [2009] estimate the impact of unconventional fuels (among biofuels also fuels derived from oil sands and other sources) to be a reduction between 5 % and 12 % of the oil price. As production (e.g., of bio diesel or ethanol fuel) is technologically more advanced at present, there is a risk of a first mover advantage within the transport industry (similar considerations apply to the chemical industry). Whether this effect actually does reduce kerosene prices and thus limits the adoption of biofuels in the aviation industry remains to be seen.

Similarly, there can be another effect on biofuels. Prices for biofuels, even if their feedstock is not in direct competition with oil, do depend on the price of oil. When oil prices reach high levels, oil consumers begin to look for alternative fuels, increasing the demand for these fuels and, ultimately, their prices. Currently, this effect is hard to quantify, as both large-scale production and the supporting data sources are still in development. Once widespread industrial production of biofuels has started, this effect should offer ample fields for further research. Lastly, as we have layed out shortly in the context of the financial impact, we believe a financial hedging strategy similar to fuel hedging for CO_2 costs will be crucial for airlines in the future. Once the aviation-ETS has been running

for a number of years, new academic and practical insights could be found from this area of research.

5

FUEL EFFICIENT AIRLINERS AS AN ALTERNATIVE MITIGATION STRATEGY

We have shown in this part how the usage of biofuels can be promoted by the aviation-ETS. Instead of reducing their CO_2 emission by using biofuels instead of kerosene, airlines can also reduce their kerosene consumption itself.

One way to do this is to purchase newer and more efficient airplanes. New airplanes can reduce the kerosene consumption by as much as 20 percent compared with the the generation of aircraft they are replacing. With reduced kerosene consumption, CO_2 emissions are reduced accordingly. CO_2 costs are only one part of the complex evaluation financial of new airplanes. It is, however, worthwile to estimate the cost impact of CO_2 on the financial evaluation separately as this is a new risk for the airlines introduced by the ETS.

The research question of Chapter 6 is then how big the influence of CO_2 emission costs is when airline finacially evaluate new airplanes. We analyze two aspects of finacial evaluation: First, a deterministic present value analysis of CO_2 costs for short- and long-haul planes. Second, the influence of CO_2 costs on the pricing of purchase options.

6

DOES THE AVIATION ETS INFLUENCE THE FINANCIAL EVALUATION OF NEW AIRPLANES? AN ASSESSMENT OF PRESENT VALUES AND PURCHASE OPTIONS

6.1 INTRODUCTION

According to estimates by the IPCC [IPCC, 2007a] , international aviation contributes about three percent to anthropogenic global warming. Despite efficiency improvements by airlines and airplane manufacturers, aviation's global emissions will likely triple by the year 2050 [IPCC, 2007b] if current industry practices do not change fundamentally.

To curb the increase in CO_2 emissions, the EU has decided to include airlines in the EU's ETS, starting in January 2012. With only limited exemptions granted, the ETS will affect almost all airlines flying in and out of European airports via Directive 2008/101/EC [European Parliament and Council, 2008]. As international aviation is not part of the current Kyoto Protocol for CO_2 emissions, the EU has created an aviation ETS through which airlines can trade among them in EUAA. This means that, in addition to the traditional ETS for stationary emitters, there will be a newly created market for aviation allowances. These EUAAs can be used only by airlines to achieve emission compliance. As abatement costs are a lot higher for airlines than for other sectors and to alleviate the financial impact of the ETS, airlines are allowed to buy and sell EUAs from the traditional ETS for stationary emitters that started in 2005.

One measure to achieve carbon neutral growth in aviation, starting in 2020, as postulated by the IATA, is the replacement of older aircraft with newer, more fuel-efficient aircraft [IATA, 2009]. Among other factors, the price of kerosene and - for airlines affected by the ETS - the price of CO_2 influence the airlines' decision to purchase these planes. Both factors, however,

show considerably uncertainty with respect to their future development. Combined with long lead times for new airplanes, real options are an appropriate tool for estimating the value provided by airplane purchase options.

Despite its recent start in the year 2012, the aviation ETS has already elicited some interest in the academic literature. Anger and Köhler [2010] give an overview of the current state of research on this topic. The main research on the aviation ETS to date has focused on the financial and operational implications of the ETS for airlines. For the financial implications of the ETS, Scheelhaase et al. [2010] estimate the cost incurred for two airlines. Their research shows that, at full cost pass through, price increases in the first years will be in the range of 3 to 13 Euros, depending on trip length. Along with the work by Vespermann and Wald [2010], a study by Scheelhaase et al., is among the few peer-reviewed papers next to a number of technical reports to assess the financial impact and the influence of various design parameters before finalization of the ETS [e.g., Wit, 2005, Morrell, 2007, Scheelhaase and Grimme, 2007]. Other authors have addressed the operational implications of the aviation ETS, such as network reconfigurations [Albers et al., 2009], effects on airfares, service offerings and airplane design [Brueckner and Zhang, 2010], or aircraft assignment [Morrell, 2009a].

Morrell and Dray [2009] proposed concepts for the purchase evaluation of new airplanes. We focus our research on the specific question of whether the aviation ETS has an impact on the financial evaluation of new airplanes. A study similar to our approach on real options, by Tarradellas et al. [2009], was conducted on a purely conceptual basis. We significantly enhance their work by establishing and executing a calculation method. In contrast to a study by Rutherford and Zeinali [2009], who stipulate a fuel efficiency standard for new aircraft, we examine the impacts of the more flexible market-based aviation ETS on the purchase decision and therefore the implied fuel-efficiency improvements.

Another relevant literature stream concerns airplane purchasing options and the financial evaluation of new airplanes

in general. Several articles have been written by Stonier [1998, 1999, 2001a,b] detailing the valuation of real options in the aircraft industry from an Original Equipment Manufacturer (OEM)'s perspective. Gibson and Morrell [2004] have published similar articles and, more recently, Hsu et al. [2011] have produced more analytically advanced work.

Our research goal is to examine the impact the ETS has on the financial evaluation of purchasing more efficient airplanes. We analyze two impacts of the ETS: First, the impact the ETS has on a present value analysis of a new airplane in a deterministic environment. Second, we examine the impact the ETS has on purchase options when there is uncertainty around kerosene and CO_2 prices. Our research contribution therefore is fourfold:

- We establish a profit model for short and long-haul airlines that enables the assessment of the cost impacts of kerosene and CO_2
- We calculate actual carbon costs for airlines under the EU's aviation ETS
- We calculate option prices for new aircraft under the uncertainty of kerosene and CO_2 prices
- We test sensitivities for both uncertainty factors and their influence on the purchasing strategy of airlines

The rest of the paper is organized as follows: Section 6.2 summarizes the design parameters of the aviation ETS and gives a short overview of airplane purchasing. Section 6.3 develops the two models that we use for our present value and option pricing analysis and introduces the data sources used. Section 6.4 gives the results for both models and Section 6.5 concludes our work and provides an outlook for further research.

6.2 THE AVIATION ETS AND AIRCRAFT PURCHASING

We briefly summarize the main parameters of the aviation ETS necessary to understand the benchmarking process for the free

allocation of emission rights, which influences the financial impact of the ETS. Secondly, we summarize the main challenges of aircraft purchasing in the aviation industry and our motivation to apply real option analysis to this field.

6.2.1 *The aviation ETS*

The European Council and the European Parliament decided upon the implementing directive [European Parliament and Council, 2008] in 2008 and it became effective in 2009. A summary of the design parameter can be found in Scheelhaase et al. [2010]. Here we briefly summarize the main parameters of the benchmarking allocation that influences airlines with respect to the financial impact:

- In the first year, the total quantity of allowances to be allocated to aircraft operators will be equivalent to 97 percent of historical aviation emissions. The historical aviation emissions will be calculated based on the average total emissions reported for the years 2004-2006. This figure has been available to the public since July 20, 2011, and was fixed at an average value of 221,420,279 tonnes per year, which is the cap for the cap-and-trade system [EEA Joint Committee, 2011]

- In 2012, 85 percent of allowances will be allocated at no cost, and the remainder will be auctioned off. The share of auctioning is likely to increase with future revisions of the directive. For comparison, the EU plans to auction off most allowances in the ETS for stationary emitters by 2013 (when the next phase of emission trading will start in the EU) and plans to reduce exemptions granted to energy and competition-intensive industries in the further process. A similar development for the airline industry, at least in future trading periods, therefore seems highly likely.

- Free allocation is based on a benchmark, which is calculated as follows. From the historical emissions the sum

of the cap reduction, the auctioned share, and a special reserve for new airlines and fast-growing operators is subtracted. The result is then divided by the sum of verified tonne-kilometer data of all participating operators in 2010. The initial free allocation for an individual airline is calculated by multiplying the benchmark with the transport activity of 2010 of the respective airline.

- Only the figure for historic emissions has been publicly available since July 2011 (published after a delay of about six months). Airlines report actual tonne-kilometer data to the administering countries by March 30, 2011, and then countries report the aggregated transport activity figures to the EU commission by June 30, 2011 at the latest. Individual airlines will know their actual allocation for the year 2012 by February 2012 (currently planned to be postponed by two months). Recently, US Congress drafted a bill prohibiting US airlines from participating in the scheme; other nations, such as China and Russia, are considering similar moves [Surgenor, 2011].

Given the start of the aviation ETS, airlines have three main options for addressing the problem of emission (and kerosene) costs:

- They find a suitable method to pass costs on to customers. Price elasticities vary significantly among the routes (and customers) airlines serve [Brons et al., 2002]. The key for airlines then will be to determine the right level of surcharge for each route. Currently, airlines have not announced any plans on a separate carbon emission surcharge in addition to the widespread practice of a kerosene surcharge.

- The airlines stabilize the purchase cost of their input factors with financial instruments. As the market for EUAAs is in its infancy we do not assess this option, but leave it for future research once the market has matured.

- They reduce their carbon emissions (and kerosene consumptions). One possible solution is to replace old air-

craft with newer, more fuel-efficient ones. However, the purchase decision is driven - among other factors - by the prices of kerosene and CO_2, which are highly uncertain. Lead times for new aircraft are typically quite long, so an airline may order aircraft when prices for both factors are at high levels and receive them when prices are lower (or vice versa). Purchase options can alleviate this problem by offering increased flexibility in fleet planning. However, their inherent value is difficult to calculate. We will show results for this question in Section 6.4.2 and results for the financial evaluation of new airplanes under the ETS in Section 6.4.1.

6.2.2 *Aircraft Purchasing*

Airlines can choose to buy their airplanes or engage in one form of leasing (financial or operational leasing). In general, airlines still purchase the majority of their airplanes [Gavazza, 2011] and therefore we focus on airlines purchasing aircraft. It has to be said, though, that similar considerations with regard to purchasing apply to leasing as they are, in turn, reflected in leasing rates.

Purchasing aircraft is a complex process due to three main factors: (i) the long economic lifetime of airplanes, (ii) multiple uncertainties during this lifetime, and (iii) the long lead time for new aircraft.

Airplanes typically have an economic lifetime of more than 20 years [Stepan and Hillinger, 1995]. This makes an airline's investment in an airplane somewhat irreversible. Airplanes configured specifically for an airline can only be sold or leased out with a discount to other airlines.

The major uncertainties for airlines are: demand for air transport (passenger and cargo), kerosene prices, and - recently introduced by the aviation ETS - CO_2 prices. Additionally, the airline industry is widely considered cyclical [Clark, 2007]. Given the long lifetime of an airplane, airlines will operate an airplane during both up and down cycles of the industry. Data compiled and provided by the two leading airplane

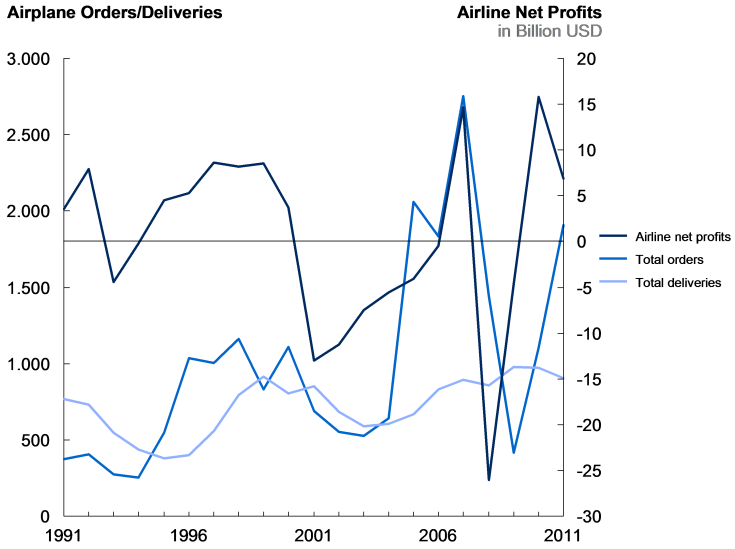

Figure 24: Airplane order/deliveries and airline profits

manufacturers, Airbus and Boeing [Airbus S.A.S., 2011a, Boeing Commercial Airplanes, 2011], for aircraft orders and deliveries, and the IATA [IATA, 2011b] for the net profits of worldwide airlines, show strong fluctuations of orders and profits and a relatively steady flow of deliveries (see Figure 24). It is worth noting that airlines still receive a large number of aircraft during periods in which they are experiencing cumulative losses.

Long lead times aggravate the first two problems mentioned. Current lead times for a narrow body jet are in the range of six years if ordered today. This means that an airline has to make a decision today to receive an airplane in about six years time that it might, from then on, operate for 20 years.

As uncertainties for the lead time period are significant, airlines have demanded more flexibility from manufacturers and received it in the form of purchase rights and purchase options, which were supported by reductions in manufacturing lead times [Crute et al., 2003, Stonier, 1999]. On the one hand,

a firm order grants an airline a fixed delivery slot in the future. On the other hand, the airline has to take the aircraft and has to make down payments leading up to delivery, irrespective of actual economic circumstances. Options allow more flexibility. They allow an airline to make a decision upon the purchase of an aircraft with an assigned delivery slot up to a predefined expiry date of the option. If economic circumstances are unfavorable, the airline either lets the option expire or, depending on the contract, can defer a decision to a later point in time. As these options are often purchased in combination with firm orders, their pricing to outsiders remains very opaque. We will develop a realistic real option analysis framework for the kerosene and carbon uncertainties mentioned above and show the results later in this article.

6.3 MODEL DEVELOPMENT AND INPUT VARIABLES

We develop two models that build on each other. First, we calculate a deterministic case of the influence of CO_2 prices on the present value for the purchase of both a long-haul and short-haul airplane. Second, in a stochastic environment, we calculate the influence of the CO_2 price on the option prices for new airplanes. A lot of the data inputs from the first model are used in the second model. Furthermore, some outputs such as the industry-wide benchmark for free CO_2 allocation and the aircraft specific benchmarks are used in the option pricing model. We therefore begin with the deterministic case in Section 6.3.1 and then proceed to the calculation of the option pricing in Section 6.3.2.

6.3.1 *Influence of the CO2 prices on the present value*

As a first step in determining the influence of the ETS on the purchasing behavior of airlines, we use present-value analysis to evaluate the financial impact of the CO_2 costs in an environment without uncertainty.

Index	y	a	t
Meaning	Time	Airplane type: Short or long-haul	Technology of airplane: Old or new
Range of Values	2015-2030	1,2	1,2

Table 7: Indecies used

We calculate the results based on a number of input variables or independent variables and calculate the intermediate results (or dependent variables) from these. We discern two aircraft types and thus two scenarios: The first is for a short-haul aircraft of current technology (an Airbus A321) that will be replaced with a modern, more efficient aircraft. The second is for a current technology long-haul aircraft, in our case a Boeing 777-300ER, that will be replaced with a new aircraft. We therefore index variables dependent on the aircraft type with the index a. We use index y for variables dependent on the specific year. The base year of our analysis is the 2015 as around this time the new technology airplanes will enter into service. To distinguish between current and new technology airplanes we introduce index t, with 1 being the old and 2 being the new airplane. Table 7 gives an overview of the indexes used.

In Section 6.3.1.1 we will introduce the independent variables, in Section 6.3.1.2 the resulting dependent variables for the present value analysis and in Section 6.3.2 proceed to the calculation steps for the option pricing.

6.3.1.1 *Input variables and data sources*

Variables in this section are introduced in alphabetical order. Figure 25 illustrates the main steps of the calculation.

Allowance prices (awp_y): We take current CO_2 prices from the EEX (a value of about 10 Euros in 2012) and assume a nor-

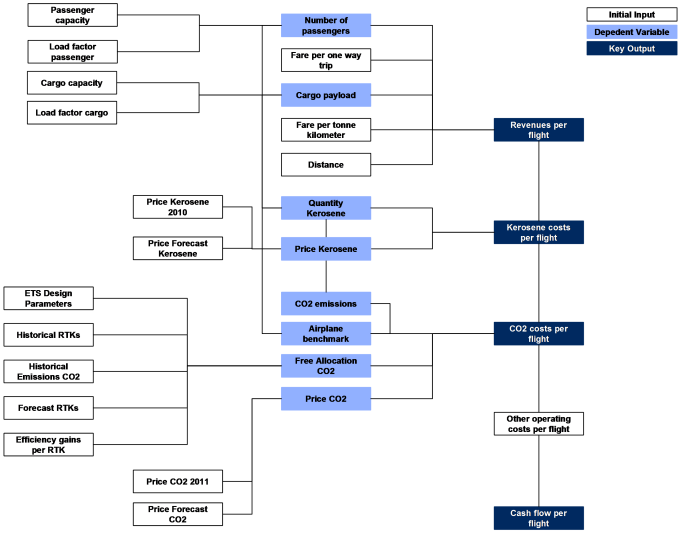

Figure 25: Calculation steps and variables

mally distributed growth trend to 38 Euros per tonne in 2030 [Schlesinger et al., 2011]. We estimate volatility from the period 2008 to 2011 (the second, more stable trading period for stationary emitters).

Cap reduction (cap_y), Auctioning share (auc_y) and Special reserve (spr_y): For the period 2012-2020 we set these values as demanded in the directive. This means a cap reduction of three percent for 2012 (five percent for 2013 and the following years), a special reserve of 0 percent for 2012 (three percent for 2013), and an auctioning share of 15 percent for 2012 and 2013. In the directive, a review of these figures is postulated once the ETS is up and running. For the rest of the period until 2020, we assume no changes to these values. For the year 2021, we assume no change to the special reserve, a cap reduction of 21 percent compared to 2005, and an increase in the auctioning share to 50 percent. The cap reduction in this case would be similar to the cap reduction for stationary emitters, and the auctioning share is comparable to competitive indus-

tries in the third trading period of stationary emitters, starting in 2013. Given aviation's global and competitive nature, we do not believe that free allocation will be reduced further than our chosen figures.

Cargo capacity (cargo_cap$_a$): Cargo capacity is set to 14 tonnes for the long-haul plane and 21 tonnes for the short-haul plane. We calculate these values by taking maximum take-off weights of the given aircraft types and subtracting the weight of the passengers (including baggage) carried, as well as the necessary fuel for the routes. Therefore, the long-haul route has a smaller cargo capacity, as much of the take-off weight is occupied by the higher fuel weight necessary for the longer route.

Distance (dis$_a$): Kerosene consumption and an aircraft's individual benchmark allocation are based on the distance flown. We choose typical values for the specific aircraft types: For the short-haul aircraft, we set the distance to 1,000 km (a typical continental distance) and for the long-haul aircraft we set it to 12,500 km (for example the distance from London to Singapore).

Efficiency gains from new airplanes (eg_new_ap$_a$): New airplanes are generally more efficient than the generation they replace. For the two aircraft types we took as our baseline models replacement aircraft that are scheduled to enter service in the coming years: A re-engined version of the A321, the A321neo, is scheduled to enter service in 2016 and Airbus claims it will be 15 percent more fuel efficient than the current A321 [Airbus S.A.S., 2011b]. For the long-haul aircraft (in our case the Boeing 777-300ER) a comparable aircraft from Airbus is scheduled to enter the market in 2017, the Airbus 350-1000. We assume a fuel burn reduction of this new airplane of 20 percent. The planes we analyze (both current and new technology ones) and the assumed fuel burn reductions were chosen as illustrative examples for values that can be expected in the near future. We neither want to support any of the planes as superior nor do we question or affirm the stated fuel burn reductions.

Emission factor ($efactor$): Set to 3.15 tonnes CO_2 per tonne kerosene as defined in the EU Directive 2009/339/EC [European Parliament and Council, 2009b].

Flights per day ($flights_a$): For long-haul aircraft we set it to 1.5 flights per day, and for short-haul aircraft the figure is six. These values are based on average speeds and thus travel times for the aircraft types.

Historical emissions (he_y): The EU Commission published historical emissions for the EU-27 on March 7, 2011. The values are 209,123,385 for 2004, 220,703,342 for 2005, and 228,602,103 for 2006. The average for the years 2004-2006, therefore, is 219,476,343 tonnes of CO_2 [Comission of the European Communities, 2011]. In July 2011, a revised average figure for the European Free Trade Area (EU-27 plus Norway and Iceland) was published, setting the annual average to 221,420,279 [EEA Joint Committee, 2011]. We slightly adjust the figure for emissions in 2006 of the EU-27 by adding 0.88 percent (the addition by the newly published average compared with the old average).

Industry wide efficiency gains (ind_eg_y): We assume airline fuel efficiency gains of around one percent per year. This figure is also often cited in the literature [Wit, 2005, Vespermann and Wald, 2010]. Previous studies [e.g., Lee et al., 2001] estimated this figure to be higher, but they also showed diminishing values in recent years as airplane technology seems to have matured. As a major advancement in aircraft technology is not expected before the mid-2020s and the time frame of our simulation ends in 2030, and because this transition will probably require long time frames [Geels, 2006], we leave the expected value at one percent per year.

Interest rate (int) and risk-free interest rate ($riskfr$): As we need to discount future cost down to the present we use an adequate interest rate for a net present value analysis. The interest rate has to reflect the risk of the specific project (i.e., the purchase of a new aircraft). As Gibson and Morrell [2004] suggest, we use the cost of equity for a large airline group, Lufthansa Aktiengesellschaft (AG), as published in their annual report [Lufthansa Group, 2011a] and set the value to 10.5 percent per

year. The risk-free rate, given our long-term perspective of 16 years, is set to four percent per year.

Kerosene prices ($kerp_y$): Historical crude oil prices for WTI until 2012 are taken from the IEA. We assume a normally distributed growth trend from current prices (about 95 US Dollars per barrel) to 120 US dollars per barrel. This forecast is taken from the mid values of a recent forecast of Natural Resources Canada [2010]. We assume the refining spread between kerosene and crude oil to be around 123 percent. Data is taken from the IEA time series of crude oil and kerosene from the years 1990 to 2011. We convert US Dollar values to Euros with the current exchange rate of 1.33 US Dollars per Euro.

Landing fees, maintenance costs, crew costs and other operating costs ($other\_cost_a$): We take values for landing fees per cycle from landing fees published by Frankfurt Airport [Fraport, 2012], one of the largest airports in Europe, and calculate landing fees for the two aircraft types. We estimate maintenance costs by taking values of maintenance cost per block hour from a report by University of Westminster [2008]. The value for a long-haul aircraft is 1280 Euro per hour, and for a short-haul aircraft 770 Euro. By assuming an average speed for the two routes, we come up with a duration of about 14 hours, and 1.5 hours for the short-haul route. This duration is also used to determine crew cost, for which we take values for crew cost per minute from Transport Studies Group [2008]. Other operating costs as a percentage of total costs are taken from a cost breakdown collected for airlines from the US by the Airline Association of the United States of America (USA), Airlines for America [2011].

Load factor passenger (lf_p_a) and cargo (lf_f_a): We estimate load factors from the published annual traffic figures from Lufthansa Group [2011b] for continental routes and for Asian routes, both for cargo and passenger transport. The values are as follows: Short-haul load factor passengers: 66 percent, short-haul freight 40 percent, long-haul passengers: 81 percent and long-haul freight: 72 percent.

One way fare per passenger ($fare\_pas_a$) and fare cargo ($fare\_car_a$): We assume a fare per passenger of 825 Euro on the long-haul aircraft and 175 Euro on the short-haul routes. Cargo revenues are assumed to be 0.23 Euro per RTK, a value taken from Clark [2007].

Operational days per year ($days\_op_a$): Airplanes are taken out of service for scheduled and unscheduled maintenance. We set this figure at 345 both for long-haul and short-haul aircraft to convert the figures we have derived for a daily basis to annual figures.

Passengers capacity (pas_cap_a): The number of passengers influences the revenues of the airplane as well as the payload carried (which, in turn, influences the CO_2 benchmark). For the short-haul aircraft we assume 170 seats, and for the long-haul aircraft 300 seats.

Resale value ($resale_a$): The resale value of airplanes can vary significantly due to different usage profiles and maintenance efforts. As we assume a typical use profile of the two aircraft types, we take a value of 30 percent of the initial price paid for the aircraft after 16 years in service life (the horizon for our analysis) [Kelly, 2008]. We gather list prices of the airplanes in our model from Airbus S.A.S. [2011c] and Boeing Commercial Airplanes [2012]. A new build A321 currently costs about 78 million Euros and a new Boeing 777-300ER 224 million Euros. Aircraft orders are heavily discounted, especially for large orders. Naturally, this data is hard to estimate from the outside. We assume a discount of 15 percent off the list prices. This gives us resale values of about 57 million Euros for the long range plane and 19 million Euros for the short-haul plane after 16 years in service.

Revenue tonne kilometer (rtk_y): We take data from Boeing Commercial Airplanes [2010a] for RPK for civil commercial aviation from the Europe segment and data from the AEA for civil (scheduled and chartered) cargo aviation for RTK. RPKs are converted into RTKs by using a fixed weight of 100 kg per passenger (including baggage), an industry standard value and also provisioned in the directive. Exemptions granted by the ETS are taken into account by subtracting a share of 3 percent. To

account for deviations from the great circle distance, we add 6 percent to the RTK figure. This yields a value of about 297 billion RTK in 2010, the benchmarking base year for the period 2012-2020. We take forecasts for the market growth from Boeing Commercial Airplanes [2010a], the passenger forecast, and Boeing Commercial Airplanes [2010b], the cargo forecast. For passenger traffic, this means an annual growth rate of about 2.5 percent per year; for cargo traffic the figure is 4.7 percent for traffic to and from Europe. These figures are matched broadly by a similar source from Airbus S.A.S. [2009].

6.3.1.2 *Dependent variables*

In order to calculate the economic influence of the aviation ETS, we calculate a profit equation for the two routes and the two airplane technologies, the current technology and the more kerosene-efficient one. We first calculate revenues and then the associated costs of operating the aircraft and then discount the calculated cash flow stream to estimate the present value of operating a more efficient plane. We introduce variables in this section in this order so that the flow of calculations can be easily followed.

Revenues (rev_a) and annual revenues ($annual\_rev_a$): The revenue potential of the old and new aircraft is constant; therefore, we only differentiate between the short- and long-haul route. Revenues are calculated by taking the passenger and cargo capacity, multiplying them with the load factors and the fare per passenger or fare per revenue tonne kilometer, respectively. Annual revenues are calculated by multiplying the revenues per flight by the number of flights per year (Equation 28)

$$\begin{aligned} rev_a &= pas\_cap_a \times lf\_p_{a\_} \times fare\_pas_a \\ &\quad + cargo\_cap_a \times lf\_f_a \times fare\_car_a \times distance_a \end{aligned} \tag{27}$$

$$annual\_rev_a = rev_a \times flights_a \times days\_op_a \tag{28}$$

Kerosene consumption per flight (ker_con_a): Kerosene consumption is calculated using Eurocontrol's Small Emitters Tool, which

was developed by Eurocontrol to alleviate the emission compliance burden of the aviation ETS for small airlines. Given an aircraft's type designator and the distance flown, the tool calculates kerosene consumption in tonnes as an output.

Kerosene consumption per year ($annual\_ker_{at}$): We calculate annual kerosene consumption per aircraft by multiplying kerosene consumption per flight by flights per day and the number of operational days. Efficiency gains of the new airplanes determine whether we are looking at a current or new airplane. Efficiency gains for current technology airplanes are set at zero.

$$annual\_ker_{at} = ker\_con_a \times flights_a \times days\_op_a \left(1 - eg\_new\_ap_{at}\right) \tag{29}$$

Kerosene Costs ($cost\_ker_{yat}$): Kerosene costs are annual kerosene consumption multiplied by the price of kerosene

$$cost\_ker_{yat} = annual\_ker_{at} \times kerp_y \tag{30}$$

Benchmarking value (b_y): We calculate the benchmark, used for free allocation, as stipulated in the directive. The benchmark influences the actual CO_2 costs for airlines by diluting the market price of CO_2 with the free allocation. The calculation is shown in Equation 31.

$$b_y = \frac{\frac{1}{3}\sum_{y=2004}^{Y=2006} he_y \left(1 - cap_y\right)\left(1 - auc_y\right)\left(1 - spr_y\right)}{RTK_b} \tag{31}$$

RTK_b is the number of RTKs in the respective benchmarking year. For the periods 2012 and 2013-2020 this is the year 2010. We assume a similar process for the period post 2020 and therefore set RTK_b for the period 2021-2030 to 2019. Values for cap_y, auc_y and spr_y are assumed as shown in Table 8.

CO_2 emissions per year ($annual\_co2_{at}$): CO_2 emission is the kerosene consumption multiplied by the emission factor ($annual\_ker_{at} \times efactor$).

Yearly payload ($annual\_payload_a$) and annual flight distance ($annual\_distance$
Annual payload and total flight distance per year are determined in a similar way as annual kerosene consumption. However, we assume no payload differences for the new airplanes.

Variable	2012	2013-2020	2021-2030	Comment
cap_y	3%	5%	21%	In line with reduction planned for IV. EU-ETS-phase
auc_y	15%	15%	50%	In line with share for competitive industries in III. EU-ETS-phase
spr_y	0%	3%	3%	No increase for special reserve

Table 8: Auctioning share, special reserve and cap reduction

The potential replacement aircraft are suitable to fly both the same distance and payload as the generation they are replacing.

$$annual\_payload_a = payload_a \times flights_a \times days\_op_a \quad (32)$$

$$annual\_distance_a = distance_a \times flights_a \times days\_op_a \quad (33)$$

Airplane benchmark (ab_{at}) and free allocation (fa_y): We calculate an airplane- specific benchmark to analyze how much CO_2 the airplane in question is emitting in excess of the freely allocated benchmark. If an airplane performs better than the benchmark, the airline operating the airplane could sell the excess allowances (or does not need to buy allowances for other aircraft at market value). Thus, an airplane benchmark better than the industry-wide benchmark means a cost reduction for an airline. By the same token, if the airplane benchmark is higher than the industry benchmark, the airline has to buy emission allowances for the proportion that exceeds the benchmark. Free allocation (as a percentage of total emissions) is then the industry-wide benchmark divided by the airplane-specific benchmark.

$$ab_{at} = \frac{annual\_co2_{at}}{annual\_payload_a \times annual\_distance_a} \quad (34)$$

$$fa_{yat} = b_y / ab_{at} \quad (35)$$

CO_2 *costs* ($cost\_co2_{yat}$): CO_2 costs are calculated by taking the annual CO_2 emissions and reducing the airplane-specific benchmark by the free allocation. This figure is then multiplied by the cost per tonne CO_2.

$$cost\_co2_{yat} = annual\_co2_{at} \left(1 - fa_{yat}\right) awp_y \quad (36)$$

Operating cash flow with CO_2 *costs* (cf_co2_{yat}): Operating cash flows are revenues minus operating costs. As we are focusing on kerosene and CO_2 costs, we use the more detailed derived values of $cost\_ker_{yat}$ and $cost\_co2_{yat}$ in the calculation with CO_2 costs. Resale value takes the value of zero if not in the last period of our model.

$$cf\_co2_{yat} = annual\_rev_{ya} - cost\_ker_{yat} - cost\_co2_{yat} - other\_cost_a + resale_a \quad (37)$$

Discounted cash flows ($dis\_cf\_co2_{yat}$): We discount the cash flows of each year to the base year.

$$dis\_cf\_co2_{yat} = cf_{yat} \exp\left(-int\left(y - 2015\right)\right) \quad (38)$$

Operating cash flow without CO_2 *costs* (cf_{yat}): To determine the influence of the aviation ETS we also calculate cash flows without CO_2 costs. Resale value takes the value of zero if not in the last period of our model.

$$cf_{yat} = annual\_rev_a - cost\_ker_{yat} - other\_cost_a + resale_a \quad (39)$$

Discounted cash flow without CO_2 *costs* (dis_cf_{yat}): Similar to the cash flow with CO_2 costs we discount the cash flows without CO_2 costs.

The benefit of a new airplane (index t = 2) over the current technology airplane (index t = 1) under the aviation-ETS can

be summarized with Equation 40 and the benefit of a new airplane without CO_2 cost is given by Equation 41.

$$benefit\_co2_a = \sum_{y=2015}^{2030} dis\_cf\_co2_{ya2} - \sum_{y=2015}^{2030} dis\_cf\_co2_{ya1} \tag{40}$$

$$benefit_a = \sum_{y=2015}^{2030} dis\_cf_{ya2} - \sum_{y=2015}^{2030} dis\_cf_{ya1} \tag{41}$$

Results for the present value analysis are given in Section 6.4.1. In the next section, the calculation method for the option pricing will be discussed.

6.3.2 *Calculation of option prices under CO2 and kerosene uncertainty*

The option we evaluate is an expansion option, or more technically, an American call on a new, more efficient airplane. Our evaluation of kerosene and CO_2 costs on the pricing of delivery options is, in principle, an adoption of the approach Copeland and Antikarov [2009] developed for modeling real options with two uncertainties. However, we add some airline specifics to the model. First, the exercise of the option is non-instantaneous. This means that even if the option is exercised, the delivery of the airplane takes place at a later point in time. This reflects industry practice where options are for fixed-delivery slots in the future. We assume it is not possible to revert the decision to exercise the option (i.e., no possibility to defer, accelerate, or cancel the delivery). Second, we assume that down payments will be required from the moment the option is exercised to the delivery of the aircraft. As these down payments happen at later points in time, we discount them back to the exercise period to account for the time value of money. We do not include other uncertainty factors. As we have mentioned, there are several more uncertainty factors such as yields (fares per passenger), load factors or traffic

growth in the future. As we assume the same seating capacity for both the new and the old technology airplane, the factors mentioned do not affect the evaluation of the differences between the planes. Higher yields, for example, would affect both airplane types and therefore keep the financial benefit between the new and the old plane constant. We focus our model on the question whether CO_2 costs have an influence on the financial evaluation of new aircraft. We therefore include only kerosene and CO_2 costs in our evaluation. It is worth noting that we do not have to take into account dividend payments (a common problem for non-instantaneous options) as the aircraft do not arrive during the life span of the option and thus cannot earn any profits/dividends during the option life.

We assume an option lifetime of four years, starting in 2012. This means that the latest moment to exercise the delivery option would be at the end of 2015. As mentioned, we assume a minimum time lag between option exercise and delivery. We take a time lag of 1.5 years, which means the fixed delivery slot is for the second half of 2017. We allow option exercise on a biweekly basis ($dt = 1/26$) and therefore divide each year into 26 periods. More time periods would marginally improve the precision of calculation, but increase the time required for the already lengthy calculations of the quadrinomial lattices to prohibitive levels.

Our approach consists of five steps: First, we build a profit equation for each year given kerosene and carbon costs. Second, we estimate the present value of the plane in each of the uncertainty states. Third, we discount back the values of each state to derive a value for the aircraft with no flexibility (i.e., not the option to purchase a more efficient aircraft). Fourth, we introduce the option to reduce kerosene consumption (and therefore CO_2 emissions) by exercising a purchase option for a new, more efficient plane. The strike price of this option is the negotiated purchase price of the new airplane (minus the expected resale value). Fifth, we determine the optimal option exercise policy by starting in the last period and moving back to the first period in time. The difference between the value without flexibility and the value with flexibility value is the

value of the option. We will provide details for each step in the following.

Our profit equation is very similar to the one used in the previous section. We have constant revenues and subtract operating costs. Out of these costs, only the costs of kerosene and CO_2 are uncertain.

$$\begin{aligned} \pi_{ya}(i, n) &= annual\_rev_{ya}dt - annual\_ker_{ya}dt \\ &\quad \left(kerp(i, y) + efactor \times awp(n, y)\left(1 - FA_y\right)\right) - \\ &\quad other\_cost_a dt \end{aligned} \tag{42}$$

We use a quadrinomial lattice to account for changes in π^{in}_{ya} induced by the two uncertainties, kerosene and CO_2. As we have assumed a normally distributed growth trend for both input factors, we are modeling both factors as a Brownian motion. As Dixit and Pindyck [1994] suggest, mean reversion is not a concern for most commodities for periods shorter than 30 years and thus our assumption of a Brownian motion is not too restricting. This assumption allows us to model the development with a standard quadrinomial (in case of only one uncertainty as a binomial) lattice. In a lattice, the development of the uncertainty factors is determined by up and down movements. For example, the kerosene price $kerp(i, y)$ in period y is given by the number of up movements (in our notation$i$ for kerosene and n for CO_2) and the number of down movements $(y - i)$ that have occurred until period y. For the two uncertainties kerosene and CO_2 we have up factor u_K (u_C) and down factor d_K (d_C). Thus, the two uncertainty factors evolve according to Equations 43 and 44

$$kerp(i, y) = kerp_0 \times u_K(i) \times d_K(y - i) \tag{43}$$

$$awp(n, y) = awp_0 \times u_C^n(n) \times d_C(y - n) \tag{44}$$

The parameters of the quadrinomial lattice are determined as shown in Copeland and Antikarov [2009] for uncorrelated uncertainties (correlation between CO_2 and kerosene prices so

far has been not significant [Alberola et al., 2008]). We estimate historical volatility from time series for kerosene and CO_2 prices. For kerosene we take a time series from the EIA from 1995 to 2011 and estimate annual volatility. Our starting value for kerosene $kerp_0$ in 2015 is 743 Euros per tonne kerosene. For CO_2 prices, we take the second, more stable period of the EU-ETS for stationary emitters from April 2008 to February 2012 from the EEX and estimate monthly volatility and scale it with the factor $\sqrt{12}$ to the annual value. Annual volatility σ_K for kerosene is 24.32 percent and σ_C for carbon is 53.38 percent. The parameters for an up and down movement are then given by the following equations:

$$u_K = \exp(\sigma_K dt) \quad (45)$$
$$d_K = 1/u_K \quad (46)$$
$$u_C = \exp(\sigma_C dt) \quad (47)$$
$$d_C = 1/u_C \quad (48)$$

The present value in each period is the current profit plus the discounted profits of the remaining periods given current kerosene and CO_2 prices. The number of remaining periods is determined by the lifetime of the airplane with the airline (16 years in our example). Equation 49 determines the present value in each state depending on the time y and the respective number of up states of kerosene and CO_2, i and n.

$$PV_{ya}(i, n) = \pi_{ya}(i, n) + \sum_{t=2}^{15/dt} \pi_{ya}(i, n) \exp(-inter \times dt \times t) \quad (49)$$

The risk-neutral probabilities p_K and p_C for the option evaluation of each uncertainty are determined by equations 50 to 53.

$$p_{UK} = \frac{\exp(riskfr \times dt) - d_K}{u_K - d_K} \quad (50)$$

$$p_{DK} = 1 - p_{UK} \quad (51)$$

$$p_{UC} = \frac{\exp(riskfr \times dt) - d_{CK}}{u_C - d_C} \quad (52)$$

$$p_{DC} = 1 - p_{UC} \quad (53)$$

Without correlation, the risk-neutral probabilities for the combined tree are simply the product of the respective probabilities (e.g., the probability of kerosene up and CO_2 up is $p_{UKUC} = p_{UK}p_{UC}$).

To calculate the expected value of the airplane without the flexibility to purchase the more efficient plane, we calculate the expected values using the risk-neutral probabilities, and discount each expected value with the risk-neutral interest rate. The lattice therefore has to be solved from the end to the beginning using backward induction. The values for the last period are simply the present values in the respective states $PV^{in}_{\text{Last},a}$.

$$\begin{aligned} Node\_NoFlex_{ya}(i, n) = {} & (p_{DKDC} Node_{y+1,a}(i, n) + \\ & p_{DKUC} Node_{y+1,a}(i, n+1) + \\ & p_{UKDC} Node_{y+1,a}(i+1, n) + \\ & p_{UKUC} Node_{y+1,a}(i+1, n+1)) \\ & \exp(-inter * dt) \end{aligned} \quad (54)$$

We now introduce the option to purchase a new, more efficient aircraft. The strike price of this option is the negotiated purchase price of the new airplane minus the expected, discounted resale value after the end of the airplane's life with the airline. For our long-haul aircraft the strike price is about 179 million Euros, and for the short-haul plane 57 million Euros. Our assumed fuel reductions are 15 percent for the short-haul airplane and 20 percent for the long-haul plane, and the long-haul aircraft has a significantly higher absolute kerosene consumption. The free allocation is taken from our deterministic calculation for each airplane by setting the plane's own

benchmark in relation to the industry-wide benchmark. The profit equation for the new aircraft is then given by the following equations:

$$\begin{aligned} \pi\_red_{ya}(i,\, n) \quad = \quad & annual\_rev_{ya}dt - annual\_ker_{ya}(1 - eg\_new\_ap_a) \\ & dt\left(kerp(i,\, y) + efactor \times awp(n,\, y)\left(1 - FA_y\right)\right) other\_cost_a dt \end{aligned} \tag{55}$$

For the present value of the new airplane, we have to subtract the investment for the new airplane from the present value. To account for an aircraft specialty, we spread the strike price over the time left until delivery of the aircraft. For example, if the option is exercised in the last possible state, there are $TimeLag/dt$ periods left for down payments on the aircraft. Therefore, the down payment required in each period is given by $strike_a/\left(timelag/dt\right)$, where $strike_a$ stands for the negotiated purchase price of the aircraft. As these down payments towards full payment occur at different points of time, we discount them with the risk-adjusted interest rate. Therefore, the costs of the new airplanes are calculated with the following equation.

$$invest_{ya} = \sum_{t=t}^{5/dt+TimeLag/dt-1} \frac{strike_a}{timelag \times 1/dt} \times \exp\left(-inter\frac{(i+1-t)}{1/dt}\right) \tag{56}$$

Combining the investment costs $invest_{ya}$ with the profit streams gives the present value of the new airplane:

$$\begin{aligned} PV\_Red_{ya}(i,\, n) \quad = \quad & \pi\_red_{ya}(i,\, n) + \\ & \sum_{t=2}^{15/dt} \pi\_red_{ya}(i,\, n) \exp\left(-inter \times dt \times t\right) - invest_{ya} \end{aligned} \tag{57}$$

For the last period, the optimal decision is given by Equation 58.

$$Node_{\text{Last},a}(i,\, n) = \max\left[PV_{\text{Last},a}(i,\, n),\, PV\_Red_{\text{Last},a}(i,\, n)\right] \tag{58}$$

For periods prior to the last period, te optimal policy is determined by calculating an expected value of the following period and comparing it with the option to exercise. The expected value of the following period is calculated using the risk-neutral probabilities and previously determined values of the nodes.

$$
\begin{aligned}
Node_{ya}(i,\, n) \quad = \quad & \max\big[(p_{DKDC} Node_{y+1,a}(i,\, n) + \\
& p_{DKUC} Node_{y+1,a}(i,\, n+1) + \\
& p_{UKDC} Node_{y+1,a}(i+1,\, n) + \\
& p_{UKUC} Node_{y+1,a}(i+1,\, n+1)) \\
& \exp(-inter * dt)\,,\, PV\_Red_{ya}^{in}\big]
\end{aligned} \tag{59}
$$

The option value finally is the difference between the value of $Node_{0,a}(0,\, 0)$ and $Node\_NoFlex_{0,a}(0,\, 0)$.

The calculation of the option value with only kerosene as an uncertainty (to analyze the impact of CO_2 on the option pricing) follows a similar process. We reduce the quadrinomial lattice to its binomial counterpart and remove the CO_2 price from the profit equation. We will show results for the option pricing in Section 6.4.2.

6.4 RESULTS

We have two main research objectives: First, we show the deterministic value a more efficient aircraft can bring to an airline when costs of CO_2 are relevant as they are under the aviation-ETS. Second, we examine the influence of the CO_2 costs on option pricing for new airplane deliveries. Section 6.4.1 gives the results for our deterministic case, Section 6.4.2 the results for the option pricing, while Section 6.4.3 briefly highlights the limitations of our research.

6.4.1 *Results for present value*

For the present value analysis of the influence of the aviation-ETS, we add the discounted cash flows of each period for the current technology and the new technology both under the aviation-ETS and without CO_2 costs. The base year for our analysis is 2015, therefore we discount back all the cash flows to this year.

For the long-haul aircraft, we find a value of about 51 million Euros over the considered time frame in the scenario with

CO_2 in favor of the new airplane. The benefit of the new airplane is reduced to about 46.9 million Euros in an environment without CO_2. As revenues for both airplanes are assumed to be the same, this means additional CO_2 costs for the current technology long-haul plane of about 4.1 million Euros. On average, this means additional CO_2 cost of the old airplane of about 250,000 Euros per year over 16 years of usage. It has to be noted that the major contribution to the present value is derived from the reduction in kerosene costs. The benefit of the kerosene reduction is more than 10 times greater than CO_2 savings (4.1 million versus 46.9 million Euros). To put it more positively, CO_2 costs are almost 10 percent of kerosene costs, the biggest single cost position of airlines.

For the short-haul aircraft, we find a value of about 14 million Euros over the considered time frame in the scenario with CO_2 in favor of the new airplane and about 12.9 million Euros for the case without CO_2. With constant revenues, this means additional CO_2 costs for the current technology short-haul plane of about 1.1 million Euros (or only 70,000 Euros per year). Again, kerosene savings clearly outnumber savings for CO_2.

What are the drivers behind these numbers? Firstly, long-haul aircraft have higher fuel consumption, both in absolute terms and as a relative cost position. For short-haul aircraft, other costs (such as crew cost, landing fees, etc.) are a higher share of total costs. As CO_2 emissions are dependent on kerosene consumption, the additional cost benefit of the new airplane is accordingly reduced under the aviation ETS for short-haul aircraft. For an exemplary comparison of a cost breakdown see also Figure 26.

Secondly, the airplane-specific benchmark for free allocation is different for the two aircraft types. Compared on the benchmarking metric (CO_2 emissions per RTK), long-haul flights are more efficient as the energy-intensive climb out phase constitutes a smaller portion of the total flight. The figures for the current technology long-haul plane are 0.776 kg CO_2/RTK and 1.135 kg CO_2/RTK for short-haul (0.699 and 0.965 for the new technology planes) in 2015. This compares with a benchmark-

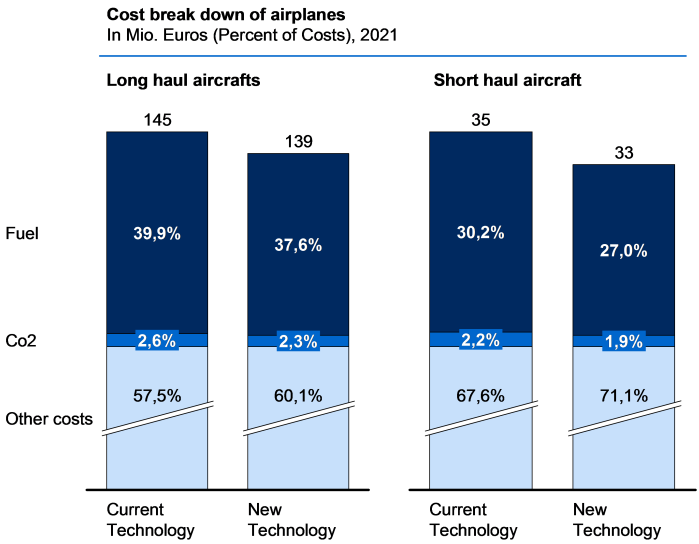

Figure 26: Cost breakdown of short and long-haul airplanes in 2021

ing value of 0.585 used for free allocation in 2015 (calculated industry wide). In other words, a current technology long-haul airplane receives about 75 percent (0.585/0.776) of its CO_2 emission for free, while the figure for a short-haul plane is only 52 percent. The present value of this free allocation is about 20 million Euros for the long-haul and 2.5 million Euros for the short-haul plane. Figure 27 gives an overview of free allocations for the short-haul (SH) and long-haul (LH) airplanes over the simulation period. There are two jumps in the free allocation: Both are triggered by reductions in the benchmarking value, which are in turn influenced by the reduced cap and the increased auctioning share of allowances.

We present a comprehensive discussion of the results for the decision making under uncertainty in the next section. To assess the sensitivities to key assumption, however, we also show results for the sensitivities in the deterministic environment. This is a proxy how different assumption could affect

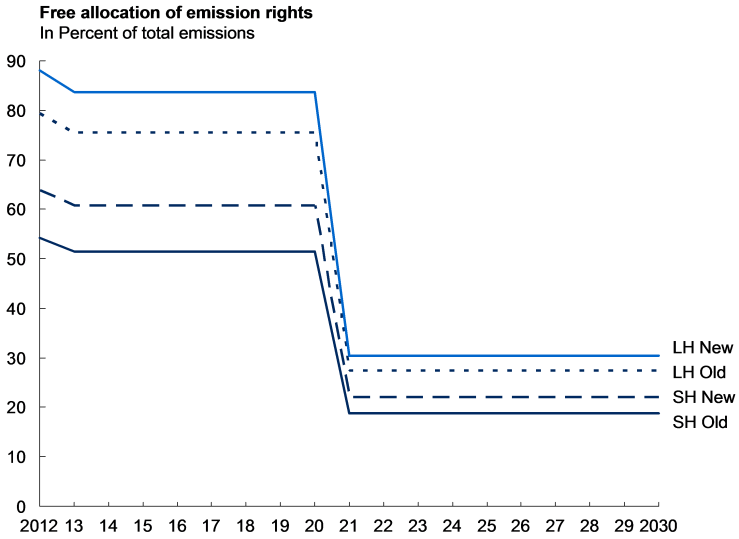

Figure 27: Free allocation as a percentage of total emissions over time

the renewal of airline fleets as they influence the present value outcome positively or negatively.

The long-haul airplane, again, is more affected by the changes in assumptions. The price of CO_2 is only a minor factor in the total evaluation, as an increase by 50 percent of the base value only leads to total costs of about 2 million Euros. Much more significant are the fuel burn improvements and the total fuel burn. An a fuel burn improvement of 37.5 percent over the current technology (an increase of 50 percent over the base value) leads to an increase in the advantage of the new airplane of 41 million Euros.

For the short-haul plane the results are similar, albeit on a smaller scale. Again, the price of CO_2 has only a moderate impact on the financial evaluation of the airplanes. A higher fuel burn reduction would have a far bigger impact on the present value.

As we assume no differences between the old and the new plane for seating capacities, load factors or yields (revenues

Change of base case by...	Price of CO2 allowance	Price of kerosene	Fuel burn improvement
Value base case in 2015	15 Euro per tonne CO3	743 Euro per tonne kerosene	20 percent
-25 percent	-1.0 milllion Euro	-5.3 million Euro	-20.5 million Euro
+50 percent	2.1 million Euro	10.6 million Euro	41.0 million Euro

Table 9: Sensitivities to key assumptions for the present value of long haul airplanes

per passengers), changes in these assumptions do not affect the the difference between the two airplanes. Both the new and the old airplane would benefit from a change in these assumption and the difference between the two, therefore, would not change. The increases in the present values for both plane types for an increase in yields and load factors can be substantial, however. For example, yield or load factor improvements of 5 percent mean an increase in present values for the long haul planes of about 20 percent or 15 percent, respectively. As these two factors are closely interlinked with classical revenue management [Talluri and Ryzin, 2005] and we focus our model on the cost factors kerosene and CO_2, we present these results as an ancillary result.

What does this mean for the willingness to pay for a new airplane? As Stonier [1999] points out, the willingness from an OEM's perspective has upper and lower bounds: the lower bound for an aircraft is its marginal production cost and the upper bound the point at which margins are becoming so healthy that further airplane producers start production and bring down prices. In areas between these points, the economic benefit of a new aircraft typically is shared between the manufacturer and airline customer. We do not assess the exact

Change of base case by...	Price of CO2 allowance	Price of kerosene	Fuel burn improvement
Value base case in 2015	15 Euro per tonne CO3	743 Euro per tonne kerosene	15 percent
-25 percent	-0.3 milllion Euro	-1.5 million Euro	-3.5 million Euro
+50 percent	0.6 million Euro	2.9 million Euro	7.0 million Euro

Table 10: Sensitivities to key assumptions for the present value of short haul airplanes

split of the willingness to pay for a new aircraft but state the total benefit of a new airplane. The actual distribution of this benefit between manufacturer and airline is up to the negotiation skills of both. Under perfect competition, producers (the aircraft OEMs) and consumers would split the resulting benefit. Assuming this split, a new technology long-haul aircraft becomes 2 million more valuable under the aviation ETS. This figure, it has to be noted, only applies to carriers with a 100 percent share of flights under the EU-aviation ETS, i.e., most EU-based carriers. For other carriers the figure is reduced accordingly. This makes it a bit more complex for OEMs to estimate the benefit of a new airplane to an airline outside of the EU. Nevertheless, price negotiations are known to be tough for new airliners and the additional benefit of the CO_2 price could be a decisive point.

The last question for the present value is by how much it influences the fleet renewal of airlines. Modeling the fleet renewal for airlines is a complex task and we only give an estimate for the impact of CO_2. We calculate the time required to achieve a positive present value after investment for the new aircraft. We compare the payback time for the new plane with the payback time of the old plane, both with and without CO_2 costs. For the long-haul plane the results are as follows:

Under no CO_2 costs, the payback time of the old plane is 25 percent longer and under CO_2 costs the payback time is 31 percent longer. By this measure then, the incentive to replace the old airplane under CO_2 costs is about 23 percent higher than under no CO_2 costs. For the short-haul plane the results are about 19 percent under no CO_2 costs and 23 percent under CO_2 costs. This means, that CO_2 increases the incentive to replace by about 24 percent. Interesting to note is that the payback times for the new plane under CO_2 costs fall between the payback times of the old and new plane without CO_2 costs. Present values of airplanes under CO_2 costs are lower as under no CO_2 costs and therefore the payback times longer. This supports the fear of airlines that the introduction of the ETS actually drains necessary funds from airlines that would otherwise be available for fleet renewal. However, once CO_2 costs apply, they raise the incentive to replace old aircraft.

This only gives an approximate idea of how CO_2 can influence the fleet renewal of airplanes. We base our calculations on net present values, which in its static form can only be one indicator for fleet replacement. However, the comparison of the different replacement times gives relevant results (which should be similar with other evaluation techniques).

6.4.2 *Results for option pricing*

We calculate the option prices as shown previously. For the long-haul plane we find an option value of 3.88 million Euros with CO_2 costs and a value of 3.45 million Euros for a world with no CO_2 costs (i.e., with only kerosene as an uncertainty). This means, that for a long-haul aircraft CO_2 has a value of about 0.43 million Euros for the pricing of purchase options.

For the short-haul plane option values are a lot less than for the long-haul plane. The difference between the option price with CO_2 and the one without is only 2,500 Euros. This clearly shows the reduced impact of the kerosene (and therefore CO_2 reduction) for the short-haul plane.

To analyze the impact of the free allocation on the option pricing, we set the fa_{ya} to zero and repeat the calculations.

Results for the long-haul aircraft show an increase of the option value by about 0.2 million Euros, whereas the value of the short-haul plane does not change by a significant value.

Lastly, we analyze sensitivities for the drivers of the option price. In Figure 28 we show the changes of the option prices for the long-haul plane to changes of the base values. These sensitivities to changes in parameters are also know as "the greeks" [Banks and Siegel, 2006] for financial options. However, there are differences between the financial options greeks and the real option greeks in our case. Financial option greeks are concerned with an underlying and the option is writen on that underlying. For real options as the one we are evaluating, the underlyings are two input factors that influence the profit of an project and therefore influence the value of the option. Thus, the greeks of real options are slightly different than the ones for financial options. As there is no analytical solution for the quadrinomial lattice, we present the results of a numerical approximation in the following.

What can be seen easily is that a reduction in fuel burn and an increase of the initial kerosene price lead to the highest increases in option values. Changes in the initial prices of kerosene and CO_2 are in our case close to the delta of financial options. The volatility of kerosene, or vega of kerosene, also has an influence on the option price. In contrast to the other parameters, an increase in the strike price or the purchase price of the new airplane leads to falling option values.

Figure 28 shows the results of the long-haul plane option with the option parameters scaled from 75 percent to 150 percent of the initial base value. The most sensitive drivers are fuel burn reduction and the initial kerosene prices. An increase of the fuel burn reduction to 30 Percent (150 percent of 20 percent) would more than quadruble the value of the purchase options. Kerosene volatility has also a strong impact on the option value. For CO_2, the results are far less than for kerosene as can be seen in the rather flat slope of both the initial CO_2 price and the CO_2 volatility. For example, the increase of the option value to a 50 percent increase in the initial CO_2 price, is only about 0.3 million Euros.

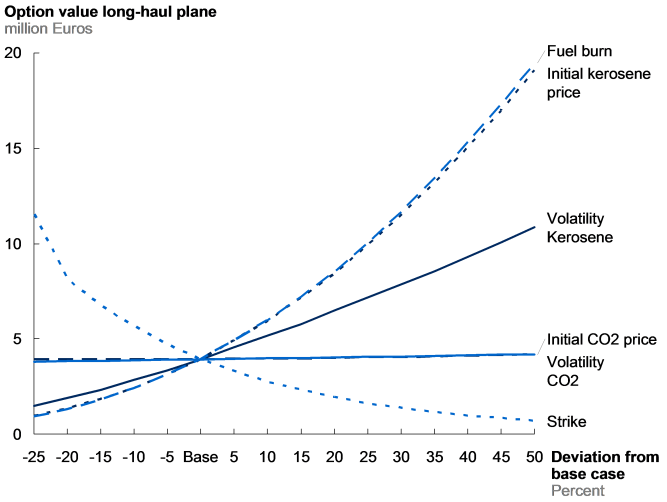

Figure 28: Sensitivities for long-haul plane option prices

Similiary, we test sensitivities for the options of the short-haul plane. In general, the option values for the short-haul plane are a lot lower. For short-haul planes, the volatility of kerosene is the most sensitive parameter. As absolute fuel burn is lower, both fuel burn reduction and the initial kerosene price do not affect the option value as much as they do for the long-haul plane. Similar to the long-haul plane, CO_2 has only a limited impact on the option values.

To summarize, CO_2 costs can have an influence on the option pricing for airlines. This is mostly relevant for long haul airplanes, where kerosene consumption and CO_2 emissions constitute a larger share of total costs.

6.4.3 *Limitations of research*

It is worth noting that we only considered CO_2 and kerosene as our uncertainties and benefits of new planes. In reality, new airplanes also offer lower maintenance costs, better performance in terms of payload and range, and higher passenger

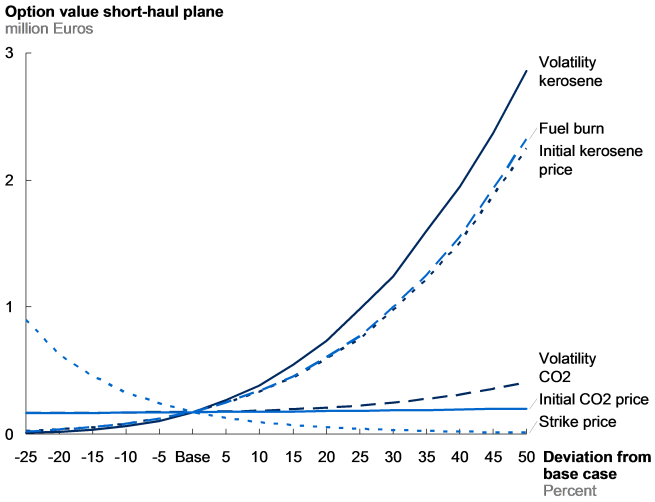

Figure 29: Sensitivities for short-haul plane option prices

appeal. Similarly, there are further uncertainties that could be included such as yields and load factors. We did not include these benefits in our assessment deliberately as we highlight the influence of CO_2 on purchase decisions.

In our simulation model we have used the most reliable sources and methods available to us. However, some parameters, such as the actual purchase price of new airplanes and resale values, are in most cases highly confidential and therefore it is hard to find reliable data sources. We did our best to estimate these inputs from the outside and validate the figures with industry experts. Furthermore, as with any major research undertaking that looks far into the future, some uncertainty is associated with the data collected. Among the parameters more susceptible to uncertainty are the design parameters of the aviation ETS for the period after 2020. In our approach we modeled the main parameters closely to the third or fourth phase of the ETS for stationary emitters. As with any political decision, this is bound to be reviewed when an implementing bill comes to the European Parliament, and therefore

it is hard to forecast. Lastly, we modeled two specific routes with two typical aircraft types used for these routes. In reality, airlines use airplanes on more than one route, which affects the revenue and cost profile of the analysis. The principle of our analysis, however, remains unchanged and therefore it is easy for practitioners to replicate this with confidential data at hand.

6.5 CONCLUSION

We examined the influence of CO_2 prices on the financial evaluation of new airplanes. We find that CO_2 prices do have an influence on the financial evaluation of a new airplane. Clearly, long-haul airplanes are more affected by CO_2 costs, but in the present value analysis, short-haul planes are also affected by CO_2 costs. Over multiple airplanes the calculated costs can make a decisive difference in an industry with such thin margins. It is worth noting that discounting reduces the impact of the CO_2 costs in later years of our analysis. In these later years, we have assumed CO_2 prices to rise and the free allocation to diminish. Both factors make the financial impact in later years more pronounced. For example, CO_2 costs for the new long-haul airplane will be about 520,000 Euros per year in 2015 at discounted values, but 5.5 million Euros per year in 2030 in undiscounted values. One feature of the aviation ETS, the benchmark on which free allocation is based, is interesting in this context. The value of free allocations granted by the benchmarking process can be considerable.

The influence of CO_2 is also reflected in higher purchase option premiums. Again, we find that long-haul planes benefit more from the CO_2 price. It is interesting to remember the high impact of fuel burn reduction we found in our sensitivity analysis. This underlines the importance of airlines, manufacturers, and other stakeholders in the airline industry in reducing the kerosene consumption of airplanes.

In a more general context, the ETS does have two effects on airlines: First, it is an incentive to renew airplane fleets with more efficient ones to save on kerosene and CO_2 costs. Second,

the costs of CO_2 on the existing fleet reduce internal financing opportunities for new airplanes.

For the first influence, it will be interesting to see the implications of the aviation ETS on the purchase strategy of airlines, both in and outside of the EU. Clearly, EU carriers are more affected by the ETS, because, basically, all their routes are affected by the ETS. For non-EU carriers a question could be to analyze whether it makes more sense to deploy a modern plane on routes to Europe to save on CO_2 emissions and the resulting costs.

For the second influence, airlines are lobbying to redistribute the proceedings from the ETS auctions back to the aviation sector. Whether this will happen is a big question, given the current drive for austerity in much of Europe. Possible (and worthwhile) opportunities for government interventions exist in the aviation sector: Basic research on engine technologies such as open rotors or infrastructure investment in the long overdue single European air traffic control that avoids unnecessary route deviations are prime examples.

It will be interesting to see the actual reactions of airlines and manufacturers in the future when CO_2 costs become more relevant to the bottom line. Analyzing the impacts of the ETS with real airline data, possibly for different carrier types such as network carriers, low-cost carriers, and cargo carriers, or exploring the influences on route deployment are interesting suggestions for future research. Also, a more detailled modeling of the fleet renewal process will be an interesting research aspect. Modeling fleet renewal for airlines is a complex task due to the numerous uncertainty factors (next to the ones discussed here, e.g., resale values, efficiency improvements of new airplanes and performance degradation of old planes). Our financial evaluation is a solid starting point for such a research.

7 CONCLUSION AND OUTLOOK

7.1 CONCLUSION

The inclusion of aviation into the EU's ETS poses new challenges for airlines, but there are also a number of ways these challenges can be addressed by the aviation industry.

Surcharges, common already for the most volatile input factor for airlines today – kerosene – certainly will be part of the solution. If surcharges are levied intelligently, as discussed in Chapter 2, airlines can improve the profit situation under adverse conditions compared with current industry practice. Given the elaborate revenue management techniques applied to ticket prices, it is surprising that most airlines do not differentiate their surcharges to match different route and travellers' characteristics. As shown, the benefits can be substantial, especially when considering the thin margins common in the airline industry. However, even with smart surcharges, airlines' profits will decrease with increasing input factor costs. Surcharges can pass on only some parts of the price increases of input factor costs and therefore cannot prevent an erosion of profits.

Biofuels and their adoption, as discussed in Chapter 4, can become a key element for a truly sustainable aviation industry. Currently, high costs and limited availability relegate their adoption to limited test trials and public relation efforts. Nevertheless, the time has come to start these trials to prepare the well-established kerosene-centric infrastructure for aviation for the arrival of biofuels. For example, Robert Sturz, United Airline's Managing Director of Strategic Sourcing, said recently on a biofuel conference: "Given the price volatility, anything we can do to wean ourselves off crude oil onto other feedstocks with more cost stability gives us the ability to run our business a whole lot better" [Surgenor, 2012b].

Building the required infrastructure up-, mid- and downstream of the production chain of biofuels is an enormous task. Finding sufficient areas to grow the feedstocks, selecting the right feedstocks (sometimes genetically modified), building the expensive refining infrastructure, and getting pipeline access to these refineries are all among the tasks that need to be accomplished before a commercially viable biofuel supply chain can be established. Despite these efforts, biofuels are still relatively easy to introduce into the aviation industry as all currently pursued fuels are of the drop-in type (they can be used in existing engines and airplanes without any modifications).

Finally, sustainability concerns also affect biofuels. If feedstocks are grown on arable land suitable for human food production, there is a risk of crowding out the human feedstock. As the most suitable biofuel production areas are in sun-rich developing countries, this makes matters worse. Second-generation feedstock that can be grown on non-arable land have addressed many of the human food concerns. However, there are fears that biofuels are grown on cleared jungle, thereby threatening the ecosystem there. Third-generation biofuels, generated from algae, could all overcome these concerns, but their technological market readiness is not expected before the end of the next decade.

The inclusion of aviation into the ETS can reduce the cost differential between biofuels and kerosene. This is one way that, as shown, the ETS can promote the usage of biofuels. With CO_2 prices near all-time lows, the influence of CO_2 currently will be only marginal. At the moment, high kerosene prices keep the total cost of kerosene at high levels and are a strong incentive for biofuels. Whether the total cost of kerosene is high because of high kerosene prices and low CO_2 prices or because of moderate kerosene prices and moderate CO_2 prices does not matter in the end. Important for the widespread adoption of biofuels is that production volumes rise to larger volumes, and producers and consumers alike can reap the benefits of moving down the experience curve.

The other strategy, redistributing the proceeds from the ETS, would certainly have its benefits. However, given the current drive for austerity in Europe, it seems unlikely that such state support could come into action. What the results of the state support scenario show, however, is that it only takes a moderate investment into refining capacities to promote the usage of biofuels. Currently, this investment is not undertaken due to high uncertainties surrounding the different technologies for the production of biofuels. No biofuel producer wants to be stuck with an expensive refinery supporting a technology that turns out to be technologically inferior and therefore more expensive to produce. Pooling biofuel purchase volumes of airlines and committing to a fixed volume at a predetermined price could help to overcome such an underinvestment without explicit state support.

For the financial evaluation of airplanes, discussed in Chapter 6, the impact of the CO_2 costs is most tangible to airlines already. Given the long economic lifetime of airplanes, airlines take into account every aspect of costs and revenues. CO_2 costs are the newest of these costs. As shown, CO_2 costs for long-haul planes can be significant. For short-haul planes, kerosene and CO_2 costs are not as significant. However, for short-haul routes, the competition usually is much higher due to many LCCs in Europe, and therefore costs savings from more efficient planes can be decisive. For non-European airlines that are only partly affected by the ETS (as most planes do not fly fixed routes), the financial evaluation of new airplanes becomes more complicated. European airlines are affected basically on all flights, as both in- and outbound flights fall under the ETS.

For the pricing of purchase options, the high volatility of CO_2 has a significant impact on purchase options. With high uncertainties around the development of CO_2 prices, the flexibility incorporated into purchase options becomes more valuable. With a more maturing ETS markets, the volatility in EUAs and EUAAs probably will decrease.

Where do the methods discussed stand in terms of implementation, and what are key barriers that need to be over-

come? Clearly, application of surcharges is one of the easiest ways an airline can react to the cost increases of the ETS. No change to the existing infrastructure is required to increase surcharges. However, these price increases trigger demand reactions. To keep these reactions to a minimum, a solution similar to the one proposed in Chapter 2 could be used. For this, changes to revenue management systems and reservation systems would be required.

Biofuels have passed one critical hurdle by gaining certification for their use in commercial jets. The task for the coming years will be to establish the necessary infrastructure. Most forecasts do not expect a major breakthrough for the adoption of biofuels before the middle of the next decade.

Purchasing more efficient airplanes has two main limitations: First, the next generation of more efficient airplanes, both for short- and long-haul routes, will not be ready for entry into service before the middle of the decade. Furthermore, these airplanes have sold hundreds of units for each of the two major OEMs already, which has created several years of order backlog. Both factors make this clearly a mid- to long-term option. Second, a complete fleet renewal for a major airline takes several years. This is mainly due to the financing of these plans and the limited production volumes available. The key to implementing the fleet renewal, then, is to cover the assumed fleet renewal needs with a combination of fixed orders and purchase options. This is necessary to have both a constant fleet renewal process and the flexibility to react to a changing environment, a critical feature of the airline industry.

The methods discussed in Parts 2 to 6 are only some of the options airlines have to reduce their exposure to the costs of CO_2. It seems as though there is no one silver bullet to solve the problem of CO_2 costs. In fact, airlines will use any method that is cost-effective under the prevailing kerosene and CO_2 prices. All three discussed methods can be combined, and certainly there are more methods that could be simultaneously employed, such as a single European air traffic control area or reduced cruising speeds to save fuel. With kerosene prices near record highs, many of the feasible emission reduction

levers have already been applied by airlines. For others, the additional cost of CO_2 can be a decisive factor when evaluating the costs and benefits of fuel-saving measures.

7.2 OUTLOOK

In this last chapter, a short outlook on further topics, both beyond the thesis and a suggestion for further research, is given.

One of the reasons the results show mostly a modest impact of the CO_2 costs on the airlines' decisions is that CO_2 prices are near all-time lows in the EU at the moment. The economic slowdown in the EU has reduced climate emissions so much that the free allocation granted in the cap-and-trade ETS is generous. Many companies can sell excess allowances on the market, which brings down prices. In fact, the price of EUAs is so low that some countries, such as Austria, have purchased allowances to avoid paying penalties agreed upon under the Kyoto protocol [Die Presse, 2012]. It is under the principle of emission trading that prices reflect the scarcity of emissions. Once economic activity returns to its normal path in the EU, prices for CO_2 emissions should increase again. Most mid-term forecasts see the price of CO_2 between 25 and 35 Euro per tonne in 2020. Clearly, this will support the importance of the topics discussed in this thesis.

Currently, international aviation is included in emission trading only in the EU. Other nations, such as New Zealand, have included domestic aviation in emission trading. International aviation was not included in the Kyoto protocol, and therefore it is very hard to reach an international agreement on aviation bunker fuels. The United Nations (UN) civil aviation subsidiary ICAO opposed international emission trading in a controversial declaration on November 2, 2011. The chance of an international agreement for emission trading for aviation therefore seems slim in the near future. It is to be hoped that the successor to the Kyoto protocol will include international aviation. The EU aviation-ETS specifically mentions the possibility for bilateral or international "equivalent measures" to

which the EU-ETS could be linked to avoid the double billing for CO_2 emissions of airlines.

One reason to fear the opposite is the heavy opposition by several countries against the EU's aviation-ETS. In particular, the US, Russia, and China are leading among a number of countries opposing the inclusion of aviation into the ETS. The retaliatory moves considered or applied range from the suspension orders with the European airplane manufacturer Airbus worth multi-billion Euros would make the participation of national airlines illegal. Legal appeals in European courts against the inclusion have so far been rejected [Court of Justice of the European Union, 2011]. It therefore remains to be seen how the EU deals with this pressure from other countries.

Potential areas for future research include the actual financial hedging strategies of airlines for their CO_2 emissions. Airlines can hold a portfolio of freely allocated EUAAs, bought EUAs, and CERs. Managing this portfolio, including the corresponding derivatives, and matching this with the emission demands of an airline resulting from CO_2 emissions minus the free allocation will be a complex task. Exploring this task academically should be an interesting point for future research.

Also, there are valuable extensions to the methods developed in this thesis. Applying, for example, the methods from Chapter 2 and 6 to real airline data and publishing the findings in anonymous form would be a interesting next step. One addition to the discussed financial evaluation of new airplanes is the actual impact on fleet renewal plans of airlines. Simulating fleet renewal for airlines is a complex task due to the numerous uncertainty factors involved. The work presented here can be a good starting point for this.

The topic of biofuels also holds presents interesting avenues for further research: Uncertainties around the ideal feedstock and refining technology are so high at the moment that it could be interesting to analyze from a retrospective view the success factors for the prevailing technology. Furthermore, it would be interesting to retrospectively compare the biofuel uptake in different parts of the world to determine whether

local emission trading schemes really did impact the adoption of biofuels.

The emission trading for airlines has just started in 2012. Undoubtedly, it will pose many more questions to academics and practitioners in the future.

A

SOLUTION FOR THE CONTROL RULE

Our detailed mathematical derivation of our control rule is developed here in the appendix.

Assuming T periods of time and a terminal value of π_T the value function in period T (the last period) can be denoted with equation 60

$$V_T^{\star}\left(p_{0r}, c_0^K, c_0^C\right) = \pi_T\left(p_T, u_T, \Delta_T^K, \Delta_T^C\right) + \underset{\Delta_t^K,\ldots,\Delta_{T-1}^K;\Delta_t^C,\ldots,\Delta_{T-1}^C}{E}\left[\sum_{t=0}^{T-1} V_t\left(p_t, u_t, \Delta_t^K, \Delta_t^C\right)\right] \tag{60}$$

The optimal policy for the control variable u_{tr} now is the set of u_{tr}that maximizes V_T

$$V_T^{\star}\left(p_{0r}, c_0^K, c_0^C\right) = \max_{u_{tr}\in U} V_T \tag{61}$$

In the following section we will provide the analytically derived optimal solution, the so called control rule, to the problem formulation and an interpretation of it.

Our analysis is a dynamic programming in discrete time. By replacing the state variable of one period with the flow equations defined above and then taking the derivative for the control variable, we can find an analytical solution for the optimal value of the control variable u_{tr}.

Theorem: *For the proposed problem formulation 2 there is an analytical solution in the form of equation 62 for the optimal solution of the control rule* u_{tr}^*

$$\begin{aligned} u_{tr}^* &= \frac{w\left(a_r d^{LH} + b_r w_r^{BC}\left(d^{LH} + d_r k^{LH}\right)\left(d_r k^F + d^{TO}\left(k^{TO} - k^F\right) - 2b_r d^{LH} p_{tr}\right)\right)}{2b_r d^{LH}\left(c_t^K \Delta_t^K\left(1+\Delta_t^K\right) + c_t^C \Delta_t^C\left(1+\Delta_t^C\right) e\right) p_{tr}} \\ \text{with} \\ w &= c_t^K\left(1+\Delta_t^K\right) + c_t^C\left(1+\Delta_t^C\right) e \end{aligned} \tag{62}$$

Proof: We can solve a dynamic programming backwards from the last period. For the final period T we assume a terminal value of p_{Tr} to bring the programming to an halt. The

profit function π_{T-1}then is a result of the current period plus the expectation of period T.

$$\begin{aligned}\pi_{T-1} &= \sum_{r=1}^{R}\left[p_{T-1,r}(u)-k_r(d)\left(c^K_{T-1}(\Delta^K)+ec^C_{T-1}\left(\Delta^C\right)\right)\right] \\ &\quad (a_r-b_r\times p_{T-1,r})-F+E(\pi_T)\end{aligned} \tag{63}$$

The expected value of π_T depends on the decisions taken in period $T-1$. Applying the transition equations for $p_{T,r}$ defined in section 4 leads to the following decision problem

$$p_T = p_{T-1,r}(1+\left(\frac{c^K_{T-1}}{c^K_{T-1}+ec^C_{T-1}}\Delta^K_{T-1}+\frac{c^C_{T-1}}{c^K_{T-1}+ec^C_{T-1}}e\Delta^C_{i-1}\right)u_{T-1,r}) \tag{64}$$

In period $T-1$, the decision variable $u_{T-1,r}$ then takes the following form:

$$u_{T-1,r}=\frac{p_{T,r}-p_{T-1,r}}{\left(\frac{c^K_{T-1}}{c^K_{T-1}+ec^C_{T-1}}\Delta^K_{T-1}+\frac{c^C_{T-1}}{c^K_{T-1}+ec^C_{T-1}}e\Delta^C_{i-1}\right)} \tag{65}$$

In period $T-2$, the profit function π_{T-2} depends on profit equation π_{T-2} and the expected value of π_{T-1}(which again depends on the expected value of π_T as shown above). The complete function then takes the form of equation 66:

$$\begin{aligned}\pi_{T-2} &= \sum_{r=1}^{R}\left[p_{T-2,r}(u)-k_r(d)\left(c^K_{T-2}(\Delta^K)+c^C_{T-2}\left(\Delta^C\right)\right)\right] \\ &\quad (a_r-b_r\times p_{T-2,r})-F+E(\pi_{T-1})\end{aligned} \tag{66}$$

Replacing $E(\pi_{T-1})$ with equation 63 gives equation 67

$$\begin{aligned}\pi_{T-2} &= \sum_{r=1}^{R}\left[p_{T-2,r}(u)-k_r(d)\left(c^K_{T-2}(\Delta^K)+ec^C_{T-2}\left(\Delta^C\right)\right)\right](a_r-b_r\times p_{T-2,r})-F+ \\ &\quad \sum_{r=1}^{R}\left[p_{T-1,r}(u)-k_r(d)\left(c^K_{T-1}(\Delta^K)+ec^C_{T-1}\left(\Delta^C\right)\right)\right](a_r-b_r\times p_{T-1,r})-F+E(\pi_T)\end{aligned} \tag{67}$$

Again substituting in the transition equations as defined in equation 2 brings us to equation 68

$$\begin{aligned}\pi_{T-2} &= \sum_{r=1}^{R}\left[p_{T-2,r}-k_r\left(d\right)\left(c_{T-2}^{K}+ec_{T-2}^{C}\right)\right]\left(a_r-b_r\times p_{T-2,r}\right)-F+\Bigg[p_{T-2,r} \\ &\left(\left(1+\frac{c_{T-2}^{K}\left(1+\Delta_{T-2}^{K}\right)}{w}\Delta_{T-2}^{K}+\frac{c_{T-2}^{C}\left(1+\Delta_{T-2}^{C}\right)e}{w}\Delta_{T-2}^{C}\right)\right)u_{T-2,r} \\ &-e_r^{BC}\left(k^{TO}\times d^{TO}+k^{F}\times\left(d_r-d^{TO}\right)\right)\left(1+k^{lh}\frac{d_r}{d^{lh}}\right) \\ &\left(c_{T-2}^{K}\left(1+\Delta_{T-2}^{K}\right)+ec_{T-2}^{C}\left(\Delta_{T-2}^{C}\right)\right)\Bigg]a_r-b_r\times \\ &p_{T-2,r}\left(1+\left(\frac{c_{T-2}^{K}\left(1+\Delta_{T-2}^{K}\right)}{w}\Delta_{T-2}^{K}+\frac{c_{T-2}^{C}\left(1+\Delta_{T-2}^{C}\right)e}{w}\Delta_{T-2}^{C}\right)u_{T-2,r}\right) \\ &-F+E\left(\pi_T\right)\end{aligned} \tag{68}$$

with

$$w = c_{T-2}^{K}\left(1+\Delta_{T-2}^{K}\right)+c_{T-2}^{C}\left(1+\Delta_{T-2}^{C}\right)e$$

Taking the first derivative and solving for $u_{T-2,r}$ gives expression 69, the control rule for optimal $u_{T-2,r}^{*}$

$$u_{T-2,r}^{*} = \frac{w\left(a_r d^{LH}+b_r w e_r^{BC}\left(d^{LH}+d_r k^{LH}\right)\left(d_r k^{F}+d^{TO}\left(k^{TO}-k^{F}\right)-2b_r d^{LH}p_{T-2,r}\right)\right)}{2b_r d^{LH}\left(c_{T-2}^{K}\Delta_{T-2}^{K}\left(1+\Delta_{T-2}^{K}\right)+c_{T-2}^{C}\Delta_{T-2}^{C}\left(1+\Delta_{T-2}^{C}\right)e\right)p_{T-2,r}} \tag{69}$$

with

$$w = c_{T-2}^{K}\left(1+\Delta_{T-2}^{K}\right)+c_{T-2}^{C}\left(1+\Delta_{T-2}^{C}\right)e$$

For period $T-3$ the solution becomes a bit more complex as both the current period $T-3$ and the following period $T-2$ are given only in dependency on u_{T-2} and u_{T-3}. However, the control rule does not grow beyond period $T-3$ and can be written in the generalized form as seen in expression 70:

$$u_{tr}^{*} = \frac{w\left(a_r d^{LH}+b_r w e_r^{BC}\left(d^{LH}+d_r k^{LH}\right)\left(d_r k^{F}+d^{TO}\left(k^{TO}-k^{F}\right)-2b_r d^{LH}p_{tr}\right)\right)}{2b_r d^{LH}\left(c_t^{K}\Delta_t^{K}\left(1+\Delta_t^{K}\right)+c_t^{C}\Delta_t^{C}\left(1+\Delta_t^{C}\right)e\right)p_{tr}} \tag{70}$$

with

$$w = c_t^{K}\left(1+\Delta_t^{K}\right)+c_t^{C}\left(1+\Delta_t^{C}\right)e$$

B

PARTIAL DERIVATIVES FOR THE CONTROL RULE

Partial derivative of the control rule u_{tr}^* for the price p_{tr}

$$\begin{aligned}\frac{\partial u_{tr}^*}{\partial p_{tr}} &= \frac{\left(c_t^K\left(1+\Delta_t^K\right)+c_t^C\left(1+\Delta_t^C\right)e\right)\left(-\frac{a}{b}-\frac{\left(c_t^K\left(1+\Delta_t^K\right)+c_t^C\left(1+\Delta_t^C\right)e\right)z}{d^{LH}}\right)}{2\left(c_t^K\Delta_t^K\left(1+\Delta_t^K\right)+c_t^C\Delta_t^C\left(1+\Delta_t^C\right)e\right)p_{tr}^2} \\ \text{with} \\ z &= \left(e_r^{BC}\left(d^{LH}+d_r k^{LH}\right)\right)\left(d_r k^F - d^{TO}\left(k^F+k^{TO}\right)\right)\end{aligned} \tag{71}$$

Partial derivative of the control rule u_{tr}^* for the constant of the demand function a_r

$$\frac{\partial u_{tr}^*}{\partial a_r} = \frac{c_t^K\left(1+\Delta_t^K\right)+c_t^C\left(1+\Delta_t^C\right)e}{2b_r\left(c_t^K\Delta_t^K\left(1+\Delta_t^K\right)+c_t^C\Delta_t^C\left(1+\Delta_t^C\right)e\right)p_{tr}} \tag{72}$$

Partial derivative of the control rule u_{tr}^* for the slope of the demand function b_r

$$\frac{\partial u_{tr}^*}{\partial b_r} = -\frac{a_r\left(c_t^K\left(1+\Delta_t^K\right)+c_t^C\left(1+\Delta_t^C\right)e\right)}{2b_r^2\left(c_t^K\Delta_t^K\left(1+\Delta_t^K\right)+c_t^C\Delta_t^C\left(1+\Delta_t^C\right)e\right)p_{tr}} \tag{73}$$

Partial derivative of the control rule u_{tr}^* for the kerosene consumption factor in the cruise phase k^F

$$\frac{\partial u_{tr}^*}{\partial k^F} = \frac{\left(d_r - d^{TO}\right)\left(c_t^K\left(1+\Delta_t^K\right)+c_t^C\left(1+\Delta_t^C\right)e\right)^2 e_r^{BC}\left(d^{LH}+d_r k^{LH}\right)}{2d^{LH}\left(c_t^K\Delta_t^K\left(1+\Delta_t^K\right)+c_t^C\Delta_t^C\left(1+\Delta_t^C\right)e\right)p_{tr}} \tag{74}$$

Partial derivative of the control rule u_{tr}^* for the price of kerosene c^K

$$\begin{aligned}\frac{\partial u_{tr}^*}{\partial c_t^K} &= \frac{\left(\frac{a_r c_t^C\left(1+\Delta_t^C\right)\left(\Delta_t^C-\Delta_t^K\right)d^{LH}e}{b_r}+\left(c_t^K\right)^2\Delta_t^K\left(1+\Delta_t^K\right)^2 z+2c_t^C c_t^K\Delta_t^C\left(1+\Delta_t^C\right)\left(1+\Delta_t^K\right)ez+\right.}{dn} \\ &\quad \frac{\left.c_t^C\left(1+\Delta_t^C\right)e\left(c_t^C\left(1+\Delta_t^C\right)\left(2\Delta_t^C-\Delta_t^K\right)ez+2\left(\Delta_t^K-\Delta_t^C\right)d^{LH}p_{tr}\right)\right)\left(1+\Delta_t^K\right)}{dn} \\ \text{with} \\ z &= \left(e_r^{BC}\left(d^{LH}+d_r k^{LH}\right)\right)\left(d_r k^F - d^{TO}\left(k^F+k^{TO}\right)\right) \\ dn &= 2d^{LH}\left(c_t^K\Delta_t^K\left(1+\Delta_t^K\right)+c_t^C\Delta_t^C\left(1+\Delta_t^C\right)e\right)^2 p_{tr}\end{aligned} \tag{75}$$

Partial derivative of the control rule u^*_{tr} for the price change of kerosene Δ^K

$$\frac{\partial u^*_{tr}}{\partial \Delta^K_t} = \frac{c^K_t \left(\frac{a_r d^{LH} \left(-c^K_t \left(1+\Delta^K_t\right)^2 + c^C_t \left(1+\Delta^C_t\right)\left(-1+\Delta^C_t-2\Delta^K_t\right)e\right)}{b_r} - \left(c^K_t\right)^2 \left(1+\Delta^K_t\right)^2 z) + \right.}{dn}$$
$$\frac{c^C_t \left(1+\Delta^C_t\right) e \left(c^C_t \left(1+\Delta^C_t\right)\left(-1+2\Delta^C_t-2\Delta^K_t\right) ez - 2\left(-1+\Delta^C_t-2\Delta^K_t\right) d^{LH} p_{tr}\right)}{dn}$$
$$\left. \frac{-2c^K_t \left(1+\Delta^K_t\right)\left(c^C_t \left(1+\Delta^C_t\right)\left(1-\Delta^C_t+\Delta^K_t\right) ez - \left(1+\Delta^K_t\right) d^{LH} p_{tr}\right)}{dn} \right) \quad (76)$$

with

$$z = \left(e^{BC}_r \left(d^{LH} + d_r k^{LH}\right)\right)\left(d_r k^F - d^{TO}\left(k^F + k^{TO}\right)\right)$$
$$dn = 2d^{LH}\left(c^K_t \Delta^K_t \left(1+\Delta^K_t\right) + c^C_t \Delta^C_t \left(1+\Delta^C_t\right) e\right)^2 p_{tr}$$

Partial derivative of the control rule u^*_{tr} for route distance d_r

$$\frac{\partial u^*_{tr}}{\partial d_r} = \frac{\left(c^K_t \left(1+\Delta^K_t\right) + c^C_t \left(1+\Delta^C_t\right) e\right)^2 e^{BC}_r \left(k^F \left(d^{LH} + 2d_r k^{LH} - d^{TO} k^{LH}\right) + d^{TO} k^{LH} k^{TO}\right)}{2d^{LH}\left(c^K_t \Delta^K_t \left(1+\Delta^K_t\right) + c^C_t \Delta^C_t \left(1+\Delta^C_t\right) e\right) p_{tr}} \quad (77)$$

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COLOPHON

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DECLARATION

Last Name: Girardet **First Name:** Daniel

Affirmation – Statutory Declaration

According to § 10 part 1 no. 6 of the Doctoral Studies' Guide Lines

(dated 5th March 2008 as amended on the 8th September 2009)

I hereby declare, that the

Dissertation

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Daniel Girardet