Internalising the climate costs of European aviation

An analysis of the damage costs and the prevention costs of CO_2 emission from EEA aviation, policy options to internalise these costs, and the impact on ticket prices and demand

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Abstract:	Considering the significant impact of aviation on global warming, the ambitious climate targets of the European Union (EU), and the potential of a carbon price as a catalyst for Sustainable Aviation Fuels (SAFs), this thesis examines whether it would be more cost-efficient to internalise the damage costs (based on the Social Cost of Carbon or SCC) or the prevention costs (based on the Marginal Abatement Cost or MAC of SAFs) of CO_2 emissions from European aviation. The comparative analysis concludes that the MAC (60-321 EUR/tCO_2) is higher in most scenarios and in most years until 2050 than the SCC (120-202 EUR/tCO_2). However, the total prevention costs (432-547 billion EUR) are substantially lower over the entire thirty-year period than the total damage costs (770 billion EUR), so internalisation of the prevention costs is more cost-efficient. The EU ETS or a fuel tax is the best policy instrument to internalise these costs. This would lead to ticket price increases of 8-34% and a downwards impact of 6-25% on the demand for aviation, compared to business as usual.
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Content

Preface

From February until May 2021, I have conducted research at the independent research and consultancy organisation CE Delft in the Netherlands on the internalisation of climate costs of European aviation, resulting in this study. It is my thesis for the Master of Science in Environmental and Natural Resource Economics at the University of Copenhagen, the study program I have been following in Denmark from September 2019. I have had an interest for environmental policy and economics since I was a child. Also taking into account my passion for traveling, with this study I hope to contribute to a more sustainable future for the transport sector, Europe, and the planet we all live on.
I could not have performed this successfully without the help and support from some important people. First of all, my parents and girlfriend, who have always been supporting me with constant love and understanding. Second, I would like to thank my two supervisors, Prof. Dr. Søren Bøye Olsen and Dr. Jasper Faber. Dr. Bøye Olsen did not only guide me through the process of writing a thesis, but also contributed for a large part to my education in the preceding one-and-a-half years as my head of studies and my teacher in the course Economic Valuation Methods and Cost-Benefit Analysis. Dr. Faber, one of the most renowned researchers in aviation, maritime transport and climate policy, regularly reviewed my methodology and results and gave me helpful advice as my direct supervisor at CE Delft. I would also like to thank all the others at CE Delft who were always available for questions. In particular, the inputs from Anouk van Grinsven and Dr. Sander de Bruyn have been very helpful. Last, but not least, I would like to thank all researchers in the academic and professional community for the many studies and reports I have consulted for this thesis.

List of abbreviations

AMS	Amsterdam Airport Schiphol (The Netherlands)
ASTM	American Society for Testing and Materials
AtJ	Alcohol-to-Jet
ATL	Hartsfield-Jackson Atlanta International Airport (United States)
CDG	Charles de Gaulle Airport (Paris, France)
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DAC	Direct Air Capture
DICE	Dynamic Integrated model of Climate and the Economy
DSHC	Direct Sugars to Hydrocarbons
DXB	Dubai International Airport (United Arab Emirates)
EASA	European Union Aviation Safety Agency
EEA	European Economic Area; European Environment Agency
EFTA	European Free Trade Association
ERF	Effective Radiative Forcing
ETS	Emission Trading System
EU	European Union
EUA	European Union Allowance
EUAA	European Union Aviation Allowance
EU+	European Union, United Kingdom and European Free Trade Association
FRA	Frankfurt Airport (Germany)
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEFA	Hydro-processed fatty acid Esters and Free fatty Acids
HFS	Hydroprocessing of Fermented Sugars
HTL	Hydrothermal Liquefaction
HVO	Hydro-treated Vegetable Oil
IAM	Integrated Assessment Model
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
ILUC	Indirect Land-Use Change
IPCC	Intergovernmental Panel on Climate Change
IWG	Interagency Working Group on the Social Cost of Greenhouse Gases
LIS	Lisbon Airport (Portugal)
LTO	Landing and Take-Off
MAC	Marginal Abatement Cost
MACC	Marginal Abatement Cost Curve
MLPY	Million Litres Per Year
MSW	Municipal Solid Waste
NDC	Nationally Determined Contribution
NO_x	Nitrogen oxide
NPV	Net Present Value

PFAD	Palm Fatty Acid Distillate
PtL	Power-to-Liquid
RED	Renewable Energy Directive
RF	Radiative Forcing
RPK	Revenue Passenger Kilometer
RTK	Revenue Ton-Kilometres
SAF	Sustainable Aviation Fuel
SCC	Social Cost of Carbon
SIP	Synthetic Isoparaffinic fuel
SPK	Synthetic Paraffinic Kerosene
UCO	Used Cooking Oil
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
VAT	Value Added Tax
VCO	Voluntary Carbon Offset

Introduction

In line with the Paris Agreement from 2015 and to achieve climate neutrality in 2050, the European Green Deal sets out the need to reduce transport emissions in the European Union (EU) by 90 percent in 2050, compared to 1990-levels (European Commission, 2021a). The aviation sector will have to contribute to this target, however is currently expected to increase by 67 percent in terms of CO_2 emissions until 2050 (NLR & SEO, 2021). Assigning a price to CO_2 emissions, and thus ensuring that climate costs will be explicitly taken into account, has been repeatedly suggested as a solution to accelerate the transition to sustainable aviation and to reduce aviation-related CO_2 emissions. Still, a thorough analysis of how high this carbon price must be, how it should be implemented, and what the impacts would be, has not been conducted to date. This study quantifies the CO_2 costs of European aviation, analyses the policy options to internalise these costs, and discusses the effects of these policies on ticket prices and demand.

Considering all global greenhouse gas (GHG) emissions contributing to climate change, CO_2 from fossil fuels and carbonates is the most dominant factor: 38 Gigaton (Gt) of CO_2 out of 54 Gt CO_2-equivalent (CO_2e) GHG emissions, or 70 percent in 2019 originate from fossil CO_2 emissions (United Nations Environment Programme, 2020). This excludes emissions from indirect land-use change (ILUC). Based on a current policies scenario, these emissions are forecast to increase to 59 Gt CO_2e in 2030 (UNEP, 2020). However, in order to stay below the 2°C goal of maximum average global warming (as stated in the Paris Agreement), annual global emissions need to be at most 41 Gt CO_2e in 2030. If the world is to stay below 1.5°C of maximum average global warming, annual global emissions even need to decrease to at most 25 Gt CO_2e in 2030; less than half of the current forecast emissions (UNEP, 2020).

The International Civil Aviation Organisation (ICAO), responsible for the principles and techniques of international air navigation, forecasted that by 2050 international aviation emissions could triple compared to 2015. According to the United Nations Environment Program (UNEP), unless states choose to include international aviation emissions in their initial Nationally Determined Contributions (NDCs), these are not addressed by national policies. To limit global warming, according to the UNEP, international aviation must be completely decarbonised by 2050 for the 1.5°C target and by 2070 for the 2°C target. ICAO Member States have therefore proposed four categories of measures to achieve these goals: aircraft technologies, operational improvements, Sustainable Aviation Fuels (SAFs) and a market-based mechanism (UNEP, 2020). This study focuses on a combination of the latter two, as these are the most promising measures to decarbonise international aviation.

The geographical scope of this research is the European Economic Area (EEA; the EU, Norway, Liechtenstein, and Iceland), although this term is used interchangeably with Europe or European throughout the thesis. If the 28 members of the EU in 2019 (when the UK was still part of the EU) are counted together, they have emitted 19 percent of the global passenger transport total. This makes the EU the second largest aviation emitter of the world, behind the United States (US) (International Council on Clean Transportation, 2020). Although the EU has committed itself to a 90 percent reduction in transport emissions by 2050, so far aviation in the EEA (thus including the EU) has increased by more than 10 percent in the last decade (EUROCONTROL, 2021).

Since 2012, CO_2 emissions from aviation have been included in the EU Emission Trading System (ETS). This means that all airlines operating in Europe are required to monitor, report, and verify their emissions, and to give up allowances against those emissions (EC, 2021a). As of 2021, a global market-based measure was added to the EU ETS: the ICAO agreed to implement the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). This scheme aims to stabilise CO_2 emissions at 2019-levels by requiring airlines to offset the growth of their emissions from 2021. It is estimated that CORSIA will result in the offset of only 12 percent of total international and domestic aviation emissions by 2030 (UNEP, 2020). The EU ETS has contributed to reducing aviation emissions by about the same amount between the entire period from 2013 to 2020, as the total amount of emissions in the EEA were in the year 2019 alone (European Aviation Safety Agency, European Environment Agency & EUROCONTROL, 2019; NLR & SEO, 2021). Emission reduction schemes for aviation have thus not yet met their full potential.

Apart from the EU ETS, there is no price on CO_2 emissions of aviation. Likewise, other negative externalities are not accounted for. For example, long-term exposure to aircraft noise is linked with a variety of health impacts, including heart diseases and sleep disturbance (EASA, EEA & EUROCONTROL, 2019). In addition, air pollution by aviation emissions can cause lung inflammation, respiratory problems, bronchitis, and asthma (EASA, EEA & EUROCONTROL, 2019). All of these costs are currently not internalised in flight ticket prices. Moreover, whereas fuels (the main source of transport emissions) on road and rail transport are mostly taxed, fuels used in commercial aviation are exempt from excise duties in the EU (CE Delft, 2018a). Many countries also exempt flight tickets from Value Added Tax (VAT) or apply a zero VAT rate in the case of international aviation (CE Delft, 2019a). Aviation Economics estimated that the true price of an average ticket in the Netherlands should be 63 percent higher than the current actual price, taking both external costs and exempted charges into account (Aviation Economics, 2018). The relatively low prices could be an important explanation for the robust demand for flight tickets, resulting in high emissions.

Out of all external costs and exempted charges in aviation, external climate costs still constitute the largest share of almost 40 percent on an average flight ticket from the Netherlands (Aviation Economics, 2018). These costs are largely caused by CO_2 emissions. One way to internalise the external climate costs, is to take its damage costs to the environment into account. These damage costs are constituted by the Social Cost of Carbon (SCC), which values the economic damages that would result from emitting one additional ton (t) of CO_2 (tCO_2) into the atmosphere. According to standard economic theory from Pigou (1920), this would be sufficient, as it would optimise economic welfare by eventually moving emitters to the optimal pollution level.

An alternative approach would be to have a focus shift from the damage costs to the prevention costs. In this case, the carbon price internalises the Marginal Abatement Cost (MAC), or the costs of preventing the CO_2 from being emitted in the first place. Apart from reducing the number of flights, which is not preferred by the airline industry and has limited political and societal support, the only way to reduce total emissions is to reduce the quantity of emissions per flight. This can partly be done by increasing the efficiency of aircrafts and engines, but it will not even be enough to make up for the expected demand growth (EASA, EEA & EUROCONTROL, 2019). Full implementation of SAFs such as biofuels and e-fuels essentially is the only way to make aviation (almost) carbon-neutral by 2050. However, the current price difference between SAFs and fossil kerosine is still obstructing large-scale implementation. Internalising this difference in the carbon price could solve the problem by making SAFs commercially available and giving them a competitive advantage;

an increase of the carbon price to make SAFs cost competitive was also suggested by NLR & SEO (2021) and this study will explore their suggestion.

Considering the impact of aviation on global warming, the ambitious climate targets of the EU, and the potential of an internalised carbon price as a catalyst for SAFs in making the aviation sector more sustainable, this thesis answers the following research question:

> *"Is the damage cost approach or the prevention cost approach more cost-efficient to internalise the climate costs of CO_2 emissions from European aviation?"*

This question will be answered through the following subquestions:

> *"What are the external CO_2 costs of aviation in the EEA measured in damage costs and prevention costs until 2050, how can these costs be internalised through policy, and what are the effects of such a policy on ticket prices and the demand for aviation?"*

The remainder of this thesis is organised as follows. Chapter 1 is a literature review of CO_2 emissions from European aviation in the past decade, as well as a projection until 2050 for different scenario's. Chapter 2 starts with a short review of the best and most recent estimations of the SCC, then quantifying the projected CO_2 emissions from European aviation in terms of damage costs and differentiating these over common flight routes. Chapter 3 presents the most recent estimations of the availability and costs of SAFs, both now and in the future. Based on the Marginal Abatement Cost Curve (MACC) of these carbon mitigation options, the prevention costs will be estimated. Chapter 4 explains how different measures could internalise these costs, discussing current and potential policy implementations and listing their advantages and disadvantages. These policy options include (adjustments of) the EU ETS and CORSIA, but also a potential fuel or ticket tax. Chapter 5 quantifies the impact of climate cost internalisation on ticket prices and demand, reflecting on the cost pass-through and price elasticity of European aviation. Chapter 6 provides a comparative analysis between the damage and prevention costs, connecting the previous chapters, and a discussion analysing the most important findings and stating the limitations of this study. Last is the concluding summary of this thesis, including suggestions for future research.

1 Past and future emissions

This first chapter provides a literature review of the climate impact of aviation, including both CO_2 and non-CO_2 emissions. After this, the specific impact of CO_2 emissions will be explained. What follows is an overview of the historical CO_2 emissions from European aviation, as well as projections until 2050. The rest of this thesis will be built upon these future scenarios.

Climate impact of aviation

Aviation-related emissions consist of both CO_2 and non-CO_2 emissions, such as contrails, nitrogen oxide, sulphates, soot, and particulate matter. It is not easy to include these different emissions as a multiple of CO_2 emissions (CO_2-equivalent) for aviation, because the climate forcing of non-CO_2 emissions depends on the altitude and geographical location of the aircraft during a flight (Schäfer & Waitz, 2014). For example, some non-CO_2 emissions undergo chemical and physical transformations at cruise altitudes. It is the combination of quantities emitted, residence time, Radiative Forcing (RF), and the temperature response profile of a particular pollutant that determines its overall impact (ICAO, 2019).

Still, to enable comparison between the different emissions from aviation in climate forcing terms, Effective Radiative Forcing (ERF) is the most widely used metric (Lee et al., 2021). Considering historical emissions from global aviation, about 34 percent of aviation-related ERF is caused by CO_2 emissions and about 66 percent is caused by non-CO_2 emissions (UNEP, 2020).
However, the share of CO_2 emissions is likely to increase in the future, as CO_2 stays in the atmosphere for a longer period of time and because the share of some non-CO_2 emissions used to be larger in the past (and efficiency improvements led to a decrease in these emissions).

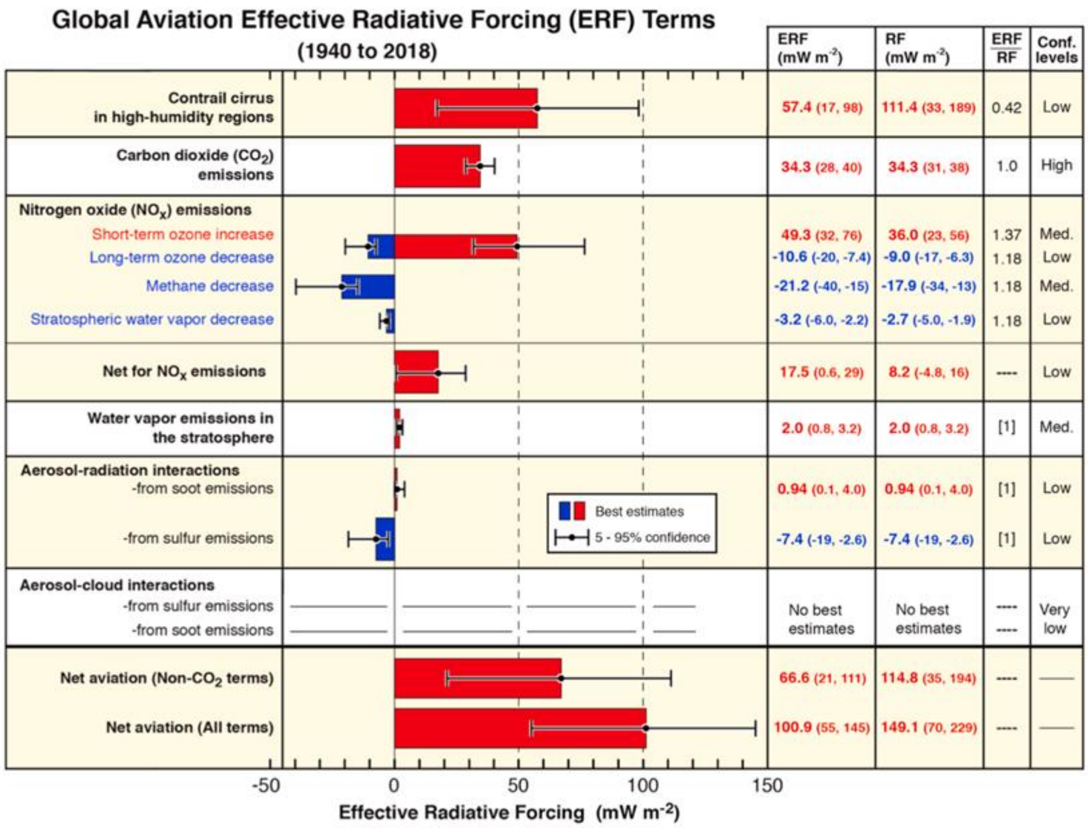
The most important non-CO_2 impacts from aviation are contrails and nitrogen oxide emissions. Water vapour only has a minimal direct warming impact (due to its short lifespan in the atmosphere), but its presence has an indirect impact by contributing to the formation of contrails. These contrails and their induced cirrus clouds (in the case of a sufficiently cold atmosphere) trap infrared rays, which produces a warming effect that can be three times the impact of CO_2 emissions (Environmental and Energy Study Institute, 2019). Nonetheless, the level of scientific understanding for this effect is ‘very low’ (EASA, EEA & EUROCONTROL, 2019).

Nitrogen oxide emissions (NO_x) chemically form ozone, producing a warming effect. On the other hand, they have a cooling effect by eliminating methane. All together, nitrous gases have a net warming influence on the climate (EESI, 2019). Although other aviation emissions are forecast to increase, current predictions for NO_x indicate that advanced engine technology could lead to a downward trend after 2030. The level of scientific understanding for this effect is ‘medium to low’ (EASA, EEA & EUROCONTROL, 2019).

Other emissions from aviation include sulphates, soot, and particulate matter. Sulphates reflect sun rays, producing a small cooling effect. Soot absorbs heat; these black carbon particles become ice crystal nuclei in the atmosphere, contributing to contrail-induced cirrus clouds (EESI, 2019). However, particles of soot only have a very small direct RF in terms of warming (EASA, EEA & EUROCONTROL, 2019). More recently, attention has been directed at non-volatile particulate matter, particularly ultra-fine particles, but this effect is still uncertain (ICAO, 2019).

A visual summary of the most recent estimations of climate forcing terms from global aviation by Lee et al. (2021) is presented in Figure 1.

Figure 1 – The best-estimates for climate forcing terms from global aviation, 1940-2018



Source: Figure copied from Lee at al. (2021).

Impact of CO_2 emissions

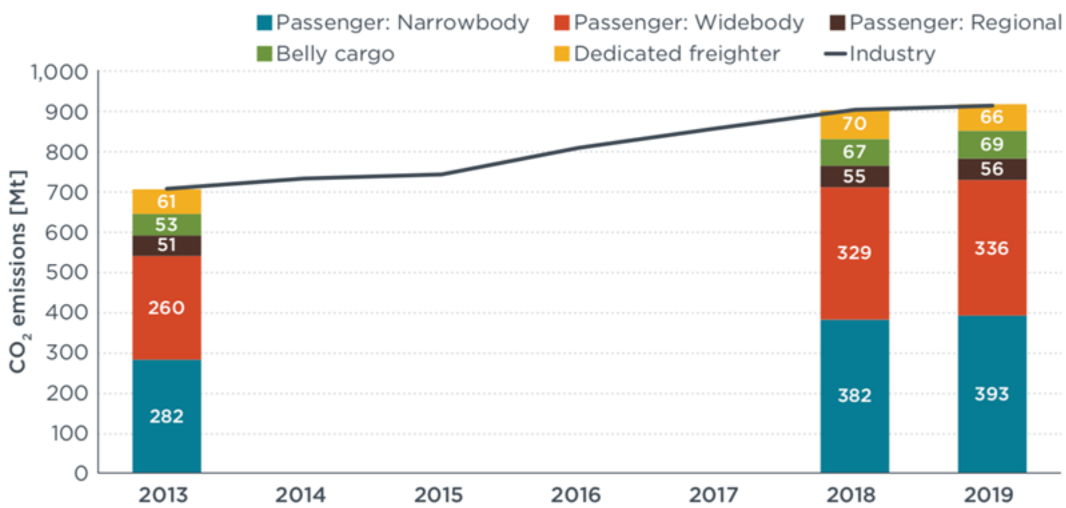
Carbon dioxide (CO_2) is the largest individual contributor to global warming from aviation, with relatively high certainty. Its long lifetime in the atmosphere, for hundreds to thousands of years, makes CO_2 especially potent as a GHG (EESI, 2019). Although the combined ERF of non-CO_2 emissions is much larger, only the ERF of water vapour is potentially larger on its own. Nevertheless, the level of scientific understanding of this effect is still 'very low', whereas the level of scientific understanding for the effect of CO_2 is 'high' (EASA, EEA & EUROCONTROL, 2019).

Global CO_2 emissions from aviation increased from 706 million tons (Mt) in 2013 to 920 Mt in 2019, which is a 30 percent increase in six years, or an average annual increase of 4.5 percent. Passenger flights are responsible for about 85 percent of all commercial aviation-related CO_2 emissions, amounting to 785 Mt in 2019 (ICCT, 2020).

Assuming that fossil jet fuels are used, 3.16 kilograms (kg) of CO_2 is produced per 1 kg of fuel consumption, regardless of the stage of the flight (EESI, 2019). Based on this, transporting one passenger emitted 90 grams (g) of CO_2 per kilometre (km) on average in 2019 (ICCT, 2020).
However, CO_2 emissions are normally assigned and differentiated based on the type of aircraft or flight (narrow-body, wide-body and regional), the seating class (premium and economy), and the distance of the flight (short-haul and long-haul).

The average narrow-body flight of 1,322 km (63 percent of departing passenger flights, 51 percent of passenger CO_2 emissions) emitted 86 g CO_2 per revenue passenger kilometre (RPK; the number of km travelled by paying passengers), whereas the average wide-body flight of 4,675 km (8 percent of departing passenger flights, 42 percent of CO_2 emissions) emitted 89 g CO_2 per RPK. The remaining regional flights (29 percent of departing passenger flights, 7 percent of CO_2 emissions) had a higher intensity of 162 g CO_2 per RPK. Total emissions by these categories in 2013, 2018, and 2019 are presented in Figure 2, also including belly cargo and dedicated freighter flights (ICCT, 2020).

Figure 2 – CO_2 emissions by operations and aircraft class in 2013, 2018, and 2019



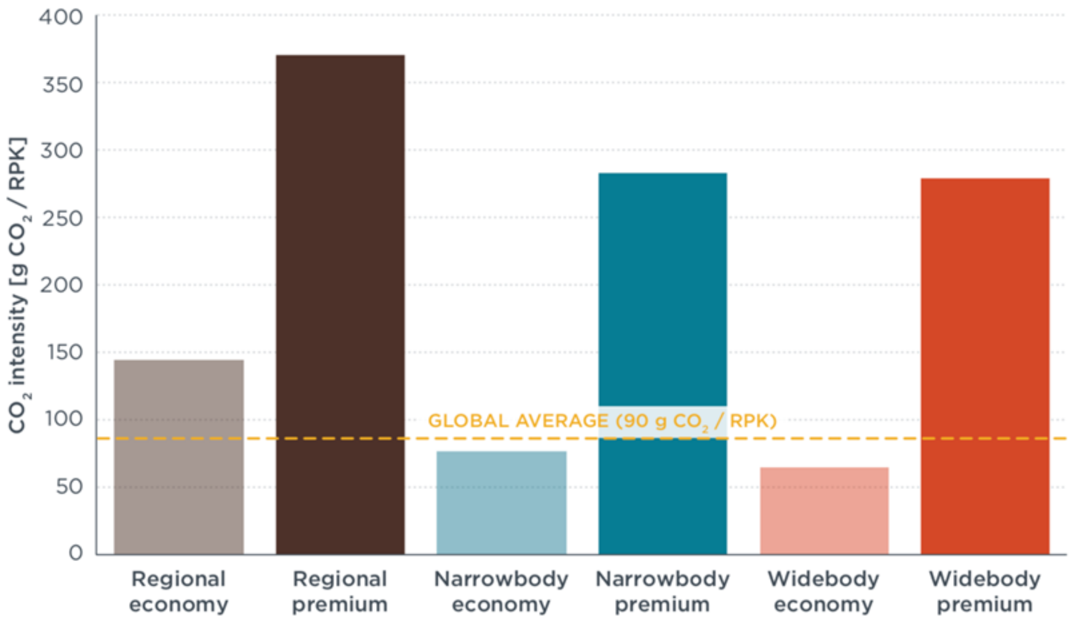
Source: Figure copied from ICCT (2020).

A larger share of the fuel consumption can be apportioned to premium seating (first and business class), because it takes up more floor area on an airplane than economy seating; premium seating emits between 2.6 and 4.3 times more CO_2 per RPK than economy seating, depending on the aircraft class (ICCT, 2019). This results in a contribution of 19 percent of CO_2 emissions in 2019 by premium seating, compared to 24 percent by wide-body economy and 37 percent by narrow-body economy class. Traveling in wide-body economy class has the lowest average carbon intensity of 65 g CO_2 per RPK (ICCT, 2020).

Lastly, the carbon intensity can be differentiated based on distances. Shorter distances (until 1,500 km) have the highest carbon intensity of more than 90 g CO_2 per RPK (which is the global average), up to 160 g CO_2 per RPK for distances under 500 km and more than 350 g CO_2 per RPK for regional premium class specifically (ICCT, 2020). Flights between 501 and 1,500 km also contribute most to total passenger CO_2 emissions, with more than 25 percent of the emissions from all distances (ICCT, 2019). The average passenger CO_2

intensity for each seating class in 2019 is presented in Figure 3 (ICCT, 2020). Nevertheless, a flight with a longer distance emits significantly more CO_2 in total than a short-distance flight.

Figure 3 – Passenger CO_2 intensity by seating class in 2019



Source: Figure copied from ICCT (2020).

Emissions from European aviation

Collectively, if the 28 EU Member States were seen as one country, it would be the second departure country for passenger aviation-related carbon emissions in 2019 (having emitted 19 percent of the global total), after the US. All flights departing from the EU and arriving in a non-EU country (thus excluding domestic and intra-EU flights) emitted 81.3 Mt CO_2 in total, making it the most emitting 'country' in the world. Within the EU, the three departing countries with most emissions were the UK (at that time still part of the EU) with 26 percent of the EU total, Germany with 18 percent, and France with 15 percent. Considering domestic flights only, flights within the EU emitted 70.2 Mt CO_2, making it the second-most emitting 'country' behind the US; all domestic flights counted up to 15.3 Mt CO_2 or 22 percent of the flights within the EU (ICCT, 2020).

Between 2013 and 2019, CO_2 emissions from intra-European flights increased by 35 percent, or 5.8 percent per year on average. The intra-European market has been the third most emitting market in the world for all these years. The highest increase in that period of all routes between Europe and other regions was between Europe and the Middle East, increasing with 61 percent in total; 10 percent per year. Lower increases were seen for the routes between Europe and North America (30 percent in total), Latin-America/Caribbean (28 percent), Asia/Pacific (26 percent), and Africa (20 percent). Considering all domestic, departing and arriving flights in Europe, most flights in 2019 were intra-European (38 percent), followed by the flights from and to North-America (20 percent) and Asia (18 percent). The passenger CO_2 emissions of all regional route groups can be found in Table 1 (ICCT, 2020).

Table 1 – Passenger CO_2 emissions by regional rout group in 2013, 2018, and 2019

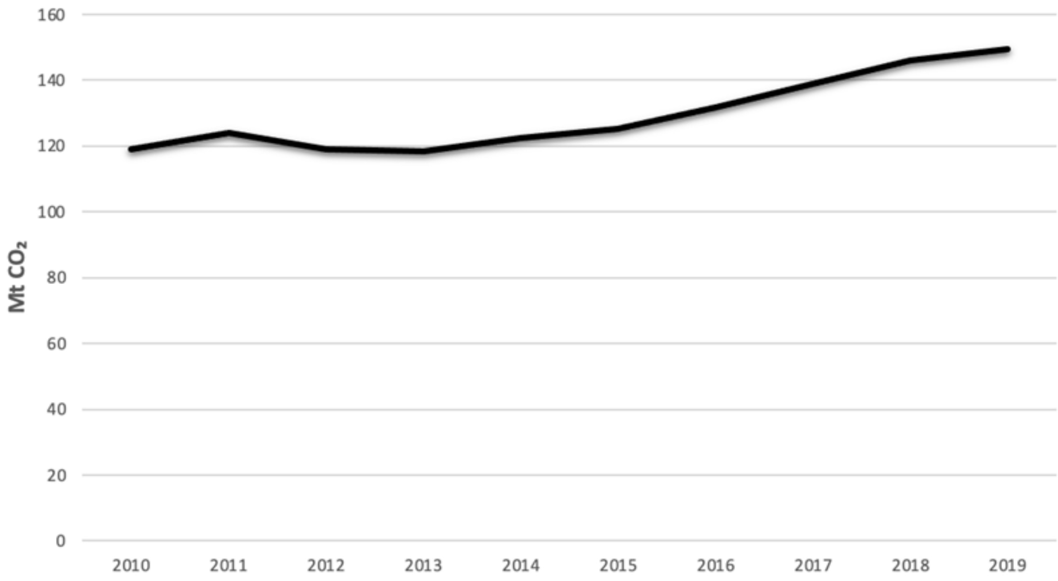
2019 rank	Route group	CO_2 emissions [Mt] 2013	2018	2019	Increase 2013-2019
1	Intra-Asia/Pacific	133	194	199	50%
2	Intra-North America	110	124	127	15%
3	Intra-Europe	79,4	105	107	35%
4	Europe - North America	43,2	53,7	56,1	30%
5	Asia/Pacific - Europe	39,1	47,1	49,4	26%
6	Asia/Pacific - North America	34,5	42,3	44	28%
7	Asia/Pacific - Middle East	23,3	36,3	34,5	48%
8	Intra-Latin America/Caribbean	26,1	30,2	31	19%
9	Europe - Middle East	17	27	27,2	60%
10	Latin America/Caribbean - North America	20,3	24	23,9	18%
11	Europe - Latin America/Caribbean	18,4	22,3	23,6	28%
12	Africa - Europe	15,1	17,4	18	19%
13	Middle East - North America	6,6	9,65	9,94	51%
14	Intra-Africa	7,72	9,03	9,37	21%
15	Intra-Middle East	7,24	9,71	9,18	27%
16	Africa - Middle East	6,09	8,29	8,04	32%
17	Africa - Asia/Pacific	2,68	2,91	2,72	1%
18	Africa - North America	1,58	2,02	1,98	25%
19	Asia/Pacific - Latin America/Caribbean	0,55	0,97	0,89	62%
20	Latin America/Caribbean - Middle East	0,72	0,86	0,79	10%
21	Africa - Latin America/Caribbean	0,36	0,49	0,48	33%
Total		**592**	**766**	**785**	**33%**

Source: ICCT, 2020.

When only looking at departing flights in the EEA, traffic increased from 6.6 million flights in 2010 to 7.3 million flights in 2019 (an increase of more than 10 percent), whereas emissions increased from 119 Mt CO_2 in 2010 to 149 Mt CO_2 in 2019 (an increase of 26 percent, or 2.6 percent per year on average). This is visualised in Figure 4. In 2020, both traffic and emissions decreased sharply with respectively 54 and 56 percent (EUROCONTROL, 2021).[1] This can be fully attributed to the Covid-19 pandemic and the resulting lockdowns and travel restrictions all over the world.

[1] For the emissions per state and the calculations for the total emissions, see Appendix A.

Figure 4 – Yearly CO_2 emissions from departing flights in the EEA



Source: EUROCENTRAL, 2021.

Considering departures from single countries within the EEA, Germany had most aviation-related emissions in 2019, with 31.1 Mt CO_2. Second was France (excluding the overseas departments) with 22.4 Mt CO_2, third was Spain (including the Canary Islands, excluding the Balearic Islands) with 22.0 Mt CO_2. Italy (15.1 Mt CO_2) and the Netherlands (excluding the overseas departments; 11.1 Mt CO_2) followed. Of these countries, especially Spain had a significant increase in emissions, growing with 31 percent from 2010 to 2019. This is mainly due to an inefficient traffic growth of only 13 percent; of these top-5 emitting countries, the Netherlands had the highest traffic growth of 23 percent over that same period, but this led to an increase in CO_2 emissions of only 19 percent (EUROCONTROL, 2021).

Projections until 2050

Before the Covid-19 pandemic, ICAO forecasted that by 2050, international aviation emissions could triple compared to 2015 (EC, 2021a). Even with the pandemic, which is estimated to impact traffic until at least 2024, the aviation industry expects emissions to increase in the coming decades. Although market analysts suggest that some of the reductions in corporate travel might be permanent, current International Air Transport Association (IATA) forecasts suggest that short-haul traffic will recover more quickly than long-haul traffic and total emissions from aviation are likely to increase. The latest projection is an increase from 0.5 Gt CO_2 in 2014 to 1.2-1.9 Gt CO_2 in 2050, while revenue ton-kilometres (RTK) are expected to increase fourfold in the same period (UNEP, 2020).

In its Global Market Forecast, Airbus states that it expects real GDP in Europe to grow by 1.5 percent per year, real trade by 2.6 percent per year, and total aviation traffic by 3.3 percent per year. Total RPK traffic growth is projected at 3.4 percent per year from 2018 until 2038. Especially the passenger flows between Central and Western Europe (5.5 percent) and between Central Europe and the Middle East (5.3 percent) are expected to grow significantly (Airbus, 2019). Boeing shows slightly lower expectations in its Commercial Market Outlook. In Europe, it projects an annual GDP growth of 1.2 percent and an annual airline traffic growth rate of 3.1 percent. Boeing expects the traffic flow growth to be highest between Europe and South Asia (5 percent), but does not distinguish between Central and Western Europe. The top-3 traffic flows will remain the same: intra-Europe (increasing from 1,045 billion to 2,003 billion RPKs, Europe-North America (620 billion to 1,012 billion RPKs), and Europe-Middle East (314 to 595 billion RPKs) (Boeing, 2020).

Current EU policies are expected to reduce general GHG emissions in all sectors, including aviation, by 60 percent in 2050 (EC, 2019). However, even assuming base traffic and advanced technology, future CO_2 emissions in the EU, UK and EFTA (EU+) from aviation alone are expected to increase by at least 21 percent above 2017-levels (163 Mt) to reach 198 Mt in 2040; an average annual increase of 0.93 percent. With a 'frozen tech' assumption, this becomes 37 percent above 2017-levels, or 224 Mt in 2040; an average annual increase of 1.63 percent. A summary of these expectations is shown in Table 2 (EASA, EEA & EUROCONTROL, 2019).

Table 2 – Average fuel consumption and CO_2 emissions from passenger flights in the EU+

Category [unit]	2005	2014	2017	2040 (Advanced Tech)	2040 (Frozen Tech)
		% change since 2005			
Average fuel consumption [L/100PK]	4,4	3,7	3,4	2,6	3
		-16%	-23%	-41%	-32%
CO_2 emissions [Mt]	141	148	163	198	224
		5%	16%	40%	59%

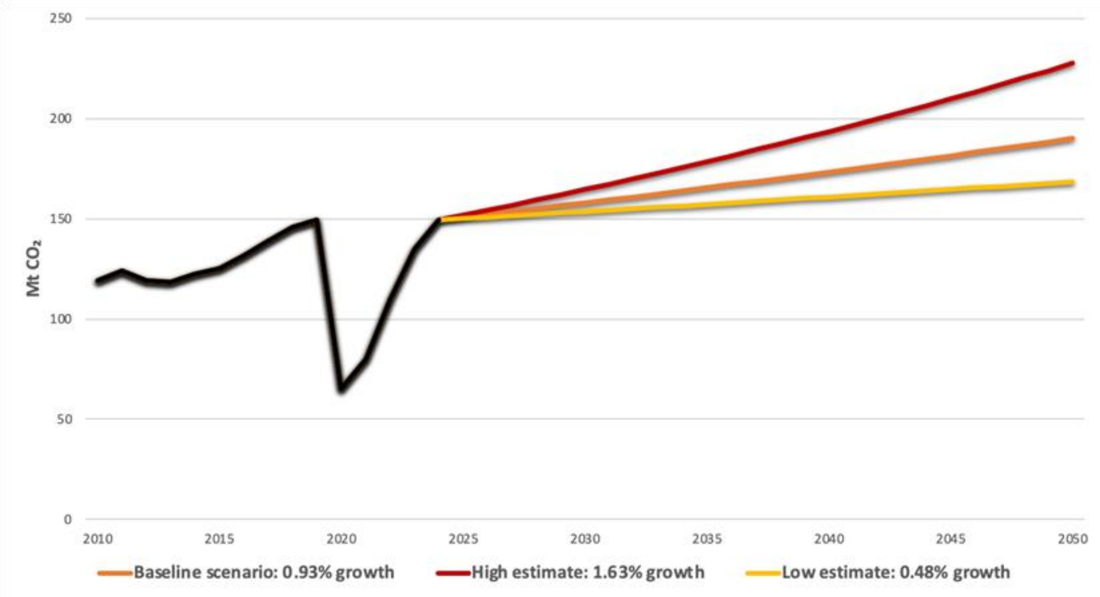
Source: EASA, EEA & EUROCONTROL, 2019.

Based on the assumption that traffic gradually recovers to pre-Covid levels by 2024 and with no extra policy measures, NLR & SEO (2021) also estimated the projections until 2050. According to this study, the number of departing air passengers in the EU+ is expected to increase from 751 million to 1.4 billion between 2018 and 2050, or 2 percent per year. The total number of flights departing from EU+ airports is forecast to increase from 7.6 to 12.4 million at the same time, or 1.4 percent per year; a conservative estimation, compared to the expectations by Airbus and Boeing. CO_2 emissions are expected to increase by 1.6 percent per year, reaching 320 Mt in 2050; 67 percent above 2018-levels. Of all commercial aviation emissions, 93 percent will be caused by passenger flights. Intra-EU+ flights are expected to contribute 39 percent of this, whereas flights to destinations outside the EU+ are responsible for the other 61 percent (NLR & SEO, 2021).

The average annual increase in CO_2 emissions for aviation in the EEA countries is set at 0.93 percent as an underlying assumption for this study, taking the 'Advanced Tech' scenario of EASA, EEA & EUROCONTROL (2019) as a reliable estimate (considering the low estimation by NLR & SEO, compared to the market forecasts of Airbus and Boeing). With emissions back at 149 Mt CO_2 in 2024 (the same level as in 2019), when the aviation sector is expected to be recovered from the Covid-19 pandemic, this will increase to 158 Mt CO_2 in 2030 and 190 Mt CO_2 in 2050. The 'Frozen Tech' scenario of EASA, EEA & EUROCONTROL (2019) with 1.63 percent growth will be taken as a higher estimate for the average expected annual increase in CO_2 emissions, resulting in emission increases to 165 Mt CO_2 in 2030 and 228 Mt CO_2 in 2050. Lastly, a more optimistic scenario of 0.48 percent per year from NLR & SEO (2021) will be included as a lower emission path, combining their estimated 1.6 percent emissions growth and 1.12 percent emission reductions through improvements in air traffic management, aircraft operations, and aircraft and engine technology. This would result in emission increases to 154 Mt CO_2 in

2030 and 169 Mt CO_2 in 2050. These three no-policy emission paths are presented in Figure 5.[2]

Figure 5 – Three estimates of the future from departing flights in the EEA, based on EASA, EEA & EUROCONTROL (2019), NLR & SEO (2021), and EUROCONTROL (2021)



2 For the projected emissions per year in each scenario and the calculations for the total emissions, see Appendix B.

2 Damage cost approach

The most preferred methodology in economics for valuing external costs is the damage cost approach. This chapter explains how this approach departs from the SCC, providing the best and most recent SCC estimations. Based on this, the damage costs of the projected CO_2 emissions from European aviation are quantified and are differentiated over common flight routes from the EEA.

Social cost of carbon

The damage cost approach monetises all damages experienced by individuals as a result of an externality, such as climate change impacts (Botzen & Van den Berg, 2012). In order to calculate the damage costs of the projected CO_2 emissions from aviation in the EEA, the social cost of carbon (SCC) is applied. This term presents the marginal external cost of CO_2 emissions and is seen as “the most important single economic concept in the economics of climate change” (Nordhaus, 2017, p.1518). More precisely, it is calculated as the Net Present Value (NPV) of the future change in economic welfare, resulting from an additional unit of CO_2 emitted to the atmosphere now.

The SCC is used to determine the level of a Pigouvian tax on CO_2 emissions; if the marginal costs of emission reduction is equal to the SCC, then the SCC equals the most efficient carbon tax (Tol, 2019). In 1982, William Nordhaus was the first to estimate the shadow price for carbon emissions, or one unit of discounted costs under the optimal path of CO_2 emissions (Nordhaus, 1982). More recently, the SCC has been computed through more complex modelling. These Integrated Assessment Models (IAMs) involve the full range of impacts from emissions, taking into account assumptions about uncertain parameters such as the social discount rate, economic growth and climate sensitivity (Ricke, Drouet, Caldeira & Tavoni, 2018).

One of the most widely used IAMs is the Dynamic Integrated model of Climate and the Economy (DICE), with the DICE-2016R model as the latest revised version. It integrated the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), resulting in a substantial increase in the estimated SCC. The DICE model modifies the Ramsey model of economic growth, in which society invests in capital goods, thereby reducing consumption today, to increase consumption in the future. In this modification, climate investments are analogous to the capital investments. The model attempts to represent simplified best practice in each area, from economics to climate change (Nordhaus, 2017).

Although IAM modelling is rather complex, it can be explained through four steps. First, future emissions are predicted based on population developments, economic growth, and other factors. Second, future climate responses are modelled, including temperature increase and sea level rise. Third, the economic impact that these climatic changes will have on agriculture, health, energy use, and other aspects of the economy, are assessed. Fourth, future damages are converted into their NPV and are added up to determine total damages. A baseline value for the damages of emissions will then be obtained, after which the entire process is repeated with a small additional amount of emissions to observe how much it changes the total cost of damages. This marginal change provides an estimate of the SCC (Rennert & Kingdon, 2019).

Most IAMs are static. The DICE model by Nordhaus is one of the few forward-looking IAMs, as it is based on dynamic models of agent decision making. On the other hand, some authors argue that the Nordhaus estimates “are limited because they come from IAMs that ignore the considerable risk and uncertainty in both the economic and the climate system, and their interactions” (Cai & Lontzek, 2019, p.2). Yet, this chapter presents the projected damage costs of CO_2 emissions from EEA aviation until 2050, so a dynamic model is preferred.

Arguably the most debated parameter of IAMs is the discount rate. Impacts at times in the future are discounted back to the NPV, so the choice of discounting schemes has a significant influence on the final estimate of the SCC. Differences between these schemes are the major driver of variability in the different estimates of the SCC. Most models employ a constant discount rate, but recent studies suggest that a time varying rate is more suitable for long-term problems such as climate change. More particularly, they have put forward arguments for using a declining discount rate, resulting in higher SCC estimates (Guo, Hepburn, Tol & Anthoff, 2006).

Regarding the DICE model, the economic assumption is that the discount rate should reflect actual economic outcomes, implying that savings rates and rates of return should be generated that are consistent with observations. According to Nordhaus (2017), this means that the discount rate would average 4.25 percent per year until 2100. This is seen as a descriptive approach to discounting, contrary to the alternative prescriptive approach where the discount rate is based on normative values and is determined independently of the real return on investment (Nordhaus, 2017).

A very different approach to the discount rate of the SCC is applied in The Stern Review on the Economics of Climate Change by economist Nicholas Stern. According to him, immediate decisive action should be taken to stabilise greenhouse gases because the benefits of strong, early action outweigh the costs. Consequently, Stern advocates a very low discount rate of 1.4 percent, treating all generations almost equally and having almost no preference between current and future consumption. Although one could see the importance of a lower discount rate for adequate climate action and some economists even argue that the concept of intergenerational justice implies a social discount rate of around one percent or a fraction of one percent (Davidson, 2006), a lot of other economists consider the discount rate proposed by Stern as too low. First, because people have a higher pure time preference that discounts utility in the future; and second, because there are high uncertainties in climate change, so the discount rate should at least reflect that uncertainty to some extent (Weitzman, 2007).

Lastly, it is important to note that CO_2 emissions are global externalities, because it does not matter where in the world the CO_2 is emitted; the impacts will remain the same. The SCC should thus be an equal estimate for the entire world, no matter where the emissions take place. This element differs from the approach mostly taken in national cost-benefit analysis, which is more concerned with the welfare of the own state. For example, the national social costs of carbon are larger in poor countries with large populations, as these countries are more vulnerable to the impacts of climate change (Tol, 2019). Still, taking into account its scope of European aviation and the global impacts from CO_2 emissions, this study focuses on the global SCC.

Estimation of the SCC

As discussed above, IAM models by different authors result in an enormous range of SCC estimations, because of the different assumptions about global income trends, wealth distribution, climate sensitivity and impacts, the growth rate, and above all the discount rate. A meta-analysis of 211 studies has shown a spread in results from less than 1 euro (EUR) to over 500 EUR per tCO_2 (Tol, 2008). Below, the chosen estimations for this study are presented and explained.

Departing from the dynamic DICE model of Nordhaus (2017), with an average discount rate of 4.25 percent and the value rising at 3 percent per year in real terms through 2050, the SCC is estimated at 31 US Dollar (USD) per tCO_2 emissions in 2015 and 103 USD in 2050. These SCC estimates are measured in 2010USD. Using an average exchange rate of 0.75 EUR per USD in 2010 and 14 percent inflation from 2010 until 2021, this converts to an estimated SCC of 32 EUR in the year 2020, 44 EUR in 2030 and 88 EUR in 2050. These SCC estimates are measured in 2021EUR.[3]

The estimated result of 32 EUR in 2020 is supported by other literature as well. In 2010, the Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) developed a methodology for estimating the SCC, combining thousands of SCC results obtained from IAMs using five different socioeconomic and emissions projections. The IWG's current estimate of the SCC in the year 2020 is 42 USD/t in 2007USD. Using an average exchange rate of 0.73 EUR per USD in 2007 and 20 percent inflation from 2007 until 2021, this converts to an estimated SCC of 37 EUR in 2021EUR in the year 2020; close to the Nordhaus (2017) converted estimate, though slightly higher because of the lower discount rate of 3 percent (National Academies of Sciences, Engineering, and Medicine, 2017).

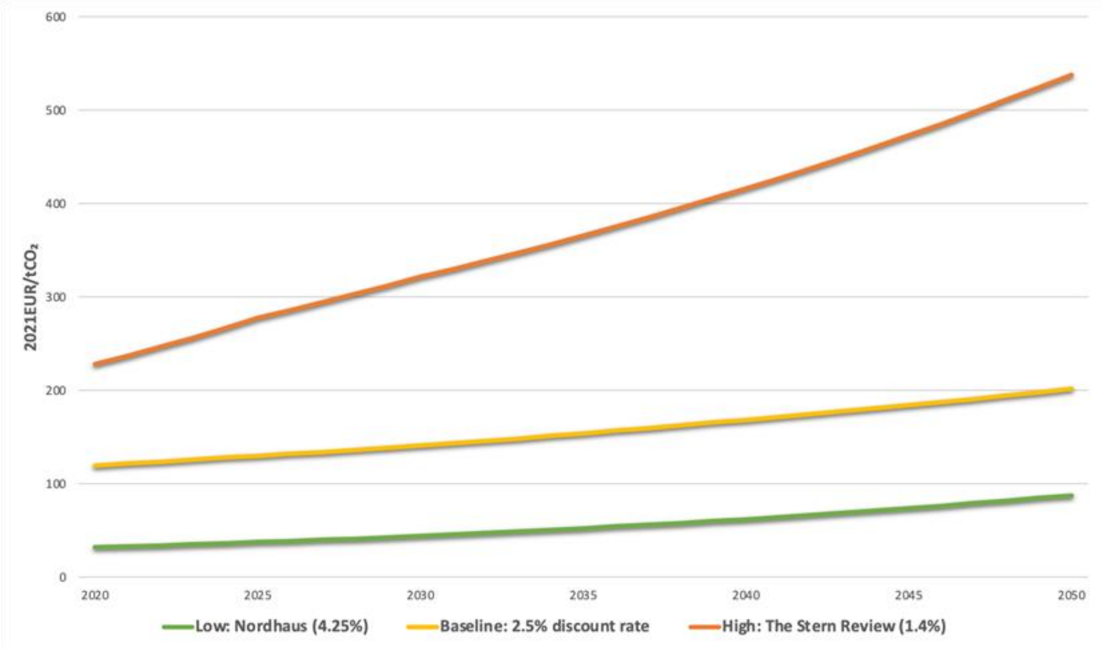
When applying uncalibrated discounting from The Stern Review, the estimated SCC becomes much higher (as expected from the literature theory). With a discount rate of 1.4 percent, the SCC is 228 EUR in the year 2020, 322 EUR in 2030, and 538 EUR in 2050. These SCC estimates are measured in 2021EUR. Since these are at the upper end of the range of estimations, an intermediate discount rate between the Nordhaus (2017) baseline (a strictly descriptive approach) and the Stern Review rate (a highly prescriptive approach) would be deemed as more appropriate. Many experts are in favour of discount rates of 1 to 3 percent for pay-offs in 100 years' time (Drupp, Freeman, Groom & Nesje, 2018). This is also in line with the discount rate of 2 to 4 percent proposed by economist Martin Weitzman in his review, as it "would create a more intermediate sense of urgency somewhere between what the Stern Review is advocating and the more modest measures to slow global warming advocated by many of its critics" (Weitzman, 2007, p.27).

The DICE model by Nordhaus (2017) with a discount rate of 2.5 percent results in SCC values of 120 EUR per tCO_2 in the year 2020, 141 EUR in the year 2030, and 202 EUR in the year 2050. These SCC estimates are measured in 2021EUR. The value for 2050 is very close to the estimated climate change price of 200 EUR per tCO_2 by CE Delft (2018b), which provides average environmental prices for the EU28, but their value for 2020 is much lower: 71 EUR per tCO_2. Nonetheless, CE Delft (2018b) has combined the damage cost with the abatement cost approach, whereas this chapter is primarily focused on the damage cost approach applied by Nordhaus (2017). Hence, the Nordhaus SCC with a 2.5 percent discount rate will be taken as the baseline estimate for this study, with the original Nordhaus SCC as the

[3] All exchange rates are from https://www.exchangerates.org.uk, inflation rates are from https://www.inflationtool.com

lower estimate and the Stern Review SCC as the higher estimate. All SCC estimates and how they increase over time are presented in Figure 6.[4]

Figure 6 – The Social Cost of Carbon according to three different estimations and discount rates



Total damage costs

In order to calculate the total damage costs of CO_2 emissions from departing flights in the EEA, the three SCC estimations in this chapter are multiplied with the projected CO_2 emissions from aviation in the EEA from last chapter. This is done for every year individually, so that the total damage costs reflect the current costs (in 2021EUR) for the CO_2 emitted in every single year until 2050 (which all have different SCC values, according to the dynamic DICE model).

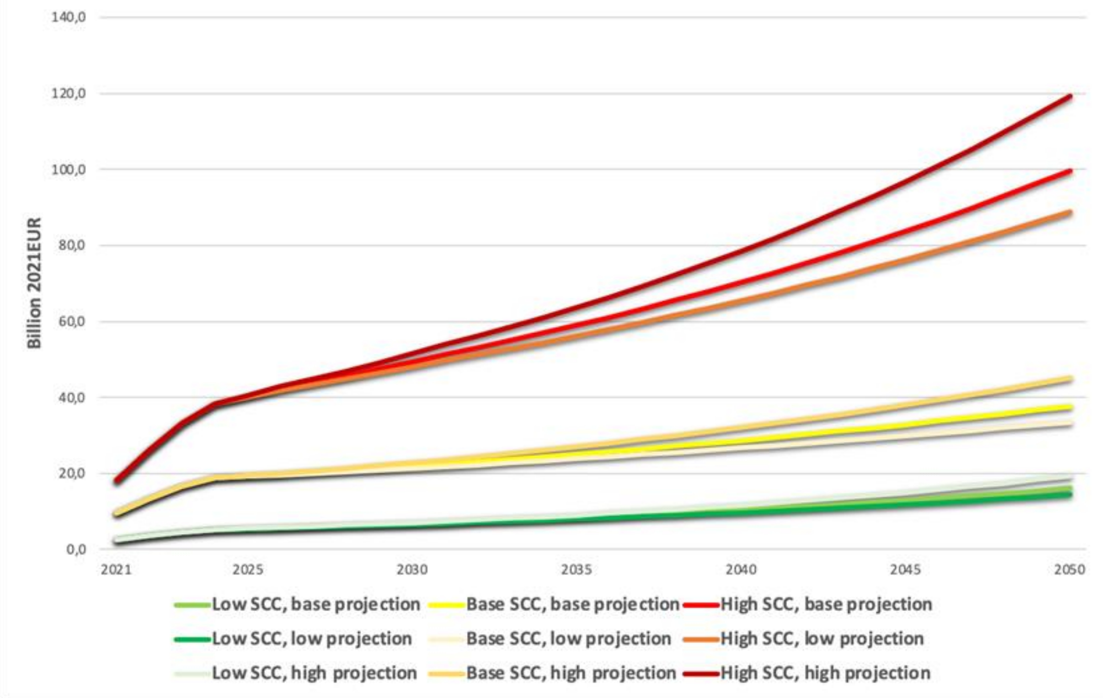
As there are three estimations for the SCC and three CO_2 emissions scenarios, there are nine possible paths for the damage costs of CO_2 from aviation in the EEA. Consequently, there are nine different total damage cost estimations. However, it is rather unlikely that both the SCC estimate and the emission projection scenario turn out to be much higher than the base, or both much lower. Assuming both the base SCC and the base emission projection, the damage costs of departing flights in the EEA will increase from 9.6 billion EUR in 2021 to 37.6 billion EUR in 2050. If this is the case, the total damage costs sum up to 770 billion EUR from 2021 until 2050.

Especially deviations from the SCC estimate would result in highly diverging damage costs. If the lower Nordhaus value would be deemed as more appropriate, this results in damage costs of 2.6 billion EUR in 2021 to 16.1 billion EUR in 2050, which means that the total damage costs are only 272 billion EUR. On the other hand, if the Stern Review SCC would be chosen, this results in damage costs of 18.2 billion EUR in 2021 to 99.7 billion EUR in 2050,

4 For the different SCC estimations per year, see Appendix C.

summing up to 1844 billion EUR in total. In other words, the range of total damage costs with different SCC values is 272 to 1844 billion EUR. With the base SCC and different CO_2 emission projections, this range becomes 725 to 849 billion EUR. These nine damage cost paths are presented in Figure 7.[5]

Figure 7 – The projected damage costs of CO_2 emissions from aviation in the EEA, according to different SCC values and future CO_2 emission scenarios



Damage costs of different routes

For contextual purposes, the damage costs are differentiated over common routes in the EEA. As explained earlier, aviation can be categorised into regional flights (29 percent of departing passenger flights in 2019), narrow-body flights (63 percent), and wide-body flights (8 percent) (ICCT, 2020). These categories are named after their aircrafts, which are mostly used for respectively short-haul flights of less than 1,500 km, medium-haul flights of 1,500 km until 5,000 km, and long-haul flights of more than 5,000 km (CE Delft, 2019b). As most flights in 2019 were intra-European, followed by the flights from and to North-America, one short-haul flight and one medium-haul flight within Europe will be taken as examples of common routes, as well as one long-haul flight to North-America and a medium/long-haul flight to the Middle East (the latter of which is one the fastest growing markets in recent years).

To determine the commonly taken routes, the three airports within the EEA and the one airport in North-America with the most passengers are selected. These are Charles de Gaulle Airport (CDG) in France, Amsterdam Airport Schiphol (AMS) in the Netherlands, Frankfurt Airport (FRA) in Germany, and Hartsfield-Jackson Atlanta International Airport

5 For the different estimations of the damage costs per year and the calculation of the total costs, see Appendix D.

(ATL) in the US (Airports Council International, 2019). From these airports, other popular destinations are Lisbon (LIS) in Portugal and Dubai (DXB) in the United Arab Emirates (Schiphol, 2019; Fraport, 2019). The four selected common routes from these destinations are the following: AMS-CDG (398 km; short-haul), AMS-LIS (1,844 km; medium-haul), FRA-DXB (4,839 km; medium/long-haul), and CDG-ATL (7,051 km; long-haul).

To calculate the damage costs of these different routes, the first step is to estimate the CO_2 emissions. According to the ICAO, this can be done by first estimating the aircraft fuel burn and the passengers' fuel burn based on a passenger/freight factor which is derived from RTK data, then calculating the seats occupied (assuming that the entire aircraft is configured with economic seats), thereafter computing the CO_2 emissions per passenger. This last step is done by multiplying the passengers' fuel burn with 3.16 (kg of CO_2 per kg of fuel burn), then dividing this number by the seats occupied. Using the methodology, the aircraft fuel burn of AMS-CDG is 2,750 kg, resulting in 61 kg CO_2 per passenger; the aircraft fuel burn of AMS-LIS is 7,929 kg, resulting in 165 kg CO_2 per passenger; the aircraft fuel burn of FRA-DXB is 59,382 kg, resulting in 299 kg CO_2 per passenger; and the aircraft fuel burn of CDG-ATL is 65,669 kg, resulting in 389 kg CO_2 per passenger (ICAO, n.d.).

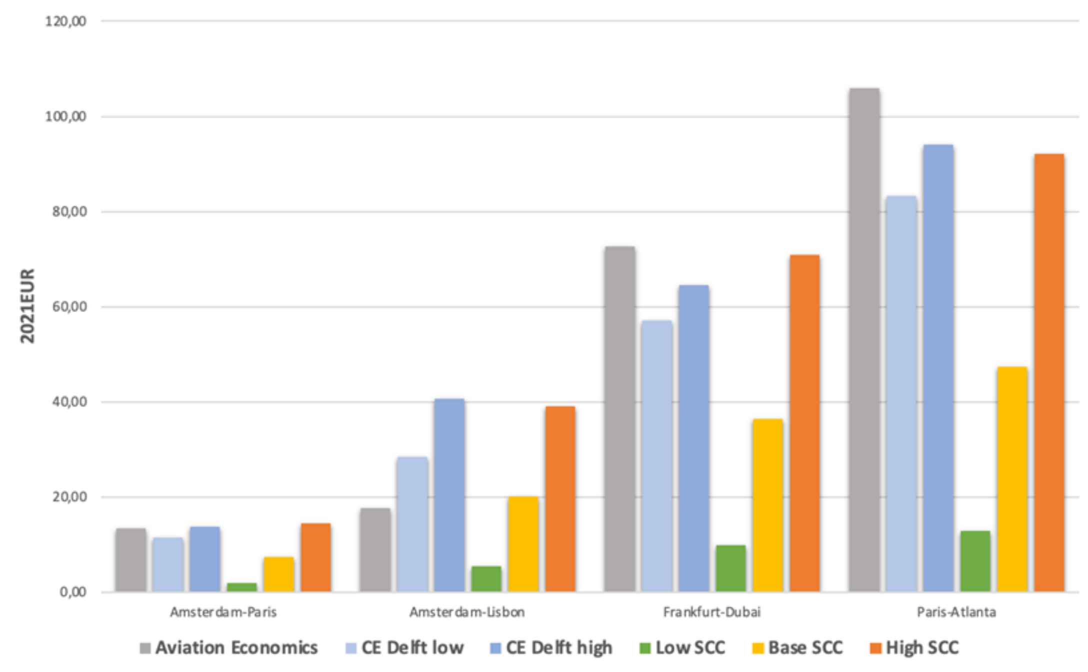
Using the ICAO estimates of emissions and the central SCC value of this study, the damage costs of CO_2 emissions would be 7 EUR for the route AMS-CDG, 20 EUR for AMS-LIS, 36 EUR for FRA-DXB, and 47 EUR for CDG-ATL. With an increasing SCC, these costs become 12 EUR for AMS-CDG, 33 EUR for AMS-LIS, 60 EUR for FRA-DXB, and 78 EUR for CDG-ATL in 2050.

The costs in 2021 deviate from the estimation of climate change costs applied by Aviation Economics (2018), also when controlling for the distance of the flight. Assuming that AMS-CDG is a regional flight, AMS-LIS is a 'low cost' flight, and FRA-DXB and CDG-ATL are both long-haul flights, controlling for the exact length of the flights, and adjusting the prices to 2021EUR, the climate change costs would become 13 EUR for AMS-CDG, 18 EUR for AMS-LIS, 73 EUR for FRA-DXB, and 106 EUR for CDG-ATL (Aviation Economics, 2018). With the exception for AMS-LIS, these estimates are all substantially higher than the estimates of this study. This is probably due to the fact that they also accounted for different airline strategies, such as low cost airlines filling the aircraft with more passengers (explaining why the estimate for AMS-LIS is higher in this study, whereas all the other routes have lower damage costs).

An alternative calculation can be applied through the Handbook on the external costs of transport by CE Delft (2019b). Using their average climate costs for aviation for selected 33 EU airports, categorised per type of flight as in this study, further specified according to the example of aircraft type, and adjusting the prices to 2021EUR, the climate change costs for a low emission class aircraft become 11 EUR for AMS-CDG, 29 EUR for AMS-LIS, 57 EUR for FRA-DXB, and 83 EUR for CDG-ATL; for a high emission class aircraft, the costs become 14 EUR for AMS-CDG, 41 EUR for AMS-LIS, 65 EUR for FRA-DXB, and 94 EUR for CDG-ATL (CE Delft, 2019b). All of these values are also much higher than the estimates for this study, even for the low emission class aircraft. However, CE Delft has also included the climate change costs from non-CO_2 emissions. In conclusion, the damage costs in this study are rather a conservative than a high estimation of the total climate costs, which can also be concluded from Figure 8.[6]

[6] For all specifications and these climate costs of the different common flight routes, see Appendix E.

Figure 8 – The SCC values of this thesis, compared to estimates of the total climate costs of CO_2 emissions from common flight routes in the EEA



3 Prevention cost approach

Apart from the damage cost approach, there is another way to internalise the climate impact of CO_2 emissions: the prevention cost approach, in this case based on the MAC of SAFs. This chapter presents the most recent estimations of the availability and costs of SAFs, both now and in the future. Based on this, the prevention costs will be calculated.

Abatement-cost method

The prevention costs are the costs of preventing the negative externality from happening in the first place, instead of estimating the costs of the damage caused. Prevention costs are essentially the same as abatement costs: it is the cost incurred for abating something, or to make it decrease. As many environmental policies are associated with quota or quantitative targets (such as the goal in the EU Green Deal to become carbon-neutral by 2050), the MAC captures the marginal costs of securing these targets. It is calculated as follows. First, one determines the most expensive technical measure out of the set of most cost-efficient measures that is required to meet the target. Second, one expresses that technology in costs per unit of the externality prevented. More specifically, this method is based on the costliest abatement measure (CE Delft, 2018b).

When using the abatement-cost method, it is important to take the minimum price of securing a given policy target, also referred to as 'efficient' or 'least-cost' prices. Assuming a fully-informed and economically-rational acting policy maker, the targets will be designed so that an 'optimal' pollution level is obtained, resulting in a Pigouvian charge that optimises economic welfare (CE Delft, 2018b). Nonetheless, in the case of emission reduction targets and climate change, the policy maker cannot be considered as fully-informed; one will never know the risks and impacts of climate change with certainty. Hence, a more risk-averse policy is often preferred, applying the precautionary principle (Farber, 2015).

In order to reduce emissions and rank mitigation measures from the least to most expensive, the Marginal Abatement Cost Curve (MACC) is applied. For every measure, the cost per ton of emissions reduced is estimated, as well as the quantity of emission reductions available at that expense. The MACC has been used to support climate policy analysis for decades, with the McKinsey curve in 2009 as the most well-known example (Gillingham & Stock, 2018).

If decision makers must meet an emission-reduction target, they need to decide which abatement options to implement using the MACC. It is important that this is done in the right order and speed, because ambitious emission-reduction targets cannot be met overnight and it takes time to implement measures. Two types of MACCs can be distinguished. First, at hand in this thesis, the full potential approach provides information on how many emissions could be saved if the measure was used at the technical maximum. Second, the achievable-potential approach also takes into account that large-scale diffusion can take up a long time. Such a slow-diffusion process would drive the full potential downwards (Vogt-Schilb & Hallegatte, 2014).

The emission-reduction target at hand in this study is the amount of CO_2 reduction by aviation in the EEA in 2050. However, the EU has not set such a specific reduction target. Although the EU Green Deal aims for carbon neutrality in 2050 (which implies 100 percent reduction), it states that the transport sector only needs to meet 90 percent reduction. Aviation would have to contribute to this reduction, but the EU has not specified to what extent this should happen; assuming that emission reductions will be easier to achieve by road and rail transport than in the maritime and aviation sector, this could mean that the EU is aiming for an even lower target for aviation. NRL & SEO (2021) have estimated that a reduction of 83 percent could be achieved. Departing from the targets set by the EU and the study by NLR & SEO, a middle reduction target of 90 percent will be taken for this thesis, with 80 and 100 percent as lower and higher targets.

Sustainable Aviation Fuels

The only way to effectively meet the policy target of either 80, 90 or 100 percent CO_2 reduction by aviation in the EEA is to use SAFs. They would replace fossil-fuelled kerosene, either partly by using drop-in fuels (blending it with conventional kerosene) or completely, which can reduce the emissions of aviation by 80 up to 100 percent. Another advantage of using SAFs is their compatibility; strict fuel specifications lead to a comparable composition of the fuel, thus leading to the same behaviour in the fuel combustion phase. In addition, it will be easier to implement the use of SAFs in aviation than in other transport systems, because of its smaller production scale and less complex supply (Kousoulidou & Lonza, 2016).

Although commercial production of SAFs increased from an average of 0.29 Million Litres Per Year (MLPY) in 2013-2015 to 6.45 MLPY in 2016-2018 (a more than 20-fold increase), even the current production of 10 MLPY represents just 0.01 percent of total worldwide fuel uptake. Publicly announced projects alone could push this to 3,500 MLPY in 2025, but there is great uncertainty about the extent to which SAFs can scale up further to a significant share of total fuel demand (ICAO, 2019). This is partly because of technical and juridical difficulties, but mainly because of the much higher price of SAFs; at current volumes, prices for SAFs are 2 to sometimes even 14 times higher than the price for fossil-fuelled kerosene (De Jong et al., 2017). This is a result of high production costs of SAF, in combination with the low levels of global supply (E4tech, 2019). On top of this, because the average margin of profit on a flight ticket is less than 10 USD, it is not affordable for single airlines to adapt to SAFs; this must be done collectively, just like airlines adapt to large oil price shocks collectively (Peeters & Melkert, 2018).

SAFs can be categorised in a variety of pathways, based on the feedstocks used, the conversion processes, and the resulting fuels. This also leads to different emission reduction potentials. Besides this, SAFs vary substantially in their chemical composition: some pathways generate fuels without aromatics, so-called Synthetic Paraffinic Kerosene (SPK), whereas others generate aromatic compounds. This has implications for the blending grades with fossil-fuelled kerosene (Kousoulidou & Lonza, 2016).

Apart from electricity and hydrogen, which are both not considered to be implementable on a larger scale and on most distances in aviation before 2050, there are two categories of technologies for SAFs: biofuels (based on feedstocks) and e-fuels (based on renewable energy). Technically, biofuels are comparable with Gas-to-Liquid and Coal-to-Liquid fuels. The advantage of biofuels is that they reduce CO_2 emissions by up to 85 percent.
A disadvantage is the relatively low conversion efficiency, resulting in large land uptake for the feedstock inputs (Peeters & Melkert, 2018). According to one study, supplying Schiphol

Airport in the Netherlands would require at least half of the size of all Dutch farmland and an amount of water equal to at least 20 times the current water usage of all Dutch households (Quintel & Kalavasta, 2018). Also, there are still some CO_2 emissions left, so biofuels will not enable carbon neutrality on their own. This is different for e-fuels, which have a reduction potential of 100 percent. E-fuels need hundred to thousand times less water and about ten times less land, but they require large amounts of renewable energy and are even more costly than biofuels (with costs two to six times higher). Also, they still have low conversion efficiencies, they are not commercially available yet, and large-scale implementation is not likely before 2030 (Peeters & Melkert, 2018). The following part of this chapter will further explore the different types of biofuels and e-fuels.

Biofuels

Biofuels can be produced with a number of different conversion technologies, the most mature of which is Hydro-processed Fatty Acid Esters and Free Fatty Acids (HEFA).
The production process of HEFA is very similar to that of Hydro-treated Vegetable Oil (HVO), which is used for the production of road transport biofuels. Its main feedstock inputs are Used Cooking Oil (UCO) and vegetable oils. HEFA is currently the cheapest SAF technology and the only process commercially available, but its costs in the EU are still estimated to be 1.9 to 2.8 times the cost of fossil-fuelled kerosene. These costs mainly depend on feedstock costs. Compared to fossil kerosene, HEFA biofuels can lead to CO_2 emission savings of 33 percent when made from palm oil, up to 84 percent when made from UCO (NLR & SEO, 2021). Nevertheless, emissions from biofuels can also be higher than fossil-fuelled kerosene due to indirect land use change, from which the emissions should thus also be taken into account.

Another well-known conversion technology for SAFs is Fischer-Tropsch (FT). This conversion process mainly uses biomass such as Municipal Solid Waste (MSW), agricultural and forestry residues, and wood and energy crops such as willow and poplar. Studies seem to agree on the superior emission performance of FT biofuels, irrespective of the feedstock used, because of the self-sufficiency of the process and the excess electricity production.
The production of biofuels can be analysed using energy allocation (which captures the energy value and is indifferent to the choice of co-product) and the displacement method (which awards an emission credit to co-products based on its yield and the emission intensity of the displaced product). Using energy allocation, FT can lead to CO_2 emissions savings of 85 percent for corn stover to 93 percent for forestry residues. With the displacement method, this becomes respectively 103 and 111 percent, hence giving negative emissions due to the emission credits exceeding the total emissions (De Jong et al., 2017).

Other SAF conversion technologies include Hydrothermal Liquefaction (HTL), pyrolysis, Alcohol-to-Jet (AtJ), and Hydro-processing of Fermented Sugars (HFS) or Direct Sugars to Hydrocarbons (DSHC, also referred to as Synthetic Isoparaffinic fuel or SIP). Of these pathways, only HTL and pyrolysis (both with forestry residues as feedstock inputs) seem to be interesting as a CO_2 abatement measure, with emission reduction potentials of 80 and 75 percent; AtJ and DSHC lead to relatively low emission reductions of sometimes lower than 50 percent (De Jong et al., 2017).

Biofuels cannot simply be adopted as airlines wish; all aviation fuels have to be approved first. The American Society for Testing and Materials (ASTM) is responsible for this and has developed standards for the approval of biofuels. Six production pathways have been ASTM-certified for blending with conventional aviation fuel so far. These include two different FT-SPK pathways, HEFA, HFS-SIP, AtJ-SPK, and Co-processing. All of these pathways currently have a maximum blending ratio of 50 percent, with the exception of HFS-SIP (10 percent) and Co-processing (5 percent) (EASA, EEA & EUROCONTROL, 2019).

E-fuels

One type of SAF that differs fundamentally from biofuels are synthetic e-fuels, or Power-to-Liquids (PtL). In this production pathway, liquid hydrocarbons are formed with electric energy, water, and CO_2. The main conversion pathway for this is FT, but there are no biomass inputs with PtL. The production comprises of three main steps. First, hydrogen is produced from renewable electricity using the electrolysis of water. Second, renewable CO_2 is provided and converted, either from a concentrated source (for example, a coal factory) or from Direct Air Capture (DAC). Third, the CO_2 and hydrogen are synthesised to liquid hydrocarbons with subsequent upgrading to refined fuels (Umweltbundesamt, 2016). It can thus be concluded that this ‘synthetic’ solution replaces the carbon atoms present in kerosene with reusable carbon atoms from a non-plant based source (Quintel & Kalavasta, 2018).

Even though PtL fuel is drop-in capable and has a similar level of technology readiness as most ASTM-certified biofuels, it is not commercially available yet because of its even higher production costs. Recently, these costs were as high as 3 to 6 times the price of fossil kerosene (EASA, EEA & EUROCONTROL, 2019). Still, because of expected decreases in renewable electricity costs, technological improvements, and economies of scale, PtL is foreseen as the most promising SAF for the medium to long-term future (Umweltbundesamt, 2016).

The emission reduction potential of PtL depends on its source of CO_2. If the carbon atoms are reused from a concentrated source like an industrial plant, total emissions drop by about 54 percent (as fossil carbon atoms are still burned while flying, but the use of fossil kerosene is avoided because of the reused carbon atoms). However, if DAC is applied, no extra carbon atoms are emitted to the atmosphere. In fact, carbon atoms are subtracted from the air first, and then released again during the flight. In theory, this could thus lead to 100 percent emission reduction when using fully renewable energy for the conversion process (Quintel & Kalavasta, 2018).

Future SAF mix: methodology

In order to determine which SAFs are most promising in the period until 2050, life-cycle CO_2 emission reductions should be considered in combination with the minimum selling price. Such an analysis can be performed by calculating the CO_2 abatement costs, both now and in the future. In other words, the projected future mix of SAFs can be estimated by computing the MACC of SAFs over time until 2050. In general, it is expected that the costs for biofuels will only increase over time because of the increased competition for feedstocks (such as UCO) with other sectors. The costs of other pathways (such as synthetic e-fuels) are expected to decrease with technological improvement, learning, and the effects of economies of scale (NLR & SEO, 2021).

For the more detailed analysis, the following methodology was applied. First, an extensive literature review on the current and future costs and CO_2 emissions of SAFs was conducted. The sources included academic research from authors such as De Jong et al. (2017), but also more recent reports from organisations such as McKinsey & Company (2020). The SAFs were categorised into biofuels and e-fuels, after which they were divided into the different conversion pathways and the feedstocks used. Food and feed crop-based biofuels such as palm oil have been omitted, as they might lead to higher emissions due to indirect land use change. For that same reason, they are limited in contribution by the European Commission's Renewable Energy Directive (RED II) covered in EU Directive 2018/2001 (2018). Also, food based biofuels face high competition from other sectors and lead to large land uptake.

The estimated costs from the various sources were first converted to the amount of 2021EUR per ton, and then to cents per mega joule (MJ). In order to eventually calculate the abatement costs, the costs from the business-as-usual scenario are subtracted. These are the costs of fossil-fuelled kerosene, estimated by IATA (n.d.) at 450 EUR/t in 2021, and 690 EUR/t in 2050. All these costs are shown in Table 3 (current estimates) and Table 4 (future estimates). The costs in the years between are calculated with the assumption of linear growth or decline.

Table 3 – The current minimal production costs of different fuels. The colours indicate how much higher the prices of the different SAFs are, compared to fossil-fuelled kerosene

Fuel type	Pathway	Feedstock	2021EUR/t	Multiple	Source
Fossil fuel	Combustion engine	Petroleum	450		IATA (2021)
Biofuel	HEFA	Used cooking oil	993	2,2	EASA, EEA & EUROCONTROL (2019)
		Various	1212	2,7	CE Delft (2019)
	Fischer-Tropsch	Forestry residues	1737	3,9	De Jong et al. (2017)
		Wheat straw	2543	5,7	De Jong et al. (2017)
		MSW	1717	3,8	ICCT (2019)
		Energy crops	2323	5,2	ICCT (2019)
		Various	2222	4,9	CE Delft (2019)
	Alcohol-to-Jet	Energy crops	3081	6,8	ICCT (2019)
		Forestry residues	2392	5,3	De Jong et al. (2017)
		Wheat straw	3583	8,0	De Jong et al. (2017)
		Various	2879	6,4	CE Delft (2019)
	DSHC	Forestry residues	4779	10,6	De Jong et al. (2017)
		Wheat straw	6432	14,3	De Jong et al. (2017)
		Various	5808	12,9	CE Delft (2019)
	Pyrolysis	Forestry residues	1388	3,1	De Jong et al. (2017)
		Wheat straw	1851	4,1	De Jong et al. (2017)
		Various	1566	3,5	CE Delft (2019)
	HTL	Forestry residues	967	2,1	De Jong et al. (2017)
		Wheat straw	1352	3,0	De Jong et al. (2017)
		Various	1061	2,4	CE Delft (2019)
E-fuel (PtL)	Fischer-Tropsch	Point sources (low temp)	1421	3,2	German Environment Agency (2016)
		DAC (low temp)	1935	4,3	German Environment Agency (2016)
		Point sources (high temp)	1202	2,7	German Environment Agency (2016)
		DAC (high temp)	1760	3,9	German Environment Agency (2016)
	Methanol	Point sources (low temp)	1268	2,8	German Environment Agency (2016)
		DAC (low temp)	1807	4,0	German Environment Agency (2016)
		Point sources (high temp)	1214	2,7	German Environment Agency (2016)
		DAC (high temp)	1756	3,9	German Environment Agency (2016)

Table 4 – The expected minimal production costs of different fuels in 2050. The colours indicate how much higher the prices of the different SAFs are, compared to fossil-fuelled kerosene

Fuel type	Pathway	Feedstock	2021EUR/t	Multiple	Sources
Fossil fuel	Combustion engine	Petroleum	690		NLR & SEO (2021)
Biofuel	Various	Various	1862	4,1	De Jong et al. (2017)
E-fuel (PtL)	Fischer-Tropsch	Point sources	1525	3,4	McKinsey & Company (2020)
		DAC (import from Middle East)	932	2,1	McKinsey & Company (2020)
		DAC (global average)	1653	3,7	International Energy Agency (2020)

Most sources presented the emissions either in g CO_2e/MJ, or the amount of emissions savings as a percentage, compared to fossil-fuelled kerosene. The emissions of fossil-fuelled kerosene were set at 89 g CO_2e/MJ for current emissions and 92 g CO_2e/MJ in 2050, according to Rosen (2017). All SAFs were then converted to the amount of kg CO_2e-reduction per MJ compared to fossil kerosene. After this, the abatement costs in 2021EUR/tCO_2 could be calculated by dividing the extra costs per MJ by the kg CO_2e-reduction per MJ.

A conversion ratio of 43.4 t/GJ and 1250 t/L was chosen for all fuels, based on the average conversions from the other sources. For the biofuels and e-fuels, if more sources were given for the same conversion pathway and feedstock input, the most recent estimation was chosen, unless the source for the costs and CO_2 emissions was the same (for the sake of consistency). Regarding the biofuels, De Jong et al. (2017) calculated the CO_2 emission reductions for both energy allocation and the displacement method. In this thesis, the estimated reductions for the displacement method are applied, as the International Standards Organisation (ISO) deems its use more appropriate, because it represents the potential emission mitigation effects of producing co-products (De Jong et al., 2017). All different CO_2 emissions and reductions are shown in Table 5 (current estimates) and Table 6 (future estimates).

Table 5 – The current CO_2e-emissions per MG of fuel. The colours indicate how high the emission savings are compared to fossil-fuelled kerosene

Fuel type	Pathway	Feedstock	g CO_2e/MJ	Emission saving	Source
Fossil fuel	Combustion engine	Petroleum	89		Rosen (2017)
Biofuel	HEFA	Used Cooking Oil	13	85%	EEA, EASA & EUROCONTROL (2019)
		Jatropha	21	76%	De Jong et al. (2017)
		Camelina	42	53%	NLR & SEO (2021)
		Rapeseed	47	47%	NLR & SEO (2021)
		Palm fatty acid distillate	20	77%	NLR & SEO (2021)
	Fischer-Tropsch	Willow	-7	108%	De Jong et al. (2017)
		Poplar	-6	107%	De Jong et al. (2017)
		Corn Stover	-3	103%	De Jong et al. (2017)
		Forestry residues	-10	111%	De Jong et al. (2017)
		MSW	5	94%	NLR & SEO (2021)
		Agricultural residues	8	91%	NLR & SEO (2021)
		Short-rotation woody crops	12	86%	NLR & SEO (2021)
		Herbaceous energy crops	11	88%	NLR & SEO (2021)
	Alcohol-to-Jet	Corn Stover	22	75%	De Jong et al. (2017)
		Agricultural residues	29	67%	NLR & SEO (2021)
		Forestry residues	24	73%	NLR & SEO (2021)
		Switchgrass	30	66%	EEA, EASA & EUROCONTROL (2019)
		Herbaceous energy crops	44	51%	NLR & SEO (2021)
	HTL	Forestry residues	20	78%	De Jong et al. (2017)
	Pyrolysis	Forestry residues	30	67%	De Jong et al. (2017)
E-fuel (PtL)	Fischer-Tropsch	Point sources	41	54%	Quintel & Kalavasta (2018)
		DAC	0	100%	Quintel & Kalavasta (2018)

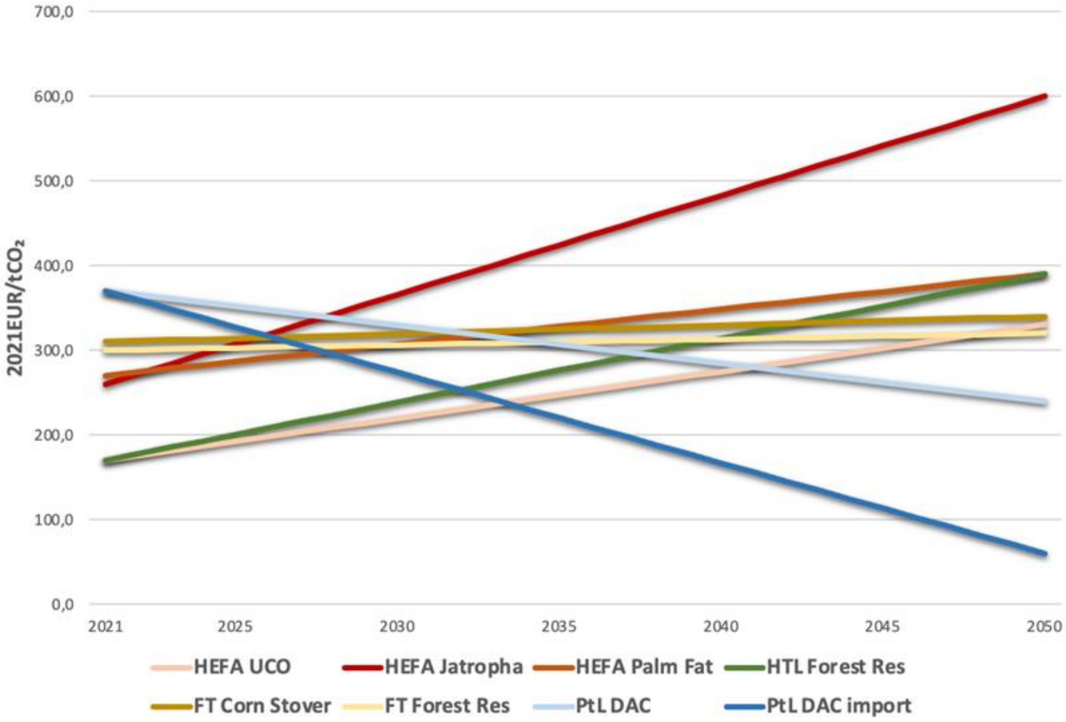
Table 6 – The expected CO_2e-emissions per MJ of fuel in 2050. The colours indicate how high the emission savings are compared to fossil-fuelled kerosene

Fuel type	Pathway	Feedstock	g CO_2e/MJ	Emission saving	Source
Fossil fuel	Combustion engine	Petroleum	92		Rosen (2017)
Biofuel	HEFA	Used Cooking Oil	9	90%	Seber et al. (2014)
		Jatropha	47	49%	Stratton et al. (2010)
		Rapeseed	39	58%	Stratton et al. (2010)
	Fischer-Tropsch	Corn stover	12	87%	Stratton et al. (2010)
		Forestry residues	7	92%	Stratton et al. (2010)
		MSW	38	59%	Suresh (2016)
		Switchgrass	16	83%	Stratton et al. (2010)

Future SAF mix: results

From the extensive overview, the five fuels with lowest abatement costs in both 2021 and in 2050 were chosen. For 2021, these are HEFA in combination with UCO, HTL with forestry residues, HEFA with jatropha, HEFA with Palm Fatty Acid Distillate (PFAD), and FT with forestry residues, respectively with abatement costs of 170 to 300 EUR/tCO_2. For 2050, these are PtL with DAC imported from the Middle East, PtL with DAC as a global average, FT with forestry residues, HEFA with UCO, and FT with corn stover, respectively with abatement costs of 60 to 340 EUR/tCO_2. All of these fuels were put together in Figure 10; linear growth or decline is assumed for the years in between. Figure 9 can be seen as a MACC, because it shows the costs of the cheapest available abatement measures for each year.[7]

Figure 9 – The Marginal Abatement Cost Curve of aviation emissions in the EEA



7 For the yearly abatement and production costs of the different SAF pathways, see Appendices F and G.

For the necessary CO_2 reduction per year to achieve the end goal of 80, 90 or 100 percent compared to 1990-levels, set at 84 Mt (Transport & Environment, 2018a), the assumption is that no reductions will be made before the European aviation sector is back to pre-Covid levels in 2024 (with 78 percent more CO_2 emissions than in 1990). The absolute yearly emission reductions until 2050 are assumed to be constant, implying that the emissions decline linearly. For the lower target of 80 percent reduction in 2050, this comes down to average reductions of 6.5 Mt per year in 2025 to 6.8 Mt per year in 2050. For the higher target of 90 percent reduction, the average reductions are 6.8 Mt per year in 2025 and 7.1 Mt per year in 2050. For the highest target of 100 percent reduction, the average reductions are 7.1 Mt per year in 2025 to 7.5 Mt in 2050.[8]

In 2025, the cheapest abatement measure is HEFA with UCO, estimated at 192 EUR/tCO_2. However, according to CE Delft (2020a), the potential import and production of UCO in the EU is at most 3.4 Mt. With an emission reduction potential of 85 percent (EASA, EEA & EUROCONTROL, 2019), this means that at most 2.9 Mt CO_2 per year can be reduced by HEFA with UCO. This is less than the required emission reduction for that year in all three reduction scenarios. Therefore, it is already necessary in the first year of abatement to use the second most cost-efficient measure: HTL with forestry residues, estimated at 200 EUR/tCO_2. Concerning the availability of forestry residues, CE Delft (2020b) concluded that the biomass supply in the EU is 40.6 Mt per year, with a potential of 69.3 Mt per year in 2030. Assuming a conversion efficiency of 84 percent for biomass to biofuels (Prussi et al., 2020), this means that 34 Mt per year is available now, with a potential of 58 Mt per year in 2030. With an emission reduction potential of 78 percent (De Jong et al., 2017), this means that at most 26.6 Mt CO_2 per year can be reduced by HTL with forestry residues now, up to 45.4 Mt in 2030. Assuming linear growth of this capacity, forestry residues from the EU provide enough biomass input to reduce emissions in European aviation until at least in 2031 for the 80 and 90 percent scenarios, and until 2030 for the 100 percent scenario. As a simplifying assumption, the biomass input is considered to be sufficient to use HTL with forestry residues until in 2031 for all target scenarios, as available secondary and tertiary forestry residues from the EU are not included and biomass could also be imported from other regions. Important to note is that in this scenario, no primary forestry residues from the EU will be available for the rest of the transport sector and other industries.

In 2032, another abatement technology will become more cost-efficient. Whereas HTL with forestry residues will have become more expensive at 253 EUR/tCO_2, PtL DAC imported from the Middle East will have become a cheaper abatement measure at 252 EUR/tCO_2. This conversion pathway will remain the most cost efficient until 2050, when it is estimated to have an abatement cost of only 60 EUR/tCO_2. Although there is much uncertainty, the assumption here is that the technology of PtL DAC will be sufficiently developed to have large-scale implementation in the Middle East with large exports to the EU starting in 2032; 6.6 Mt per year in the lowest reduction scenario to 7.2 Mt per year in the highest reduction scenario. As the reduction potential of PtL DAC is 100 percent, the Mt CO_2 abated is equal to the supply in Mt of fuel. Also, it is assumed that the capacity in the Middle East will be high enough to export the even greater amount of e-fuels necessary until 2050; 128 Mt per year in the lowest reduction scenario to 140 Mt per year in the highest reduction scenario.

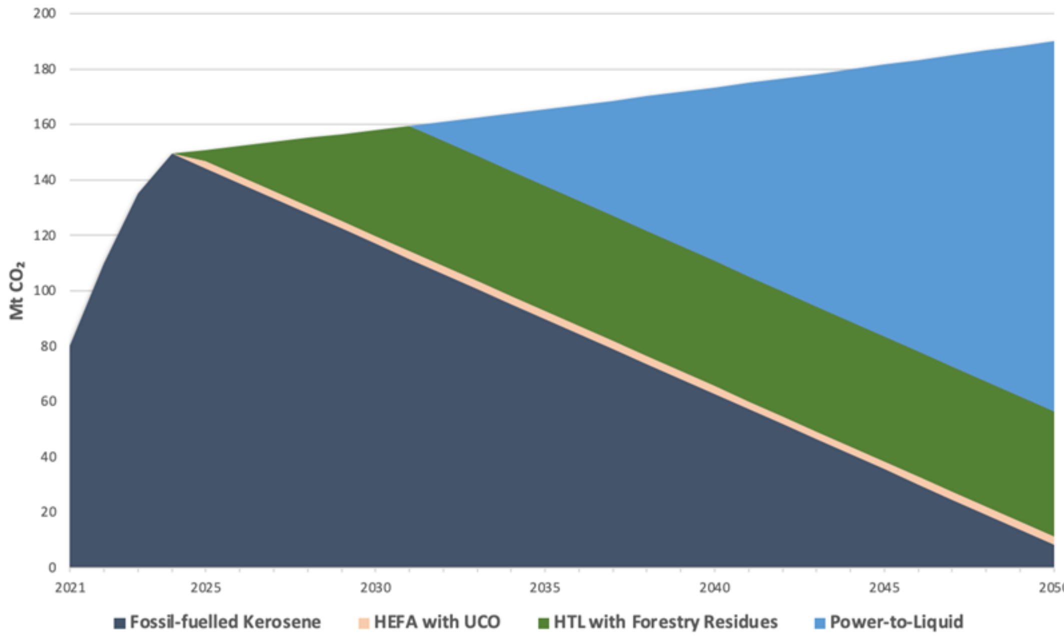
If for some economic, technical, geopolitical or other reason, the production of PtL DAC in the Middle East or exports to the EU will not be possible, an alternative scenario will be taken into account. In 2032, the most cost-efficient abatement technology after PtL DAC imported from the Middle East will be FT with forestry residues. However, the capacity of forestry residues will most likely already be reached by that year, assuming that the first

[8] For the necessary CO_2 emission reduction and the allowed emissions per year, see Appendices H and I.

transition phase will be supplied by HTL with forestry residues. One year later, in 2033, PtL DAC from other regions (the world average) will become (and stay) the most cost-efficient abatement technology after this. Hence, the assumption for the alternative scenario is that instead of imports from the Middle East, the EU will produce domestic PtL DAC against the average global price from 2032 onwards. Its abatement cost will then be 321 EUR/tCO_2 in 2032 and will decrease to 240 EUR/tCO_2 in 2050.

Lastly, an important assumption made in these calculations is that the new shares of SAFs in each year are there to stay until 2050. In reality, however, it is likely that both HEFA with UCO and HTL with forestry residues will be phased out again, especially towards 2050; by then, they will have abatement costs of respectively 330 and 390 EUR/tCO_2. The reason for making the assumption that these biofuels will still be part of the total fuel mix, is because there are many uncertainties about when these fuels will be phased out. For example, almost 50 Mt of biofuels will have to be produced each year after 2030, involving both large amounts of labour and capital. These factories and employees will not be 'discarded' overnight. How fast or slow this transition will be, is beyond the scope of this thesis. Nonetheless, it is important to note that the actual prevention costs will likely be lower as a result of this simplifying assumption: a share of approximately 26 percent in 2050 is now covered by biofuels against inefficient abatement costs, whereas it would be more realistic that the share of PtL DAC will be even greater (and the total prevention costs lower).
For illustrative purposes, the complete future mix of aviation fuels in the EEA under the baseline emission reduction scenario is presented in Figure 10.[9]

Figure 10 – The projected aviation fuel mix in the EEA, in terms of Mt CO_2 emitted (for fossil-fuelled kerosene) or abated (for the SAFs), with an emission reduction scenario of 90 percent in 2050

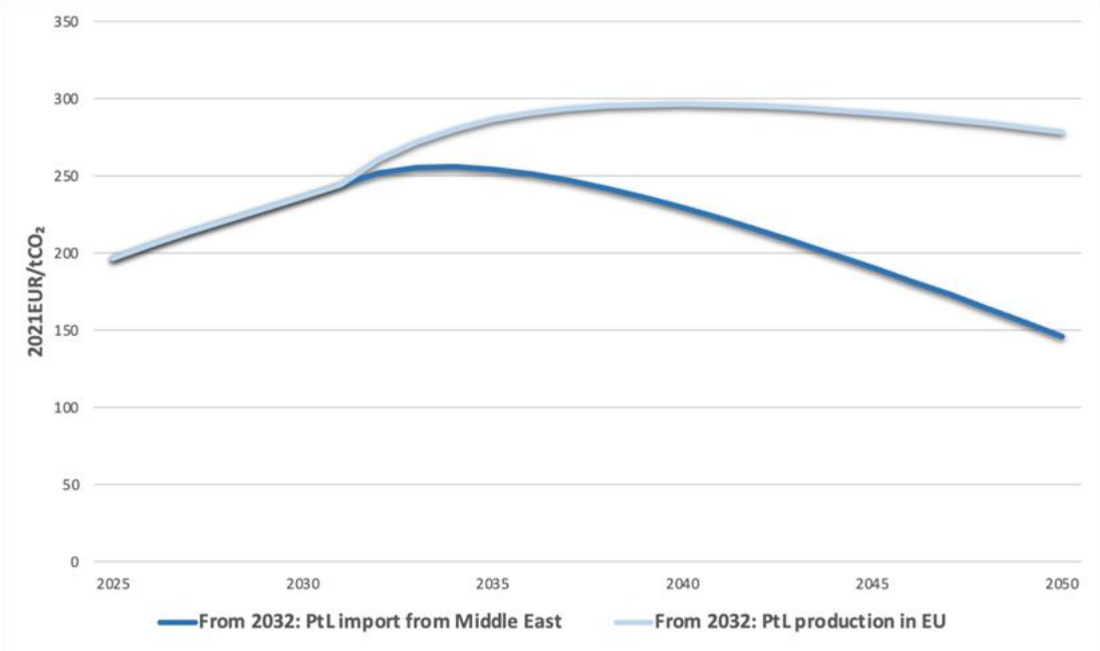


9 For the exact amount of CO_2 emitted or abated in each year, see Appendix J.

Average, marginal and total prevention costs

With the projected future mix of SAFs described above, consisting of HEFA with UCO in 2025, HTL with forestry residues from 2025 until 2031, and PtL DAC from 2032 until 2050 (either imported from the Middle East or produced within the EU), the average abatement costs for each year are approximately the same for all three emission reduction targets, so the baseline scenario will be applied. In the case of PtL imports from the Middle East, these costs start at 197 EUR per tCO_2 in 2025, increasing to 256 EUR in 2034, after which the costs are expected to fall to 230 EUR in 2040 and 146 EUR in 2050. If PtL will be produced in the EU, the costs increase to 297 EUR in 2040 and then fall to 279 EUR in 2050. This is also the cost development that can be expected from the theory: the cost increase in the beginning is due to the increasing price of biofuels (because of the scarcity of and the competition for biomass inputs with the rest of the transport sector and other industries) and the higher costs of PtL; for both scenarios, the average prevention costs eventually decrease due to the falling price of e-fuels (because of technology improvements, economies of scale and the decreasing price of renewable electricity). This development is shown in Figure 11.[10]

Figure 11 – The development of the average prevention costs, based on the projected future mix of SAFs

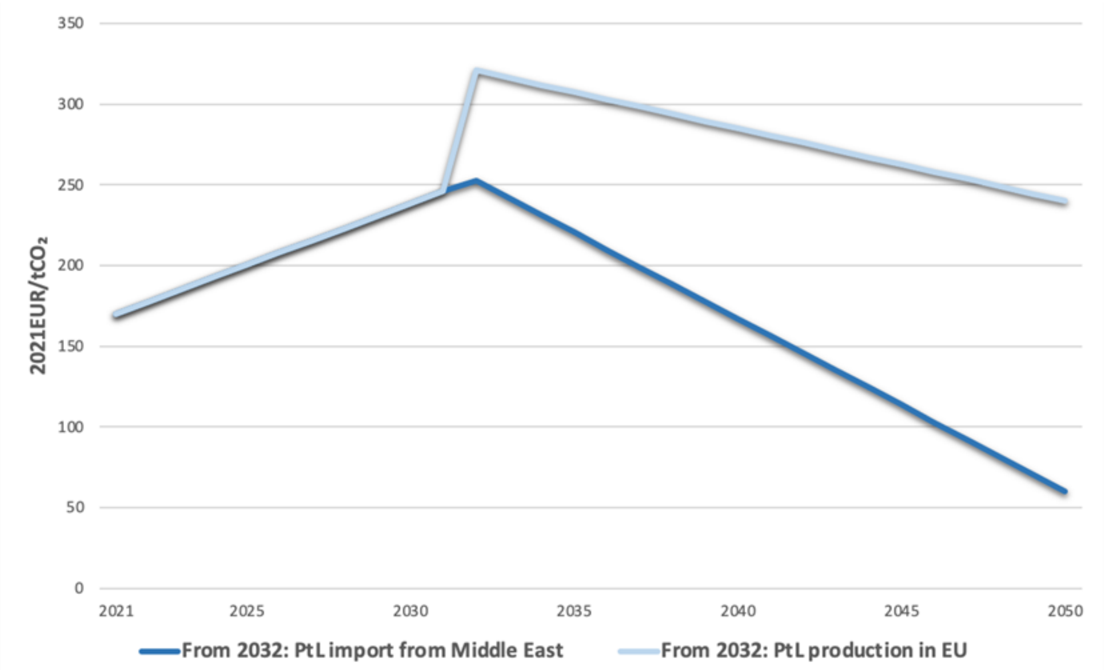


Even more important are the marginal prevention costs, or the costliest abatement measure necessary to make the transition to SAFs, constituting the actual MACC. These costs are equal to the marginal abatement costs of HTL with forestry residues from 2025 until 2031 (increasing from 200 to 246 EUR per tCO_2) and the marginal abatement costs of PtL from 2032 onwards. For import from the Middle East, this means that the costs are 252 EUR per tCO_2 in 2032 and decrease to 60 EUR per tCO_2 in 2050. For domestically produced PtL, the costs will first vastly increase to 321 EUR in 2032 and then decrease to 240 EUR in 2050. This MAC would be the carbon price that is necessary to achieve the policy target and optimise economic welfare. Both MACCs are shown in Figure 12.[11]

[10] For the average abatement costs per year for the different SAF scenarios, see Appendix K.

[11] For the marginal abatement costs per year for the different SAF scenarios, see Appendix L.

Figure 12 – The development of the MACC, based on the projected future mix of SAFs

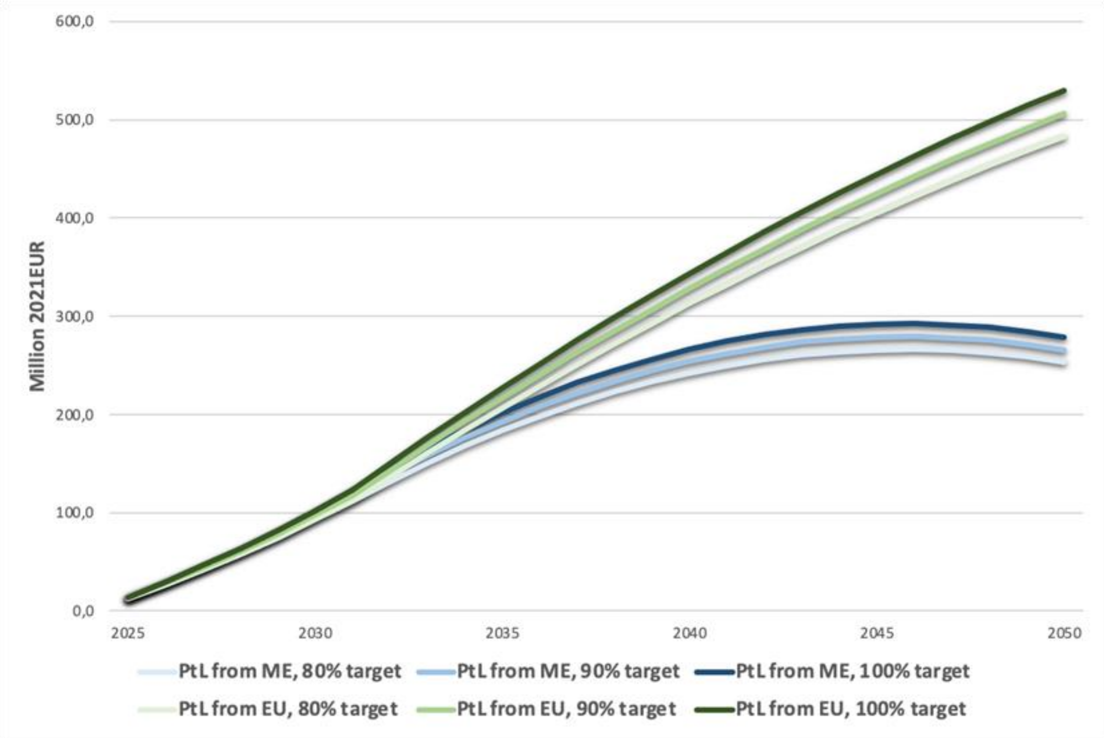


Intuitively, it might seem odd that the MACC for PtL production in the EU has such a sharp ‘spike’ in 2032, but this can be explained by the much higher abatement costs in that year with respect to the lower costs of HTL with forestry residues (which will be ‘depleted’ by that year). In reality, it might be more realistic that the costs will evolve more gradually, as the producers of HTL with forestry residues can increase their costs once the supply becomes more scarce, and the producers of PtL might have to start with lower supply costs to become competitive (which they can make up for by making the costs decrease at a slower pace in the following years).

To make an estimation of the total prevention costs, the abatement costs for each fuel type are multiplied with the amount of CO_2 abated by these fuels in each year for the three different reduction scenarios and for both PtL production scenarios. First assessed are the total prevention costs in the case of PtL imports from the Middle East. For the lower reduction target of 80 percent, total prevention costs start with 13 million EUR in 2025 and increase to 253 million EUR in 2050, counting up to 4.8 billion EUR in total. For the medium reduction target of 90 percent, the total prevention costs start with 13 million EUR in 2025 and increase to 266 million EUR in 2050, counting up to 5 billion EUR in total. For the higher reduction target of 100 percent, the total prevention costs start with 14 million EUR in 2025 and increase to 278 million EUR in 2050, counting up to 5.2 billion EUR in total.

Second, the total prevention costs for PtL production in the EU follow. These costs are the same until 2031. After this, for the lower reduction target of 80 percent, the total prevention costs increase to 483 million EUR in 2050, counting up to 6.6 billion EUR in total. For the medium reduction target of 90 percent, the total prevention costs increase to 507 million EUR in 2050, counting up to 6.9 billion EUR in total. For the higher reduction target of 100 percent, the total prevention costs increase to 530 million EUR in 2050, counting up to 7.2 billion EUR in total. All yearly total prevention costs are shown in Figure 13.[12]

Figure 13 – The yearly total prevention costs for the different SAF and emission reduction scenarios



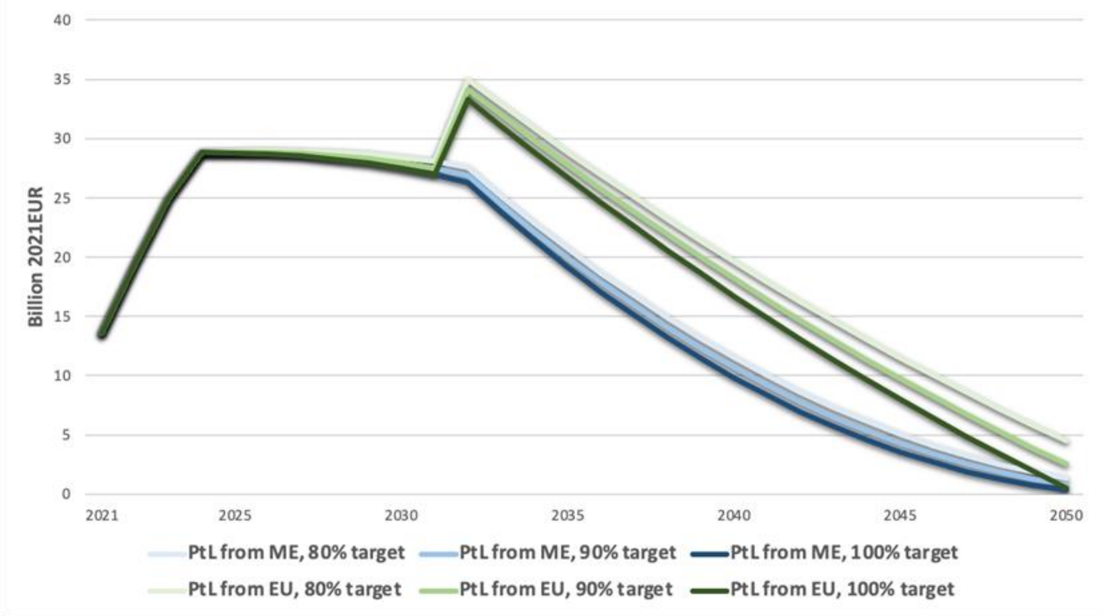
Last, it should be noted that the projected future mix of SAFs will most likely only become reality if the uptake of SAFs is sufficiently incentivised through the carbon price. This price should be at least as high as the MAC in each year. If this would be the case, the total costs become much higher due to the costs of the CO_2 that is still emitted every year. Also, it would not be the higher reduction target of 100 percent that leads to the highest costs, but the lower reduction target of 80 percent; the CO_2 emissions that still exist in this scenario are priced with the marginal abatement costs, in addition to the prevention costs of the shift to SAFs.

If the MACC was thus internalised in the price of CO_2, in the case of PtL from the Middle East, the total prevention costs increase to 478 billion EUR in the lower reduction scenario, 455 billion EUR in the middle reduction scenario, and 432 billion EUR in the higher reduction scenario. If PtL is produced in Europe, the total prevention costs become 547 billion EUR in the lower reduction scenario, 515 billion EUR in the middle reduction scenario, and 483 billion EUR in the higher reduction scenario. The yearly total costs start at 28 billion EUR for every scenario and fall to a maximum of 5.2 billion EUR in the lower reduction scenario with PtL from Europe, and a minimum of 0.3 billion EUR in the higher reduction scenario with

[12] For the yearly abatement costs for the different scenarios and the calculation of the total costs, see Appendix M.

PtL from the Middle East; this yearly cost development in all scenarios is shown in Figure 14.[13]

Figure 14 – The total prevention costs for the different scenarios when the carbon price would reflect the MACC



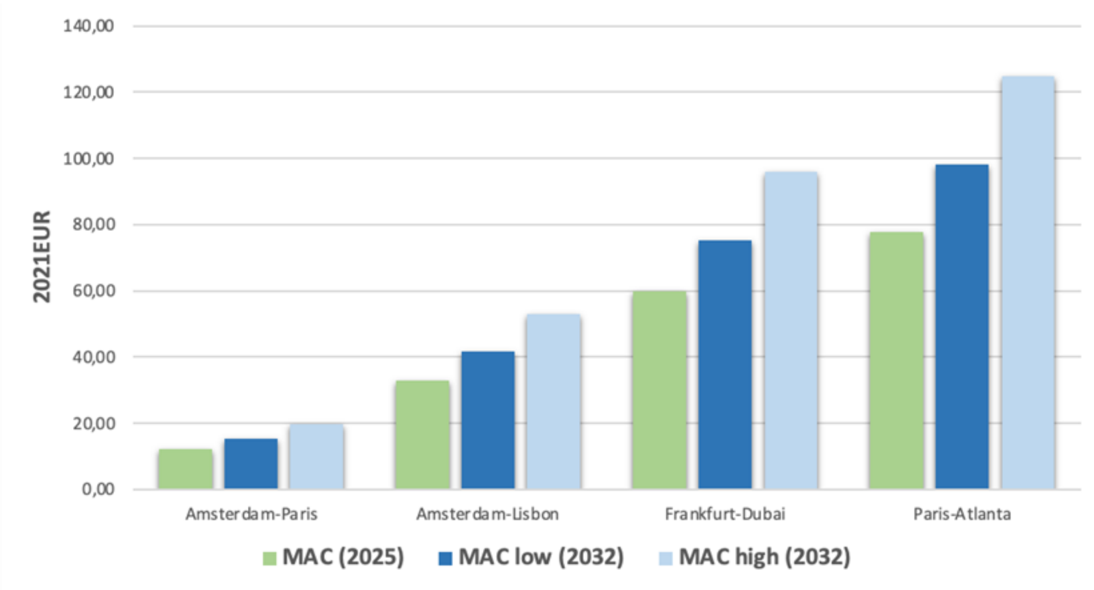
Prevention costs of different routes

Just like for the damage cost approach, the prevention costs are differentiated over common routes in the EEA for contextual purposes. This differentiation entails the internalisation of the MAC in the ticket price. With the MAC at 200 EUR per tCO_2 in 2025, 252-321 EUR in 2032, and 60-240 EUR in 2050, the extra fuel tax costs per flight are the following. For the flight from Amsterdam to Paris, this results in extra costs of approximately 12 EUR in 2025, 15 to 20 EUR in 2032, and 4 to 15 EUR in 2050. For the flight from Amsterdam to Lisbon, this results in extra costs of 33 EUR in 2025, 42 to 53 EUR in 2032, and 10 to 40 EUR in 2050. For the flight from Frankfurt to Dubai, this results in extra costs of 60 EUR in 2025, 75 to 96 EUR in 2032, and 18 to 72 EUR in 2050. For the flight from Paris to Atlanta, this results in extra costs of 78 EUR in 2025, 98 to 125 EUR in 2032, and 23 to 93 EUR in 2050. The differentiated prevention costs until 2032 are presented in Figure 15.[14]

[13] For the yearly prevention costs if the MACC is internalised in the carbon price for different scenarios and the calculation of the total costs, see Appendix N.

[14] For all specifications and the prevention costs of the different common flight routes, see Appendix O.

Figure 15 – Additional costs for tickets on common flight routes in the EEA if the carbon price would reflect the MACC



Important to note is that these are the costs for fossil-fuelled aircrafts, whereas according to the prevention cost model, a share of up to 100 percent of all flights in 2050 will be fuelled by SAFs. This means that over time, not the level of the fuel tax will determine the increase in prices per flight, but the price increase of the SAFs with respect to fossil fuels. For example, on a fully PtL-fuelled plane, the costs in 2050 would be 35 to 140 percent higher than the expected fossil fuel price (with an increase of 35 percent for PtL imports from the Middle East and an increase of 140 percent for PtL production in the EU).

4 Policy options

There are different policy instruments that can be considered to internalise the costs of CO_2 emissions in EEA aviation, the most important of which are emission trading, carbon offsetting and reduction, a fuel or kerosene tax, and VAT or an aviation ticket tax.
This chapter will assess these economic measures one by one. For each of the options, first, the general economic theory behind it will be explained. Then, both existing policies and potential new policy plans will be discussed. Last, the advantages and disadvantages of the policies will be analysed, as well as their potential to effectively internalise the climate costs of CO_2 emissions in EEA aviation.

Emission trading

One way for governments to reduce GHG emissions is to implement a 'cap and trade' system, which means that a cap is set on the maximum level of emissions that are allowed in a market. This cap is reduced over time, so that it incentivises firms to reduce their emissions. If firms emit more than the cap allows, they can purchase permits (or allowances) for every additional unit of emissions. These permits can be obtained from the government, which may choose to give them away for free or auction them for the highest bid, or by trading them with other firms; such a scheme is also referred to as a tradable permit system or emission trading (London School of Economics and Political Science, 2018).

Tradable permit systems have been created from theoretical considerations. Their origins are traced back to the article 'The Problem of Social Cost' by Ronald Coase (1960), which was one of the fundaments for environmental taxes. After this, J.H. Dales (1968) suggested to introduce transferable pollution rights to deal with such externalities. Other economists argued that tradable permits would be an improvement of the command-and-control policies that were in place then, because it would be a more cost-effective way to reduce emissions (Philibert & Reinaud, 2004).

Emission trading is the only policy already in place to internalise the costs of CO_2 emission in EEA aviation, through the EU ETS. It was set up in 2005 as the world's first international emission trading system. It is operational in the entire EEA and it covers about 40 percent of all GHG emissions in the EU (EC, n.d.).

Aviation was brought into the EU ETS in 2012. Initially, its cap was based on average emissions between 2004 and 2006, which was 221.4 Mt CO_2 per year for all participating countries (EASA, EEA & EUROCONTROL, 2019). In 2013, in order to allow the ICAO to develop a global approach to mitigate international aviation emissions, the EU 'stopped the clock' and temporarily limited the EU ETS coverage to flights that both take-off and land within the EEA (EC, 2021b).
Since that year, the amount of annual EU Aviation Allowances (EUAAs) issued has been around 37.5 million. About 15 percent of these were auctioned, whereas the other 85 percent were allocated for free. For all emissions exceeding the cap for aviation, aircraft operators have to purchase EU Allowances (EUAs) (EASA, EEA & EUROCONTROL, 2019).

For the following phase, from 2013 to 2020, the cap for aviation activities was set to 95 percent of the emissions from 2004 to 2006. Through the funding of emission reduction in other sectors, it is estimated that aviation achieved a net saving of 193.4 Mt CO_2 in the period of 2013 to 2020 (EASA, EEA & EUROCONTROL, 2019). During this phase, the cap for stationary installations decreased by 1.74 percent every year. In the next phase, running from 2021 until 2030, this annual reduction is set at 2.2 percent and also applies to aviation allowances. The number of these allowances to be issued in aviation is about 24.5 million in 2021. About 20.7 million of these (82 percent) are provided for free, whereas about 3.8 million (15 percent) remains to be auctioned. The rest (3 percent) is set aside for new entries (EC, n.d.).

On average, the EU ETS has so far contributed to reducing CO_2 emissions from aviation by more than 17 Mt per year (EC, 2021a). However, not all emissions from international aviation are covered by the system, as only intra-EEA flight have been included since 2013; in 2016, the EU has decided to extend this suspension until the end of 2023 (EC, 2021b). If there will be no new amendment, the EU ETS will revert back to its original full geographic scope from 2024 onwards (EC, 2021a). Regarding the 15 percent auctioning share, the European Commission is examining alternative policy options, ranging from slow reduction of the freely allocated allowances to 55 percent in 2030, to an immediate phase-out with 100 percent auctioning from the entry into force of the revision (EC, 2020).

The overall effect of the EU ETS on CO_2 emission reduction within the aviation sector remains to be uncertain. One important advantage of the system are the high compliance levels, due to the fact that the scheme is legally binding and penalties apply in the case of non-compliance (NLR & SEO, 2021). Also, in the early years of the system, some authors estimated that emission trading would achieve the single largest reduction as a measure until 2050 (Lee, Lim & Owen, 2013).

On the other hand, some researchers expected the overall effects to be small, especially in the beginning with a maximum decline of 3.8 percent in CO_2 emissions for the year 2020 (Anger & Köhler, 2010). Furthermore, with the exclusion of international aviation from and to countries outside of the EEA, and with a low price for EUAs, the impact of the system remains low (Transport & Environment, 2018b).

Still, in general, there are some positive aspects of including aviation in the EU ETS (Anger & Köhler, 2010). If its full geographic scope returns and if the amount of allowances that is allocated for free to airlines will be reduced, this would significantly increase the potential of the EU ETS as an emission reduction policy. These policy changes are in line with the expectations and ambitions of the EU (EC, 2019).

Regarding its potential to effectively internalise the costs of CO_2 emissions from EEA aviation, this especially depends on the price of the EUAs. In the first phase, the price per tCO_2 initially rose to over 30 EUR, but then collapsed to essentially zero by mid 2007 because of too many allowances that were given away for free (Hintermann, 2010). After a period of a stable but low price of 4 to 8 EUR, the price started to increase again in 2018. As of 28 May 2021, the price has reached a record high of more than 50 EUR (Ember, n.d.). It is approaching a price that might be high enough to fully internalise the damage costs of CO_2 emissions in EEA aviation (assuming the base line from this thesis), but is still much lower than the price that would be necessary to incentivise a transition to SAFs (assuming the approximation of the prevention costs). Also, the price is only applicable to the tradable EUAs, not the many permits that are still given away for free. Only if all permits would be auctioned or sold at a price that is high enough, emission trading would effectively internalise the costs of CO_2 emissions in EEA aviation.

Carbon offsetting

As mentioned earlier, ICAO has been working on a global approach to mitigate international aviation emissions. This resulted in the carbon offsetting scheme CORSIA. Carbon offsetting is essentially a compensation for excess emissions in one location through carbon reductions in another. For example, the emissions from an intra-EEA flight could be compensated by an afforestation project in Africa. The economic rationale is that paying for emission reductions elsewhere in the world, most notably in developing countries, would be easier, cheaper, and faster than domestic reductions. In addition, when offsetting involves projects in developing countries, this would contribute to their sustainable development (Bumpus & Liverman, 2008).

The first known carbon offsetting system emerged in the Kyoto Protocol's flexible mechanisms in 1997, allowing developed countries to meet their emission reduction targets by purchasing emission reduction credits from projects in the developing world. This was called the Clean Development Mechanism (CDM). Alternatively, they could be purchased from eastern European countries that were in transition, called Joint Implementation. Beyond the regulated CDM, a parallel market was developed for Voluntary Carbon Offsets (VCOs), so that individuals and organisations could compensate for their emissions on their own behalf. For example, frequent fliers could 'offset' their aviation emissions from then on (Bumpus & Liverman, 2008).

CORSIA, the newly implemented carbon offsetting system by ICAO, was agreed upon in October 2016. Back then, it set the target of not increasing net CO_2 emissions from international aviation from 2021 onwards, compared to the average levels in 2019 and 2020. CORSIA requires airlines to purchase eligible emission units above this baseline. Also, airlines can reduce these offsetting requirements by claiming emission reductions from eligible SAFs, incentivising their use (UNEP, 2020).

Yet in 2020, as a response to the Covid-crisis, ICAO has decided to calculate the emission baseline using only 2019 emissions, instead of averaging 2019 and 2020 emissions. Because of this, the baseline will increase by around 30 percent. Furthermore, the implementation of CORSIA carbon offsets is expected to be delayed for three to five more years (Gordon-Harper, 2020).

Under the scheme, airlines are required to monitor their emissions on all international routes. They can purchase their eligible emission units above the baseline, generated by projects that reduce emissions in other industries such as the renewable energy sector. Still, during the first period until 2035, the scheme is estimated to offset only 80 percent of the emissions above 2019-levels due to voluntary participation until 2026 and exemptions for states with low aviation activity (EC, 2021a). The phase from 2027 until 2035 cover all states that had a share above 0.5 percent of total Revenue Tonne Kilometres (RTKs) in 2018 or whose cumulative share in the list of states from highest to lowest amount of RTKs counts up to 90 percent of all RTKs (EC, 2021b).

For now, the coverage and environmental impact of CORSIA is still low, as it only includes any post-2020 emission growth and not the emissions up to that level. The environmental net benefits could become even lower if the Certified Emission Reductions (CERs) elsewhere will be subject to some kind of failure (Maertens, Grimme, Scheelhaase & Jung, 2019). A journalistic investigation, including assessments from researchers, pointed out recently that the market for carbon credits from forest protection projects "faces a significant credibility problem" (Greenfield, 2021). According to Britaldo Soares-Filho, deforestation modelling expert and professor at the Institute of Geosciences at the Federal University of

Minas Gerais, these projects “have a tendency to inflate threats to the forest and current modelling approaches result in phantom carbon credits” (Greenfield, 2021).

Even if there is a net benefit of the CERs, it is estimated that CORSIA will only result in the offset of 12 percent of total emissions from international and domestic aviation by 2030. This would be in the case of full additionality, which means that these carbon offsetting projects would not have happened without the offset buyers in the market. As this is hard to prove, it is often considered as a rather controversial claim to make. Also, offsetting projects such as carbon sequestration by afforestation or reforestation may become scarce in the future, because of limited availability and competition from other markets (UNEP, 2020).

The main differences between the EU ETS and CORSIA are summarised in Table 7. In general, CORSIA is less ambitious than the regulation of aviation within the EU ETS. The European Commission even concludes that “there are a number of features of CORSIA which imply its level of ambition for the international aviation sector is misaligned with, and weaker than the global level of ambition required to keep within the temperature goals of the Paris Agreement. (…) Participating in CORSIA would risk undermining the objectives and weakening current EU climate policies” (EC, 2021b, p.15).

In sum, CORSIA is not expected to effectively reduce CO_2 emissions, despite ‘reduction’ being part of the scheme’s name. It internalises the climate costs of CO_2 emissions to limited extent, as it only targets emissions above 2019-levels. Also, it is unclear whether the CER projects actually succeed as planned.

Table 7 – The main differences between the EU ETS and CORSIA

Element	EU ETS	CORSIA
Scheme	Cap and trade	Carbon offsetting
	Caps the level of emissions. Operators reduce their emissions or buy EUAs in the market. CERs can be used to offset up to 1.5 percent of emissions (until 2020).	Operators buy international carbon credits to offset their emissions above 2019-levels. Conditions apply to offsetting programs.
Applicability	2012-2023	2021-2035
	Reverts to full-scope in 2024, unless there is a revision in the light of CORSIA.	Voluntary from 2021 to 2026, mandatory from 2027 to 2035.
Target	2030: -43% compared to 2005	Carbon-neutral growth from 2020
	General and aviation caps are reduced by 2.2 percent each year.	Cap remains fixed at 2019-level.
Certainty	Available allowances correspond to target, ensuring that target is met under full compliance	Depends on the quality of the carbon credits and the compliance level
	Legally binding system with penalties in the case of non-compliance.	Only legally binding when implemented in national law. Uncertain how compliance is enforced.
Coverage	Intra-EEA flights and within Outermost Regions	International flights between participating states
	Initially, all flights to and from EEA airports. 'Stop the clock decision' limited the scope in 2013 to give ICAO time to develop CORSIA. Reverts to full-scope in 2024 unless there is a revision.	Exemptions apply for domestic flights, least developed countries, small island states, landlocked developing countries, small operators and aircrafts, and flights with public purpose.
SAFs	SAF are attributed zero emissions if mathcing RED requirements	Reduced offsetting obligation for 'eligible fuels' depending on life-cycle emissions

Source: NLR & SEO, 2021.

CORSIA and EU ETS

Within the EEA, the question persists whether and how CORSIA and the EU ETS will co-exist from 2024 onwards. In that year, the EU ETS is scheduled to revert back to its full geographic scope, including international flights to and from countries outside the EEA (which are only covered by CORSIA until then). Different policy options are currently still being assessed regarding whether and how to implement CORSIA by the EU: first, in case no amendment is adopted by December 2023, the EU ETS full legal scope will return; second, the EU ETS could be applied exclusively to intra-EEA aviation (and the system as it is now would be maintained); third, in the case of CORSIA-only implementation, international aviation would be removed from the EU ETS (and only domestic flights within the EEA would remain part of it); fourth, the EU ETS could continue to apply to the current intra-EEA scope, and CORSIA could be introduced for the other international flights in the EEA; fifth, CORSIA could only apply above the 2020-level emissions for intra-EEA flights (and the EU ETS below that level); and sixth, CORSIA could only apply to intra-EEA flights for operators with licences issued by third countries (and the EU ETS would cover operators with licenses issued by member states) (EC, 2020).

According to CE Delft (2020c), most emission reductions within the EU would be reached if the current scope of the EU ETS is maintained with CORSIA covering all international flights (option four from above). Overall world-wide emission reductions are even higher if the cap within the EU ETS is adjusted downwards, so that the demand from aviation for allowances is not changed by the introduction of CORSIA. Total emission reductions are the lowest if the EU ETS system will be only applicable to domestic aviation and CORSIA would ‘take over’ all international flights (as in option three from above), because the CORSIA baseline is less ambitious than the EU ETS emission cap for aviation (CE Delft, 2020c).

Other researchers also conclude that a ‘full scope’ approach of EU ETS would lead to the largest CO_2 compensations in the short and medium term: from 8 percent of global CO_2 emissions from passenger traffic in 2018 to 16 percent in 2036. Until that year, the EU ETS would offer larger environmental benefits than CORSIA (Maertens et al., 2019).

The advantage of the EU ETS over CORSIA might change beyond 2036, if the CORSIA carbon offsets prove to be effective until that time, but not if the price of EUAs continues to increase as it does now. Several studies find a parallel coverage of international and domestic EEA flights by the EU ETS and of the other international flights by CORSIA the best option, both in terms of environmental benefits and expected political acceptance on a global level (Scheelhaase, Maertens, Grimme & Jung, 2018). On top of that, applying CORSIA to a continued EU ETS would reduce transaction costs because of the lower administrative burden, compared to CORSIA-only implementation (Maertens et al., 2019).

Concerning the internalisation of climate costs of CO_2 emissions, the EU ETS seems to be more effective than CORSIA. Especially if the criticisms of the carbon offsets are justified and the price of the EUAs continues to rise, maximum implementation of the EU ETS would be preferred over CORSIA. Nonetheless, applying CORSIA to the international flights to and from non-EEA countries could still be beneficial compared to no international policy on those routes, as long as the carbon offsets fulfil their potential.

Fuel taxation

Apart from emission trading and carbon offsetting, taxation is another economic measure that could internalise the costs of emissions. One option would be to implement a tax on fossil-fuelled kerosene. Important here is that the ICAO Chicago Convention does not allow for the taxation of fuels that are on board of aircraft when they land in a jurisdiction. Also other ICAO documents urge its member states to refrain from taxing international aviation (CE Delft, 2019a).

A legal analysis by CE Delft shows that, despite the fact that fuels used in commercial aviation are currently exempt from excise duties in the EU, it appears to be possible for EU Member States to tax aviation fuels on flights between them. The Energy Taxation Directive permits them to impose a tax on aviation fuels used in domestic flights without limitations, as well as on international flights within the EEA, as long as the affected states have entered into a bilateral agreement to do so. Even if non-EU carriers with mutual exemption from fuel tax are operating on intra-EEA routes, the introduction of a de minimis threshold would minimise the chances that a legal challenge by these carriers would be successful. This threshold could be based on the total amount of fuel, the number of flights, or the total tax receipt; as long as it is established for intra-EU fuel taxation so that foreign carriers (that mostly only cover a small proportion of the intra-EU flights) are exempt, no legal issues prevent such a tax (CE Delft, 2018a).

The potential revenues of an excise duty on aviation taxes is several billion EUR per year. Assuming a fuel tax of 330 to 530 EUR per cubic meters of fuel, revenue estimates even amount 20 to 32 billion EUR (CE Delft, 2013). A more recent study estimated that introducing a kerosene tax in Europe at 0.33 EUR, the agreed EU minimum, would generate 17 billion EUR in fiscal revenue. In this case, emissions would be reduced by 11 percent (CE Delft, 2019a).

However, no such intra-EEA fuel taxes are known as of today. So far, only the Netherlands and Norway have implemented fuel taxes on domestic flights, although the Netherlands have phased out these flights. Internationally, among others the US, Japan, India, and Brazil have implemented domestic fuel taxes (CE Delft, 2018a). According to Transport & Environment, one reason for the absence of such a tax is that air service agreements continue to provide mutual fuel tax exemptions for foreign carriers operating on intra-EEA routes. Nevertheless, these operations have decreased strongly in numbers and also these authors state that an intra-EEA fuel tax could now be introduced with a de minimis provision, exempting all foreign carriers (Transport & Environment, 2018b).

In theory, fuel taxation could be an effective way to internalise the climate costs of CO_2 emissions, either by applying the damage costs or the prevention costs. EEA countries could enter into a bilateral agreement to impose the tax on flights between them. This tax would be CO_2-emission based, focusing on the amount and type of fuel, which might result in an administrative challenge with significant transaction costs. In addition, the tax would have to be introduced with a de minimis provision. To achieve full effectiveness, a discontinuation of this exemption for foreign carriers would be desirable in the long term.

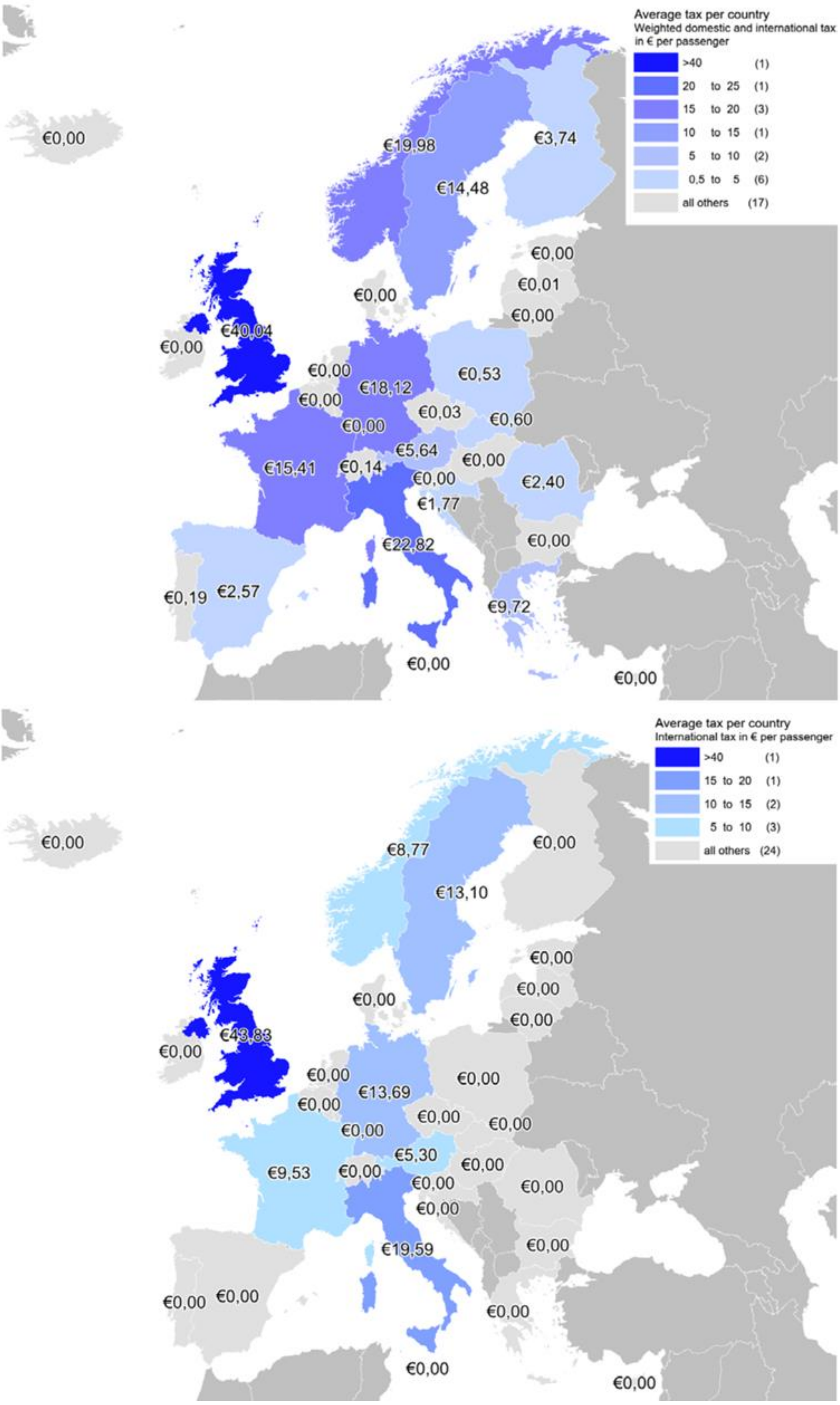
VAT or ticket taxation

Other forms of taxation include a VAT or an aviation ticket tax. Also aviation ticket taxes can withstand legal challenges, as long as they are not linked to fuel consumption on international non-EEA routes and if they do not differentiate rates within the EU. On the other hand, a tax with a single rate is not desirable, because it does not take the actual environmental impacts of a passenger on a specific flight into account; longer flights emit more CO_2 than shorter flights and priority seats are considered as more emitting than economy seats (because of their space uptake in the aircraft).

Four options to implement an effective ticket tax in a legally feasible way are the following: first, a tax could be differentiated based on the average lifecycle emissions of fuels that the airline has used in the previous period; second, a tax could be differentiated based on the distance to the destination; third, a tax could be differentiated based on the LTO NO_x emissions (the certified NO_x emissions during landing and take-off); and fourth, a share of the tax could be replaced by a charge related to the distance flown and the LTO NO_x emissions of the aircraft, which constitutes a combination of the second and third option (CE Delft, 2018c).

Many countries are already subject to some of these more specific taxes and charges, such as a departure tax or a solidarity levy. Within the EU in 2019, VAT or other taxes on domestic aviation existed in 17 states. Six states levied taxes on international aviation. The highest average tax rates (weighted for domestic and international passengers) were in the UK at 40 EUR per passenger, followed by Italy (23 EUR), Norway (20 EUR), Germany (18 EUR), and France (15 EUR). For international passengers, the highest average aviation taxes could also be found in the UK at 44 EUR per passenger, followed by Italy (20 EUR), Germany (14 EUR), and Sweden (13 EUR). All average aviation taxes are shown in Figure 16 (CE Delft, 2019a).

Figure 16 – The average aviation taxes per passenger in the EEA



Source: Figure copies from CE Delft (2019a).

If the EU decided to introduce an average 20 percent VAT on air travel in all countries and it would abolish other aviation taxes, it would raise tax revenues by 7.1 billion EUR (CE Delft, 2013). According to CE Delft, imposing new or increased taxes would reduce the number of passengers and flights, as well as the environmental impacts. At the same time, it would have a negative impact on the aviation industry because of lower direct employment and direct value added, but its impact on the overall employment, fiscal revenue, and GDP would be close to zero (CE Delft, 2019a).

Lastly, there are some fundamental questions that arise with the introduction of any form of taxation in the aviation sector. For example, what should be done with the tax revenues? Are these taxes used by governments to balance out budgets, or to make sustainable investments and give out subsidies for e.g. SAF deployment? And is it ethically desirable to make no difference between consumers who rarely purchase aviation tickets, and frequent flyers? An answer to these complex issues is beyond the scope of this thesis, but should be considered.

As long as an aviation ticket tax or VAT would be differentiated to some extent, based on the lifecycle emissions of the flight, it could be an effective way to internalise the climate costs. In this case, it would be in fact comparable to a fuel tax, because the CO_2 emissions of a flight mainly depend on the amount of fuel and the fuel type used. The most important difference would be where the tax is levied; in the case of a fuel tax, airline operators would pay the tax for their fuel consumption (and might pass these costs through to the passenger), whereas a ticket tax or VAT would be added directly to the passenger ticket price. As a consequence, a fuel tax reduces emissions through both an impact on demand and on supply, with the supply effect likely to be larger in the long term (Transport & Environment, 2020).

In conclusion, a fuel tax would be more effective than an aviation ticket tax or VAT, because it taxes CO_2 emissions more directly; it would be quite complex to calculate the CO_2 emissions for every ticket or flight individually, whereas an airline knows how much of each type of fuel it uses on its flights. Also, the demand of airlines for SAFs might be more directly enhanced if operators recognise their competitiveness, compared to the fossil fuels with a tax imposed directly upon them.

Policy recommendation

To conclude this chapter with a recommendation, any combination of the EU ETS and a fuel tax would be best to internalise the climate costs of CO_2 emissions from EEA aviation. This can be done either by expanding the EU ETS to international aviation on extra-EEA flights and increasing the price of EUAs to the desired level (of either the damage cost or prevention cost in each year); or by implementing a tax on fossil-fuelled kerosene with the same price per tCO_2; or any combination that would represent a carbon price equivalent. What the specific impact of these choices would be and which policy option would be best in practice, is beyond the scope of this thesis and is thus a suggestion for future research.

Carbon offsetting through CORSIA is not considered to be a viable option to internalise the climate costs of CO_2 emissions from EEA aviation, both because it is less effective hypothetically and in theory, as well as because of the criticisms of the implementation in practice so far. However, as long as international flights to and from countries outside the EEA are not included in the EU ETS for aviation or are excluded from a potential fuel tax, CORSIA could supplement these policies if the carbon offsets become more trustworthy and effective than they are at this moment.

Last, in addition to these economic measures, NLR & SEO (2021) made some useful general policy recommendations, including regulatory measures such as the implementation of an EU-wide SAF blending obligation. To further reduce the costs of SAFs and increase the emission reductions, "a transparent monitoring and accounting framework should be implemented, similar to the framework of renewable electricity. This would give airlines the possibility to claim the use of SAF in the most economically efficient way across the fleet, regardless of where SAF has been physically uplifted" (NLR & SEO, 2021, p.v).

5 Effect on demand

If the climate cost of CO_2 were to be internalised through policy, either using the damage cost approach or the prevention cost approach, this would not only have an impact on the costs for airlines and the supply side of aviation. The demand of passengers for tickets will be affected by this increased cost as well. As for most products and services, an increased price will lead to lower demand. Consequently, this will also lead to lower CO_2 emissions. To what extent this will be the case, depends on the policy imposed, the cost pass-through of the airlines to the ticket prices, and the price elasticity of flight tickets. These issues will be discussed in this chapter.

Cost pass-through

Depending on the choice of measures from the chapter 'Policy options', airline operators can determine whether they want to impose the full cost increase upon the passenger or not. The impact of the policy on the demand for flight tickets depends on the extent to which the cost increase is passed through. If the cost pass-through is 100 percent, the costs are fully borne by the passengers. However, the airline might also choose to carry part of the costs, because higher fares will result in lower sales and profits. On the other hand, if the airline opts for a cost pass-through of e.g. 50 percent, the volume of demand might remain the same, but the profits will decrease because of the higher costs (Koopmans & Lieshout, 2016). This is the trade-off that airlines need to make if their costs increase.

The cost pass-through depends on whether the cost increase is firm-specific or sector-wide, as well as on the market conditions. For the case of EEA aviation, an effective policy to internalise the costs of CO_2 will always have a sector-wide implementation, as some firms will otherwise benefit from the policy, resulting in carbon leakage (CO_2 being emitted where the policy is not applicable). Regarding the market conditions, most aviation markets can be characterised as differentiated oligopolies, as there is a high concentration of a limited amount of different airlines that offer slightly different products, ranging from low-cost carriers to high-service airlines. According to Koopmans & Lieshout (2016), the Cournot model for oligopolies is considered best in this case, because airlines choose quantities (flight schedules) first and then adapt their prices to ticket demand (yield management). In this sort of markets, they argue, sector-wide cost changes are passed through by a rate of more than half (Koopmans & Lieshout, 2016).

The specific policy has an influence on how much the cost pass-through exactly is. For example, in the case of a fuel tax, the cost increase can be considered as a fuel price increase, whereas an increase of the allowance price in the EU ETS is a non-fuel cost increase. Still, any policy that effectively mitigates CO_2 emissions will always depend on the amount of fossil-fuelled kerosene used. Hence, the simplified assumption is that any cost increase by the chosen policy is considered as a fuel price increase. This means that the ticket price increase mainly depends on the share of the fuel costs in the total costs of airlines, estimated around 20 to 50 percent in 2014 (Koopmans & Lieshout, 2016).

Studies that estimate the exact level of ticket price increases as a response to fuel price increases are limited. Wang, O'Sullivan, Dray & Schäfer (2018) developed an airfare model that explicitly captures airline operating costs. Airlines in the intra-EU market are estimated to have a pass-through elasticity of 0.23 to 0.25, whereas the market between Europe and Asia and the Pacific have a pass-through elasticity of 0.31 to 0.37, and the market between Europe and South America follows with a coefficient between 0.25 and 0.39. The markets between Europe and North America, Africa, Central America, and the Middle East have lower pass-through elasticities of respectively 0.18 to 0.25, 0.11 to 0.19, 0.08 to 0.20, and 0.07 to 0.17 (Wang et al., 2018). The relatively low prices of oil (and hence for fuel) in the Middle East are reflected in these lower coefficients. Using the share of total passenger CO_2 emissions per market in 2019 from ICCT (2020) and calculating a weighted average for European aviation, this would result in a coefficient of 0.21 to 0.27. This means that for every ten percent increase in the fuel price, the ticket price increases by 2.1 to 2.7 percent.

Transport & Environment (2018b) estimated a fuel price fraction of the total ticket price at 20 percent for extra-EU flights and 25 percent for intra-EU flights. This is consistent with the theory, as well as with the fuel share estimations of Koopmans & Lieshout (2016) and the pass-through elasticities of Wang et al. (2018). If the sector-wide changes are indeed passed through by a rate of more than half or even to the fullest, as suggested by Koopmans & Lieshout (2016), the ticket price increase as a result of a fuel price increase should reflect the share of the fuel price in the total expenses of the airline. The 21 to 27 percent ticket price increase from Wang et al. (2018) is thus consistent with a fuel share of 20 to 25 percent from Transport & Environment (2018b), as well as with the broader range of 20 to 50 percent from Koopmans & Lieshout (2016).

Another reason to assume that the ticket price increase reflects the fuel share in the total costs (and airlines impose the entire cost increase upon the passenger) is that the profit margins for airlines are relatively low and the extent to which airlines can absorb costs is limited as well (NLR & SEO, 2021). Hence, for this study, the ticket price increase as a result of fuel price increases in EEA aviation to passenger tickets is set at 24 percent (as a middle value of 21 to 27 percent). This means that for every 10 percent increase in the fuel price, the price of a flight ticket increases by 2.4 percent on average.

Demand elasticities

With an approximation of the average expected increase in ticket prices, the effect of this change on the demand for these tickets remains uncertain. This effect is largely determined by demand elasticities, measuring the change in the quantity demanded as a result of change to other economic variables. Three of the most well-known demand elasticities that are also applicable to the aviation market are income elasticity, cross-price elasticity, and price elasticity.

First, higher incomes are generally associated with a higher demand. As flight tickets are considered a luxury good, this is especially the case for aviation. Studies on the demand for aviation that include an income variable indeed all show income elasticities above one, generally between 1 and 2 (InterVISTAS, 2007). This high income elasticity would imply that if people’s income increases by a certain rate, the population increases its expenditure for flight tickets even more. This finding is confirmed by IATA (2008), stating that in twenty years global passenger traffic has increased by 5.1 percent per year on average, whereas global GDP grew by an average annual rate of 3.7 percent over the same period; an average income elasticity of 1.4 (IATA, 2008). This should be taken into account as a control variable, in order to correctly estimate the other elasticity coefficients.

Second, if substitutes are available, price increases often lead to lower demand because of these competing goods or services (which will then increase in demand). For aviation, possibilities of transport substitution will be especially present on short-distance routes, as there are alternatives in road or rail transport. Switching between these modes of transport for shorter distances depends mainly on the cross-price elasticity, or how much the demand for aviation reacts on a price change in road or rail transport and vice versa. Typically, the elasticity is higher if there is a larger number of available substitutes, so that a consumer can easily switch between these different options (IATA, 2008). Different aviation analyses confirm that the presence of this opportunity for inter-model substation on short-haul routes is reflected in the higher price elasticity on these routes (InterVISTAS, 2007).

This general price elasticity is the third and most important elasticity for an increase in ticket fares. The price elasticity is a measure to capture the sensitivity of consumer demand in response to changes in the price. The price elasticity of a product or service is defined as the percentage change in the quantity demanded, divided by the percentage change in the price. As an example, if a 10 percent increase in the price results in a 5 percent decrease in the quantity demanded, the price elasticity is -0.5 and this is called inelastic or price insensitive; whereas if a 10 percent increase in the price results in a 15 percent decrease in the quantity demanded, the price elasticity is -1.5 and this is called elastic or price sensitive (IATA, 2008).

A number of factors generally affect the price elasticity. Some of them were already mentioned above, such as the availability of substitutes and the degree of necessity (distinguishing between necessities, such as water, and luxury products). Other factors that play a role are the proportion of a consumer's budget that is consumed by the good, and whether it is demanded as an input to a final product or as the final product itself. For aviation, tickets generally do not consume a large portion of the consumer's budget, which means that this will most likely not drive the price elasticity up. Also, a flight ticket can be considered as an input for the total product of a trip, meaning that it is only one share of the total costs. This means that the price elasticity at least partly depends on the price elasticity of the final product, or the total trip expenses. Lastly, one factor that is particularly important for the sensitivity of aviation demand as a result of a policy change, is the time period considered. Elasticities tend to increase over time, as consumers have more time to adjust their behaviour. In the case of a structural policy change, this means that demand changes are expected to be greater in the long term (IATA, 2008).

Estimated price elasticity

The availability of price elasticity estimates in aviation is low, mainly because data about the changes of prices and the number of tickets sold per route are not publicly available. The most well-known and widely used study in this field is the report by InterVISTAS (2007), summarising analyses that examine fare elasticities in the passenger aviation market. The particular aim of this study was to provide robust elasticity estimates to address policy issues related to, among others, taxation and emissions schemes. Although the report is quite outdated, these are still the best estimates currently known and the purpose of the study fits an application to this thesis.

The most general result, ceteris paribus, is that business travellers are less sensitive to changes in ticket prices than leisure travellers. In other words, business tickets are less elastic than other tickets. This can be explained by the fact that business travellers often have less flexibility to postpone or cancel their trip, while these travels are often considered as more necessary than holidays for pleasure (InterVISTAS, 2007). The elasticity multiplier for business travellers is about 0.6, according to Brons, Pels, Nijkamp & Rietveld (2001). Based on the fact that 19 percent of CO_2 emissions in 2019 can be assigned to premium seating and about 60 percent of premium seats consist of business class seats (ICCT, 2020), the weighed seat multiplier for this thesis is 0.95.

Furthermore, as a base multiplier for this thesis, the price elasticity at the supra-national or pan-national level (such as the EU), was found to be -0.6 (InterVISTAS, 2007). This is relatively inelastic, because as the number of routes covered expands (from the national to the supra-national level), the number of choices for passengers to avoid a travel price increase diminishes (IATA, 2008). Nonetheless, the largest multiplier in the world can be found for intra-European flights at 1.4, which is also applicable to the price elasticity in this thesis. The other multipliers that are applicable are those for the markets between North America and Europe (1.2) and between Europe and Asia (0.9). Again, using the share of total passenger CO_2 emissions per market in 2019 from ICCT (2020) and calculating a weighted average for European aviation, the multiplier becomes 1.23. One last multiplier that should be taken account is the short-haul adjustor of 1.1. Assuming that approximately half of the flights are short-haul and half are long-haul, based on the global shares estimated by ICCT (2020), the multiplier applied in this thesis is 1.05. Multiplying all these coefficients (-0.6, 0.95, 1.23, and 1.05) results in an average price elasticity for all EEA aviation of -0.74 (InterVISTAS, 2007).

With an average cost pass-through elasticity of 0.24 and an average price elasticity of -0.74, the following conclusions can be made. If any policy instrument imposed in the EEA would result in a fuel cost increase of 10 percent for airlines, average EEA ticket prices would increase by 2.4 percent. As a result of this cost increase for passengers, EEA aviation demand would decrease by 1.8 percent. It must be emphasised that this is a very simplified calculation and should be merely used for illustrative purposes, as there are many differences between the imposed policies and their consequences, the affected airlines or routes, and the different types of tickets and passengers. Also, the demand response to the price change will most likely not take fully effect immediately, and probably increases over time. Still, these approximations give a general indication of the average impact of CO_2 cost internalisation policies on EEA aviation demand.

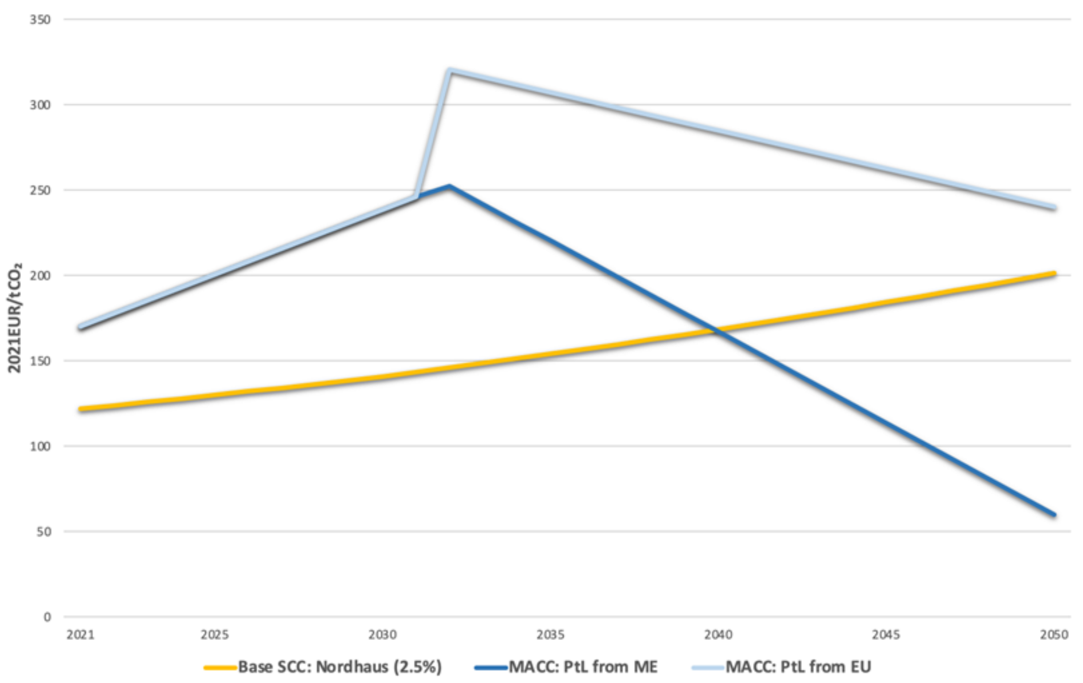
6 Analysis and discussion

This last chapter discusses how the most important findings of this thesis relate to each other. What follows is a comparative analysis between the damage costs and prevention costs of CO_2 emissions from EEA aviation, determining which approach is most cost-efficient and thus preferred. Lastly, the policy implications of this approach and its impact on aviation tickets and demand will be discussed, as well as the limitations of this study.

Comparative analysis

In order to compare the different cost approaches, first the SCC from the damage costs and the MAC from the prevention costs are compared to each other. Both terms indicate the marginal costs of an additional unit of CO_2 emitted to the atmosphere; for the SCC, it reflects the resulting damage costs in the future, whereas for the MAC, it shows the costs of preventing the CO_2 from being emitted in the first place. In 2021, when the central SCC value is at 122 EUR, both MAC projections are estimated at 170 EUR. Both the MAC and SCC are expected to increase until 2032, after which the MAC decreases due to the lower costs of PtL production. In the case of imports from the Middle East, the MAC even drops below the SCC from 2040 onwards. In 2050, the SCC is expected to be 202 EUR, while the MAC is 240 EUR for PtL from the EU and 60 EUR for PtL from the Middle East. It can thus be concluded that the marginal prevention costs are always higher than the marginal damage costs, except for the scenario in which PtL is imported from the Middle East from 2032 onwards (which results in lower marginal prevention costs after 2039). Both the development of the base value of the SCC, as well as the two MACCs are presented in Figure 17.

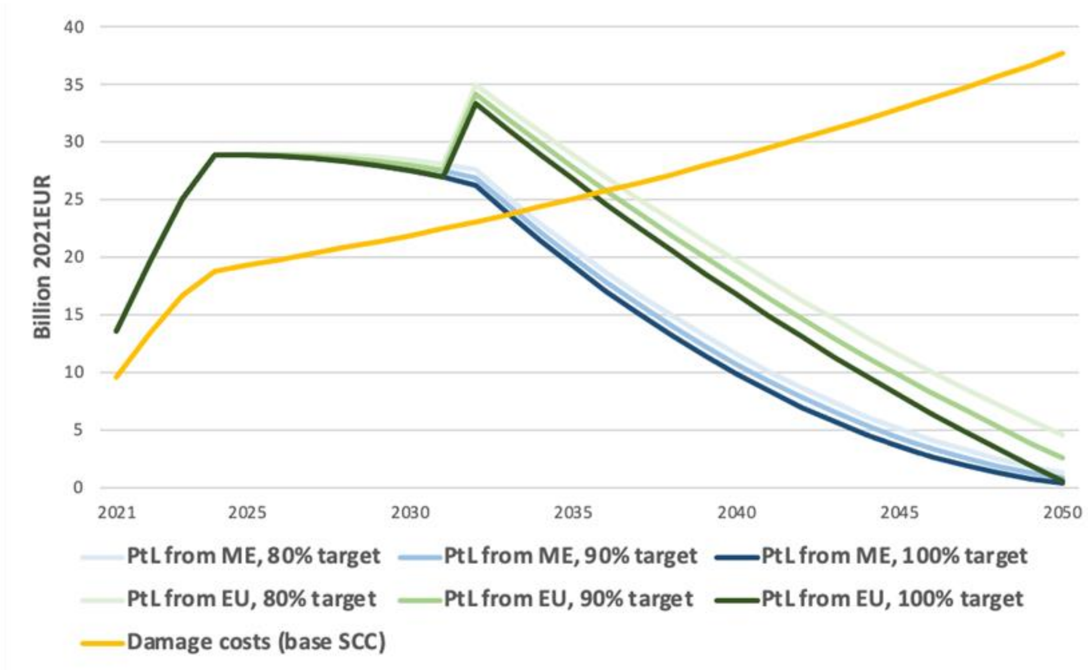
Figure 17 – The base value SCC from the damage cost approach and MACCs from the prevention cost approach



To assess the cost-efficiency of the internalisation of both cost approaches, however, the total costs should be considered. For the damage costs, this is simply the costs that have to be paid for all expected emissions, times the SCC (as the marginal costs are equal to the average costs, in this case). On the other hand, the total prevention costs are calculated by multiplying the weighted average abatement costs of the fuel mix in each year, with the emissions that need to be abated to achieve an emission reduction target. In addition, for an effective comparison, the MAC times the remaining emissions should be added (as the transition to SAFs will most likely only take place if the most expensive necessary abatement measure is competitive with fossil fuels, which is the case if the marginal abatement costs are internalised in the carbon price).

This results in yearly total prevention costs of 14 billion EUR for all scenarios in 2021, with the base value for the SCC resulting in yearly total damage costs of 10 billion EUR in 2021. From this year, the yearly prevention costs increase to 29 billion EUR for all scenarios in 2024, after which the costs stabilise. In the case of PtL imports from the Middle East, the costs increase again in 2032. From then onwards, for all PtL scenarios, the costs sharply decrease until 2050. The SCC only increases from 2021 until 2050, which is inherent to the damage cost approach. The implication is that the total yearly prevention costs become lower than the yearly damage costs in 2034 for PtL from the Middle East, and in 2036 or 2037 (depending on the reduction target) for PtL from the EU. These developments can be observed in Figure 18.

Figure 18 – Different estimations of the yearly total prevention costs, together with the baseline of the total damage costs

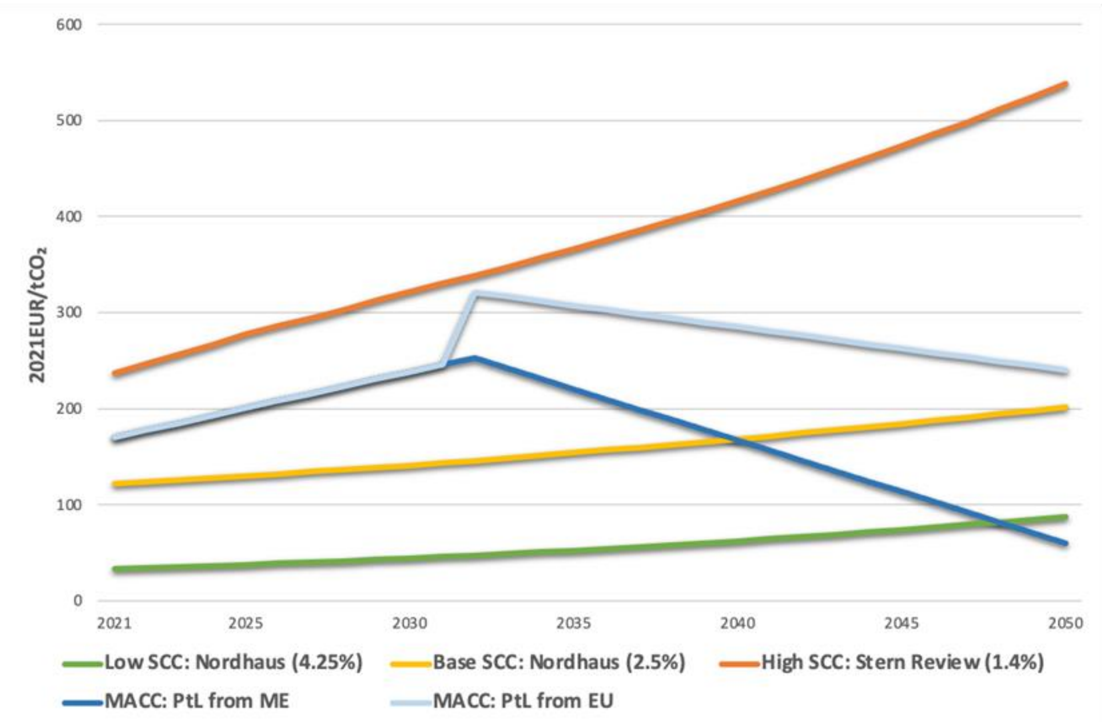


The total prevention costs over the entire thirty years assessed, from 2021 until 2050, are 477 to 509 billion EUR if PtL is imported from the Middle East, and 581 to 641 billion EUR if PtL is produced in the EU. In all cases, this is lower than the total damage costs of 770 billion EUR. **This indicates that if the total costs in the entire period are considered, it would be more cost-efficient to internalise the costs of CO_2 emissions from EEA aviation**

using the prevention cost approach, instead of using the damage cost approach. Although this finding can be explained intuitively (because the total abatement costs of SAFs are only a fraction of the CO_2 costs of the remaining emissions, and emissions are not reduced in the damage cost approach whereas these costs are approaching zero in the prevention cost approach), it is quite surprising from an economic theory point of view; the argument of cost-efficiency is not often brought up when advocating for a rapid transition to a more sustainable economy, because this involves such high investment costs.

An important sensitivity analysis to make is whether the outcome of cost-efficiency still holds for other SCC values, departing from different discount rates. Concerning the marginal costs, the Stern Review SCC with a discount rate of 1.4 percent is higher in every year than the MAC for both scenarios — even in the 'expensive transition year' of 2032 for PtL production in the EU. On the other hand, the Nordhaus SCC with a discount rate of 4.25 percent is lower in every year than the MACC for both scenarios, except for the years 2048-2050; in this last phase of the SAF transition, the marginal prevention costs of PtL from the Middle East become lower than the original Nordhaus SCC. This comparison of all SCCs and MACCs is shown in Figure 19.[15]

Figure 19 - Different SCC values from the damage cost approach and MACCs from the prevention cost approach

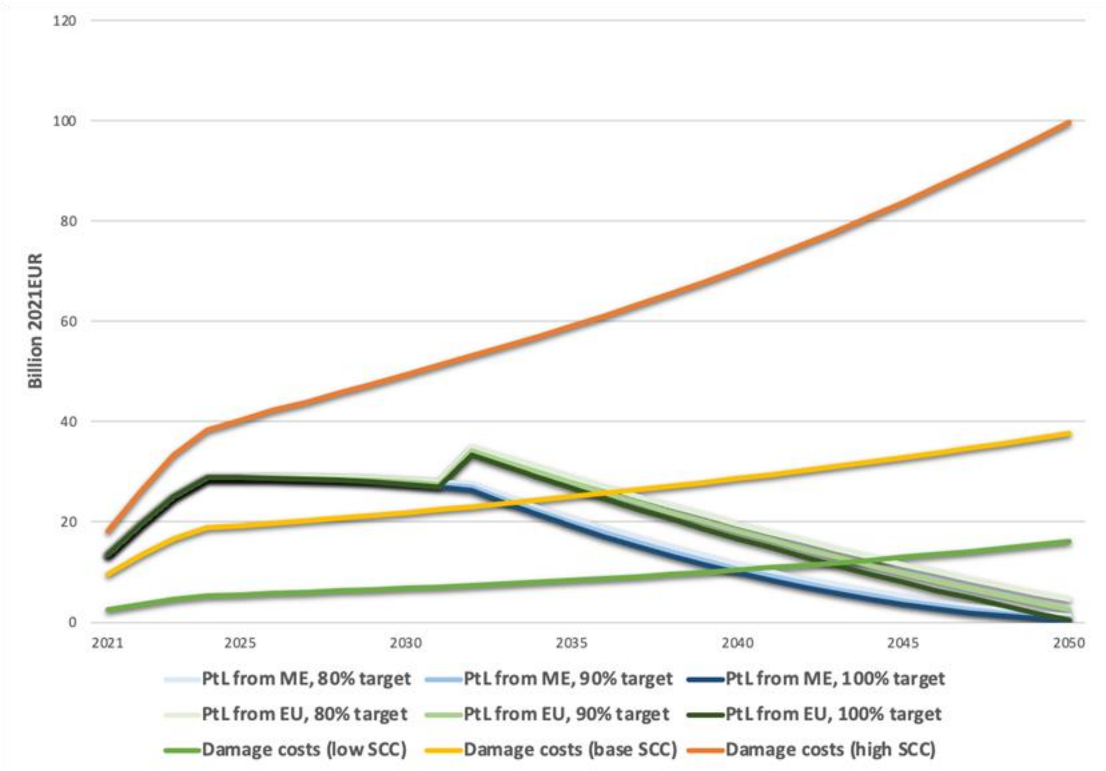


These alternative SCC values result in similar deviations in the total damage costs. Here too, internalisation of the higher SCC results in substantially higher yearly total costs than in both SAF scenarios. In the case of the lower Nordhaus SCC, the yearly total damage costs stay below the prevention costs of the SAF scenarios until 2040. From that year, the SAF scenarios one by one become more cost-efficient than the conventional scenario with internalisation for the damage costs. In 2045, the total yearly prevention costs of every SAF

[15] For all estimations of the marginal damage and prevention costs per year from 2021 to 2050, see Appendix P.

scenario are below the damage costs of this lowest SCC value. These developments are presented in Figure 20.

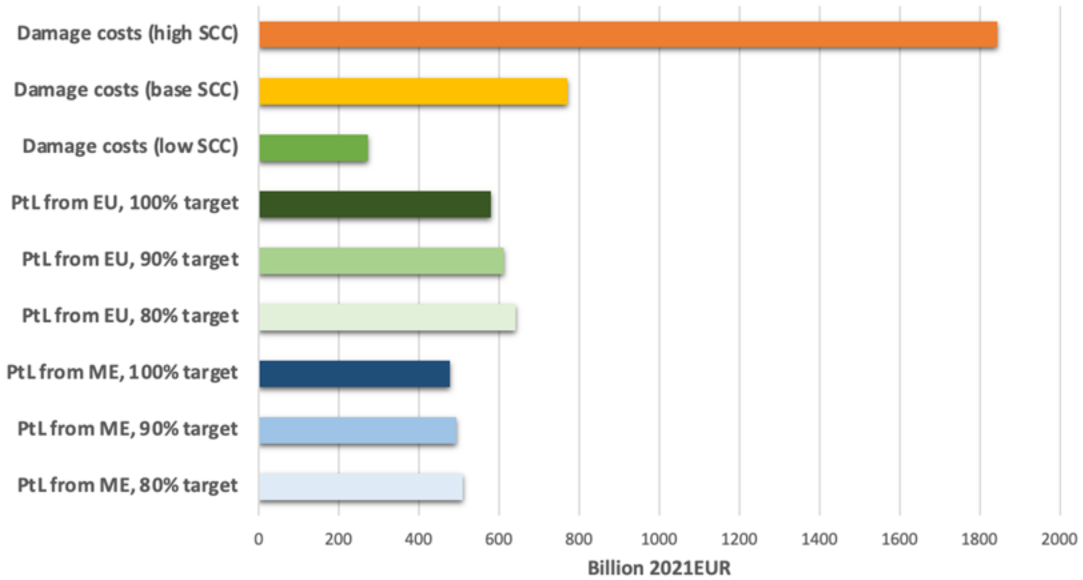
Figure 20 - Different estimations of the yearly total prevention costs and the yearly total damage costs



Lastly, the total costs over the entire thirty-year period highly deviate with other SCC values and their different discount rates as well. In the case of the higher SCC from the Stern Review, the result of higher cost-efficiency for internalisation of the prevention costs becomes even more significant: whereas that range is between 477 and 641 billion EUR, the total damage costs resulting from the higher SCC count up to 1844 billion EUR. On the other hand, if the lower SCC from Nordhaus is applied, it becomes more cost-efficient than applying the prevention costs of any of the SAF transition scenarios, with total damage costs at only 272 billion EUR. All of these total damage and prevention cost estimations are compared in Figure 21.[16]

[16] For the estimations of the damage and prevention costs per year and the calculations of the total, see Appendix Q.

Figure 21 - Different estimations of the total damage and prevention costs over the entire thirty-year period



All in all, even though internalisation of the base value for the SCC always results in higher total costs than if the MAC of the prevention costs would be internalised, this is not the case for the lower SCC. This is mainly due to the high sensitivity to the discount rate. The discount rate that determines the threshold from which internalisation of the MAC would be more cost-efficient over the entire thirty-year period is approximately 3 percent.[17] Apart from the relatively uncertain estimations of both the damage and prevention costs that are more illustrative than precisely accurate, the outcome of cost-efficiency for either of the approaches to internalise the external costs of CO_2 emissions from EEA aviation essentially comes down to the following question: is a discount rate of 3 percent higher or lower than what is considered to be right in climate policy for aviation? The chapter 'Damage cost approach' gives a preliminary answer to this question (no), however a more thorough analysis needs to be conducted to answer it definitively.

Still, even with the many assumptions and uncertainties inherent to this thesis, applying the prevention costs for the internalisation of CO_2 emissions from EEA aviation can be justified. First, one must realise that time does not stop beyond 2050. After that year, life on earth most probably continues and so does aviation and climate change. If the yearly cost estimations would be continued, the resulting costs from the different SAF transition scenarios would only further approach zero, whereas the damage costs would continue to increase. Eventually, assuming the same values after 2050 as in 2050 (which is a conservative assumption, with the constant growth of the damage costs and the constant decline of the prevention costs until that year) this means that from the year 2082, even internalisation of the lowest SCC would result in higher total costs than any of the SAF

[17] The total damage costs for the Nordhaus SCC of 3 percent from 2021 to 2050 count up to 498 billion EUR, which is more than the total prevention costs in the case of 90 or 100 percent emission reduction in 2050 and PtL imports from the Middle East, but less than the total prevention costs in all other SAF scenarios.

scenarios. [18] Second, although there is uncertainty and risk (due to high costs and low availability) in the implementation of SAFs, it is not as high as the risk and uncertainty of climate change. Thus, if a policymaker would be risk averse, precautionary measures such as climate mitigation would be preferred due to the uncertain nature and high stakes of the hazard.

Implications and impact

As explained in the chapter 'Policy Options', either the EU ETS or a fuel tax would be the best policy option by design to internalise the costs of CO_2 emissions from EEA aviation. With adoption of the prevention cost approach, this means that either the price of EUAs or the tax on fossil-fuelled kerosine needs to reflect the MACC. Additionally, the extra fuel costs due to the implementation of SAFs must be taken into account.

Considering the EU ETS, in addition to the policy changes that must be made regarding the international scope of the scheme (also including extra-EEA flights) and the reduction of permits that are given away for free, the price of EUAs would need to rapidly increase from its current level of more than 50 EUR to 200 EUR in 2025 (after which the price increases to a peak of 252 to 321 EUR in 2032). This is rather unlikely, as there does not seem to be enough political or societal support for such a raise and the economic effects could be devastating due to high increases in the costs for not only aviation, but all industries that are covered by the EU ETS.

A fuel tax with the same level per tCO_2 would also have an impact on aviation, but would exclude other industries. Furthermore, if the tax applies to all flights and carriers that depart from EEA airports, no airline would be harmed more by such a tax than the others. Nevertheless, with these increasingly high fuel and tax costs, it is questionable whether ticket prices would not significantly increase as well (and, subsequently, if aviation demand will drop).

To make an estimation of the effect of a fuel tax on aviation tickets and demand, we revert back to the contextual ticket price increases of four common flight routes from EEA airports in the chapter 'Prevention cost approach'. With these ticket price increases, it is hard to estimate the impact on aviation demand, as the price elasticity is only applicable to a percentage change in the price, not to an absolute value. The relative increase also cannot be estimated by taking the current and future average ticket prices on these specific routes into account, as these are not publicly available and highly volatile, depending on e.g. the season, operator, and seating class. For illustrative purposes, if the minimum ticket prices of these routes are assumed to be respectively 55 EUR, 51 EUR, 221 EUR, and 476 EUR[19], the average maximum price increase — the share of the extra cost would only become smaller if the ticket is more expensive — would be 22, 65, 27, and 16 percent in 2025. With these price increases, the demand on these routes would go down by 16, 48, 20, and 12 percent.

Important to note is that these are the costs for fossil-fuelled aircrafts, whereas according to the prevention cost model up to 100 percent of all flights in 2050 will be fuelled by SAFs.

[18] The difference in costs between the total damage costs with the low Nordhaus SCC (272 billion EUR) and the total prevention costs in the least optimal scenario of 80 percent emission reduction and PtL production in the EU (641 billion EUR) is 369 billion EUR. With yearly damage costs of 16.1 billion EUR and yearly prevention costs of 4.5 billion EUR in 2050 for these scenarios, the difference per year is 11.6 billion EUR. This means that after 32 years, the total damage costs become higher than the total prevention costs.

[19] These were the lowest available prices so far in 2021 on https://www.skyscanner.net as of 14 May, 2021.

This means that over time, not the level of the fuel tax will determine the increase in prices per flight, but the price increase of the SAFs with respect to fossil fuels.
For example, on a fully PtL-fuelled plane, the costs in 2050 would be 35 to 140 percent higher than the expected fossil fuel price (depending on the production location). This would mean that in 2050, ceteris paribus, ticket prices would be 8.4 to 33.6 percent higher, and aviation demand is then expected to be 6.2 to 24.9 percent lower. Assuming that the 48 percent demand decrease in 2025 is an outlier, the demand decreases in the short term are within this range for 2050.

Although it is highly uncertain how large the price increase in all different types of tickets will be, as well as its impact on the demand for aviation on all different routes, it is clear that full internalisation of the carbon price using the prevention cost approach results in high price increases and possibly heavy shocks to aviation demand. This means that the prevention costs might be an overestimation, because it does not take into account further emission reductions due to demand shocks. Still, an important takeaway from this thesis is that if the EU is serious about meeting its climate targets, it might be hard to achieve the forecasted growth of aviation in terms of flights and passengers simultaneously.

Limitations

This thesis holds some important limitations, which will be highlighted in this section.
First, there are more external costs, and possibly also benefits, that are not internalised in aviation. Some of them have already been mentioned in the introduction of this thesis, such as noise and air pollution. Also regarding the climate costs, even though CO_2 is the major individual contributor from aviation to global warming with relatively high scientific certainty, other emissions such as NO_x and water contrails could potentially have an impact at least as high. These are not accounted for in this study (because of the lack of scientific certainty), hence the total external costs could be even higher.

Second, the emission projections for the EEA are quite uncertain, especially due to the Covid-19 pandemic and the insecurity of further technological improvements in the future. It is likely that in one or two years, hopefully in the aftermath of the pandemic, a much better estimation of the developments of flights, passengers, and emissions can be made. For example, it is currently unknown to what extent business travel will go back to its previous level, and how fast other aviation demand will restore to pre-Covid levels.

Third, regarding the damage costs, the lack of consensus among environmental economists and climate policy makers about the correct discount rate is perhaps the most important limitation of this thesis, as the conclusion of this thesis depends on the different values of the SCC and their corresponding discount rates.

Fourth, concerning the prevention costs, the full potential approach and not the achievable-potential approach was applied; every SAF was used to its full potential and possible slow-diffusion processes have not been taken into account. It is questionable whether all available UCO and forestry residues in the EU can be 'reserved' by aviation only, and it is uncertain whether these inputs can be supplied to the extent this thesis suggests. Furthermore, it is uncertain whether PtL will be up-to-scale by 2032, either in the EU or the Middle East, and if the even greater amounts necessary in 2050 will be available by then. Additionally, the total prevention costs might be an overestimation because it is unlikely that the share of biofuels will remain the same until 2050, when e-fuels will be a more cost-efficient abatement measure. If and when biofuels will be phased out again, is beyond the scope of this thesis.

Fifth, for the policy analysis, more transparency and clarity about the carbon offset projects in CORSIA would enable better conclusions about the effectiveness of this scheme. Especially the question of additionality persists due to the lack of information, making it a doubtful system to mitigate emissions in aviation. In addition, there are more possible policy options that could help mitigate emissions in aviation or internalise the costs of CO_2, such as an emission cap on EEA airports. These options have not been assessed in this study.

Sixth, concerning the price elasticity of flight tickets, the cross-price elasticity has been mentioned but not widely assessed. If short-distance alternatives for aviation, such as road and rail transport, become more attractive (because of comfort, time or cost benefits), this could result in significant demand shifts within the transport sector. Furthermore, these alternatives are mostly less carbon-intensive, making such a substantial shift in transport modes another (cost-efficient) abatement measure for aviation that has not been taken into account in this thesis.

Seventh and last, one aspect that has been left out is the distribution of costs. It might be considered undesirable if the internalisation of CO_2 costs results in more inequality, because some people in society could not afford flight tickets anymore as a result of the cost increase. Possible solutions would be to have a lower price for someone’s first flight of the year, with an increasing price for every extra flight in that same year. However, this equity element is beyond the scope of this thesis.

7 Conclusions

Considering the significant impact of aviation on global warming, the ambitious climate targets set by the EU, and the potential of an internalised carbon price as a catalyst for SAFs in making the aviation sector more sustainable, this thesis examined whether the damage cost approach or the prevention cost approach would be more cost-efficient to internalise the climate costs of CO_2 emissions from European aviation. It quantified the CO_2 costs of European aviation, analysed the policy options to internalise these costs, and discussed the effects of these policies on ticket prices and demand.

The findings are built upon a projection of the future CO_2 emissions from EEA aviation. Three scenarios are considered. For the baseline, the 'Advanced Tech' scenario with 0.93 percent annual growth results in 158 Mt CO_2 per year in 2030 and 190 Mt CO_2 in 2050. The 'Frozen Tech' scenario is the high projection, with 1.63 percent growth resulting in 165 Mt CO_2 in 2030 and 228 Mt CO_2 in 2050. The low projection, based on a more optimistic expectation of 0.48 percent growth per year, results in 154 Mt CO_2 in 2030 and 169 Mt CO_2 in 2050.

The damage cost approach was considered first to put a value on the external costs of these emissions, as it is the most preferred methodology in economics and it is often used to determine the level of a Pigouvian tax on emissions. It is derived from the SCC, calculated as the NPV of the future change in economic welfare, resulting from an additional unit of CO_2 emitted to the atmosphere now.

Three estimates of the damage costs are taken into account. Departing from the DICE model by Nordhaus with a discount rate of 2.5 percent, the SCC base value is set at 120 EUR/tCO_2 2020, increasing to 141 EUR in 2030, and 202 EUR in 2050. As a lower value, the same model is applied with a discount rate of 4.25 percent, resulting in a SCC of 32 EUR in 2020, 44 EUR in 2030, and 88 EUR in 2050. For the higher value, The Stern Review with a discount rate of 1.4 percent is considered. The corresponding SCC is 228 EUR in 2020, 322 EUR in 2030, and 538 EUR in 2050.

The total damage costs can be calculated by multiplying the projection of CO_2 emissions with the SCC. Assuming the base value for the SCC and the baseline emission projection, this results in total damage costs of 770 billion EUR from 2021 to 2050. With different future emission projections, the range of these costs is 725 to 849 billion EUR. With different SCC estimates, this range becomes 272 to 1844 billion EUR. This wide range is especially due to a high sensitivity of the SCC to the applied discount rate.

As an alternative approach, the abatement-cost method is applied to calculate the prevention costs, or the costs of preventing the negative externality from happening in the first place. The MACC is used to rank mitigation measures from least to most expensive. In the case of CO_2 emissions from EEA aviation, these measures are using different types of SAFs, as this is the only way to effectively meet a policy target of 80 to 100 percent emission reduction. This projected future mix is estimated by computing the MACC of SAFs over time until 2050.

The future projection of SAFs contains a mix of HEFA with UCO, HTL with forestry residues, and PtL with DAC. This results in marginal prevention costs of 200 to 246 EUR per tCO_2 from 2025 until 2031. After this, the costs either decrease from 252 EUR in 2032 to 60 EUR in 2050 for PtL imports from the Middle East, or decrease from 321 EUR in 2032 to 240 EUR in 2050 for PtL production in the EU. All of these costs together constitute the MACC, showing the carbon price in each year if the prevention costs would be internalised.

For the total prevention costs, the abatement costs of every fuel type are multiplied with the amount of CO_2 abated by these fuels. This results in 4.8 to 5.2 billion EUR in the case of PtL imports from the Middle East, and 6.6 to 7.2 billion EUR if PtL is produced in the EU. However, a more realistic estimation would be to also include the MAC in the price of CO_2 emissions for each year, as this would enable the SAFs to become competitive. This results in costs of 432 to 478 billion EUR for PtL from the Middle East and 483 to 547 billion EUR for PtL from the EU.

The comparative analysis concludes that whereas the marginal prevention costs are higher in most scenarios and for most years until 2050 than the marginal damage costs, the total prevention costs are substantially lower over the entire thirty-year period than the total damage costs. Hence, as an answer to the main research question, internalisation of the prevention cost approach is more cost-efficient for the CO_2 emissions from EEA aviation than internalisation of the damage cost approach.

This outcome becomes even more apparent when applying a higher SCC with a lower discount rate, but the conclusion changes for a lower SCC with a higher discount rate. The discount rate that determines the threshold from which internalisation of the SCC is more cost-efficient over the entire thirty-year period is approximately 3 percent; for a discount rate below this, internalisation of the MAC becomes more cost-efficient. However, when extending the period beyond 2050, even internalisation of the lower SCC in this study eventually becomes more expensive than internalisation of the MAC, justifying application of the prevention cost approach.

The EU ETS or a fuel tax would be the best policy instrument to internalise these costs. To achieve full effectiveness, the EU ETS would have to be expanded to international aviation on extra-EEA flights, and the price of EUAs would need to reflect the SCC or MAC in each year. In the case of a fuel tax, the same price should apply per tCO_2. Here too, exemptions of foreign carriers and extra-EEA flights would need to be lifted for full effectiveness. Any combination of these instruments that collectively represents the necessary carbon price could also be effective.

If the prevention costs would be internalised, this would have an effect on the ticket prices and demand for aviation. Assuming full cost pass-through, the pass-through elasticity for fuel price increases in EEA aviation is 0.24. This means that for every 10 percent increase in the costs for airline operators, the price of a flight ticket (and the cost for passengers) increases by 2.4 percent on average. The average price elasticity is estimated at -0.74. With a ticket price increase of 2.4 percent, this would result in a reduction of EEA aviation demand by 1.8 percent.

To conclude, with internalisation of the MAC in the carbon price and fuel price increases from SAFs, this means that ticket prices would increase with 8 to 34 percent. The impact on the demand for aviation would be major, with a drop of at least 6 to at most 25 percent. In other words, if the EU is serious about meeting its climate targets, it might be hard to achieve the forecasted growth of aviation at the same time.

Future research needs

At last, there are some suggestions for future research. First, a cost-benefit analysis of all external costs and benefits is needed to quantify the full 'true price' of aviation. For the full climate costs, more research is wanted to assess the ERF of non-CO_2 emissions, and their climate cost internalisation through specific policies. Furthermore, a thorough analysis about the appropriate discount rate for climate policies in aviation is recommended, as it could confirm the outcome of this thesis (or debunk it, if a very high discount rate would be deemed as more appropriate). Last, more research is needed on the availability of SAFs, especially on the capacity of UCO and forestry residues for biofuels on the short term and the possibilities of producing e-fuels in the EU and importing them from the Middle East in the longer term.

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A Emissions from departing flights per state, in tCO_2

Country in the EEA	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Increase	Avg/year
Austria	2227097	2312257	2241121	2182547	2316484	2397755	2451897	2476656	2742048	3114975	40%	3,80%
Belgium	4060758	4213767	3876110	3650648	3858341	4087530	3954394	4373101	4750848	4879819	20%	2,06%
Bulgaria	590879	584931	547437	546779	587079	600603	729206	798016	843301	799939	35%	3,42%
Croatia	359275	355440	361892	385549	399298	421299	478475	578254	672881	709589	98%	7,86%
Cyprus	937877	975861	911257	851011	848209	814353	933992	1051858	1073508	1051499	12%	1,28%
Czech Republic	1033785	1089333	994602	942697	953973	967116	1078215	1236660	1381672	1439472	39%	3,75%
Denmark (incl. Faroe Islands, excl. Greenland)*	2456461	2517302	2524376	2583795	2702518	2736850	2950054	2914992	3064795	3100761	26%	2,62%
Estonia	100475	143965	155812	128704	142801	154000	155749	190499	213065	210027	109%	8,54%
Finland	1925566	2260888	2094725	2095731	2121358	2093594	2176119	2269421	2510109	2675337	39%	3,72%
France (excl. overseas departments)*	19226365	20144641	19686739	19858180	20105056	20414022	20482394	21087812	21763129	22402612	17%	1,71%
Germany	27910475	29093267	28252770	27464774	28011561	28443621	29342428	29937163	30678150	31089434	11%	1,21%
Greece	3158161	3188671	2800072	2847160	3235886	3328576	3571062	3941553	4388457	4430025	40%	3,83%
Hungary	698950	718074	586951	581691	621494	687044	764073	839096	1008884	1102382	58%	5,19%
Iceland	400036	451503	484289	531692	613568	735526	998174	1258669	1386402	1054925	164%	11,38%
Ireland	1971479	1977296	1882160	1966354	2122124	2387507	2641198	2959928	3231985	3304911	68%	5,91%
Italy	12364210	12445507	11950239	11624536	12104894	12323740	12965738	13502038	14339896	15106924	22%	2,25%
Latvia	321777	362196	366690	391685	361508	357593	359826	399703	459733	494258	54%	4,88%
Liechtenstein	2		1	1		1	1		1	2	2%	0,17%
Lithuania	186695	198307	220382	237821	265987	282016	301680	328558	388557	393580	111%	8,64%
Luxembourg	1193563	1165545	1086204	1075264	1156394	1280871	1417344	1608782	1738840	1772959	49%	4,49%
Malta	302650	313606	306612	331052	347474	361972	395418	439024	483139	518276	71%	6,16%
The Netherlands (excl. overseas departments)	9403220	9844981	9690434	9862523	10191528	10420367	10756127	11123852	11305354	11144285	19%	1,91%
Norway	2593899	2674237	2796392	3038582	3129776	2972054	2966216	3020391	3129712	3113182	20%	2,05%
Poland	1653874	1657599	1725895	1798962	1942728	2032595	2308434	2629156	3072056	3266975	98%	7,86%
Portugal (incl. overseas departments)	3199085	3223013	3231196	3318767	3517527	3663916	4017499	4522995	4907164	5256609	64%	5,67%
Romania	907167	870.851,01	833548	820893	959316	976648	1144697	1324763	1412622	1474542	63%	5,55%
Slovakia	140984	139747	122197	115144	122978	147300	156179	169507	188553	190339	35%	3,39%
Slovenia	119597	116585	114949	121836	108637	111230	101087	114443	125559	116614	-2%	-0,28%
Spain (incl. Canary Islands, excl. Balearic Islands)***	16873651	18001418	16501496	16145539	16756801	17172874	19082930	20363837	21313558	22036525	31%	3,01%
Sweden	2712323	2930220	2760839	2860618	2977915	2994861	3169467	3361090	3347011	3234226	19%	1,97%
Total CO2 emissions from departing flights in the EEA	119030335	123971010	119107384	118360538	122583213	125367435	131850073	138821817	145920989	149485002	26%	2,56%
Mton CO2 from departing flights in the EEA	119	124	119	118	123	125	132	139	146	149		

B Emissions of EEA aviation, in Mt CO_2

Different emission growth scenarios	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019		
Baseline scenario: 0.93% growth	119	124	119	118	123	125	132	139	146	149		
High estimate: 1.63% growth	119	124	119	118	123	125	132	139	146	149		
Low estimate: 0.48% growth	119	124	119	118	123	125	132	139	146	149		
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029		
Baseline scenario: 0.93% growth	65	80	110	135	149	151	152	154	155	157		
High estimate: 1.63% growth	65	80	110	135	149	152	154	157	159	162		
Low estimate: 0.48% growth	65	80	110	135	149	150	151	152	152	153		
	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039		
Baseline scenario: 0.93% growth	158	159	161	162	164	166	167	169	170	172		
High estimate: 1.63% growth	165	167	170	173	176	179	181	184	187	191		
Low estimate: 0.48% growth	154	154	155	156	157	157	158	159	159	160		
	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	Total 2021-2050
Baseline scenario: 0.93% growth	173	175	177	178	180	182	183	185	187	188	190	4889
High estimate: 1.63% growth	194	197	200	203	207	210	213	217	220	224	228	5345
Low estimate: 0.48% growth	161	162	162	163	164	165	165	166	167	168	169	4678

C Social Cost of Carbon, in 2021EUR/tCO_2

Different SCC estimates	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low: Nordhaus (4.25% DR)	33	34	35	36	38	39	40	41	43	44
Baseline: Nordhaus (2.5% DR)	122	124	126	128	130	132	134	136	139	141
High: *The Stern Review* (1.4% DR)	237	247	256	267	278	286	294	303	312	322
	2031	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Low: Nordhaus (4.25% DR)	46	47	49	51	52	54	56	58	60	62
Baseline: Nordhaus (2.5% DR)	143	146	149	151	154	157	160	162	165	168
High: *The Stern Review* (1.4% DR)	330	339	347	356	366	375	385	395	405	416
	2041	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
Low: Nordhaus (4.25% DR)	64	67	69	71	74	76	79	82	85	88
Baseline: Nordhaus (2.5% DR)	171	175	178	181	184	188	191	194	198	202
High: *The Stern Review* (1.4% DR)	427	438	449	461	473	485	498	511	524	538

D Total damage costs, in billion 2021EUR

Yearly Total Damage Costs	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low SCC, base projection	2,6	3,6	4,6	5,3	5,5	5,7	6,0	6,2	6,5	6,8
Base SCC, base projection	9,6	13,4	16,7	18,8	19,3	19,8	20,3	20,8	21,3	21,9
High SCC, base projection	18,2	26,1	33,3	38,3	40,3	42,3	43,9	45,7	47,5	49,4
Low SCC, low projection	2,6	3,6	4,6	5,3	5,5	5,7	5,9	6,1	6,3	6,6
Base SCC, low projection	9,6	13,4	16,7	18,8	19,2	19,6	20,0	20,4	20,9	21,3
High SCC, low projection	18,2	26,1	33,3	38,3	40,1	41,9	43,3	44,9	46,4	48,0
Low SCC, high projection	2,6	3,6	4,6	5,3	5,5	5,8	6,1	6,4	6,7	7,0
Base SCC, high projection	9,6	13,4	16,7	18,8	19,4	20,1	20,7	21,4	22,1	22,8
High SCC, high projection	18,2	26,1	33,3	38,3	40,5	42,9	44,9	46,9	49,1	51,4

	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Low SCC, base projection	7,0	7,3	7,7	8,0	8,4	8,7	9,1	9,5	10,0	10,4
Base SCC, base projection	22,4	23,1	23,7	24,4	25,0	25,7	26,4	27,2	27,9	28,7
High SCC, base projection	51,3	53,1	55,0	57,0	59,0	61,1	63,3	65,5	67,9	70,3
Low SCC, low projection	6,8	7,1	7,4	7,7	8,0	8,3	8,6	9,0	9,3	9,7
Base SCC, low projection	21,8	22,3	22,8	23,3	23,8	24,4	24,9	25,5	26,1	26,7
High SCC, low projection	49,7	51,3	52,8	54,5	56,2	57,9	59,7	61,6	63,5	65,4
Low SCC, high projection	7,4	7,8	8,2	8,6	9,0	9,5	10,0	10,5	11,1	11,6
Base SCC, high projection	23,6	24,4	25,2	26,1	27,0	27,9	28,9	29,9	31,0	32,0
High SCC, high projection	53,8	56,1	58,5	61,1	63,7	66,4	69,2	72,2	75,3	78,5

	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	Total 2021-2050
Low SCC, base projection	10,9	11,4	11,9	12,4	13,0	13,5	14,1	14,8	15,4	16,1	272
Base SCC, base projection	29,5	30,3	31,1	32,0	32,9	33,8	34,7	35,6	36,6	37,6	770
High SCC, base projection	72,8	75,4	78,1	80,8	83,7	86,7	89,8	93,0	96,3	99,7	1844
Low SCC, low projection	10,1	10,5	10,9	11,3	11,8	12,3	12,7	13,3	13,8	14,3	255
Base SCC, low projection	27,3	27,9	28,6	29,2	29,9	30,6	31,3	32,0	32,8	33,5	725
High SCC, low projection	67,5	69,5	71,7	73,9	76,2	78,6	81,0	83,5	86,1	88,8	1730
Low SCC, high projection	12,2	12,9	13,5	14,2	15,0	15,7	16,6	17,4	18,3	19,3	302
Base SCC, high projection	33,1	34,3	35,5	36,7	38,0	39,3	40,7	42,1	43,5	45,1	849
High SCC, high projection	81,9	85,4	89,0	92,8	96,8	100,9	105,2	109,7	114,4	119,3	2042

E Climate and damage costs of common flight routes, in 2021EUR

Route	Distance	Type flight	Fuel burn	kg CO2/p	Aviation Economics	CE Delft low	CE Delft high	Low SCC	Base SCC	High SCC	Base SCC (2050)
AMS-CDG	398 km	Short-haul	2,750 kg	61	€13,37	€11,42	€13,83	€2,01	€7,42	€14,46	€12,29
AMS-LIS	1,844 km	Medium-haul	7,929 kg	165	€17,68	€28,50	€40,60	€5,44	€20,08	€39,11	€33,25
FRA-DXB	4,839 km	Medium/long	59,382 kg	299	€72,72	€57,18	€64,51	€9,86	€36,38	€70,87	€60,26
CDG-ATL	7,051 km	Long-haul	65,669 kg	389	€105,96	€83,32	€94,00	€12,82	€47,34	€92,20	€78,39

F Abatement costs (borders around SAF mix), in 2021EUR cents/kg CO_2

Pathway	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
HEFA UCO	17,0	17,6	18,1	18,7	19,2	19,8	20,3	20,9	21,4	22,0	22,5	23,1	23,6	24,2	24,7	25,3	25,8	26,4	26,9	27,5	28,0	28,6	29,1	29,7	30,2	30,8	31,3	31,9	32,5	33,0
HEFA Jatropha	26,0	27,2	28,3	29,5	30,7	31,9	33,0	34,2	35,4	36,6	37,7	38,9	40,1	41,2	42,4	43,6	44,8	45,9	47,1	48,3	49,4	50,6	51,8	53,0	54,1	55,3	56,5	57,7	58,8	60,0
HEFA Palm Fat	27,0	27,4	27,8	28,2	28,7	29,1	29,5	29,9	30,3	30,7	31,1	31,6	32,0	32,4	32,8	33,2	33,6	34,0	34,4	34,9	35,3	35,7	36,1	36,5	36,9	37,3	37,8	38,2	38,6	39,0
HTL Forest Res	17,0	17,8	18,5	19,3	20,0	20,8	21,6	22,3	23,1	23,8	24,6	25,3	26,1	26,9	27,6	28,4	29,1	29,9	30,7	31,4	32,2	32,9	33,7	34,4	35,2	36,0	36,7	37,5	38,2	39,0
FT Corn Stover	31,0	31,1	31,2	31,3	31,4	31,5	31,6	31,7	31,8	31,9	32,0	32,1	32,2	32,3	32,4	32,6	32,7	32,8	32,9	33,0	33,1	33,2	33,3	33,4	33,5	33,6	33,7	33,8	33,9	34,0
FT Forest Res	30,0	30,1	30,1	30,2	30,3	30,3	30,4	30,5	30,6	30,6	30,7	30,8	30,8	30,9	31,0	31,0	31,1	31,2	31,2	31,3	31,4	31,4	31,5	31,6	31,7	31,7	31,8	31,9	31,9	32,0
PtL DAC	37,0	36,6	36,1	35,7	35,2	34,8	34,3	33,9	33,4	33,0	32,5	32,1	31,6	31,2	30,7	30,3	29,8	29,4	28,9	28,5	28,0	27,6	27,1	26,7	26,2	25,8	25,3	24,9	24,4	24,0
PtL DAC import	37,0	35,9	34,9	33,8	32,7	31,7	30,6	29,5	28,4	27,4	26,3	25,2	24,2	23,1	22,0	21,0	19,9	18,8	17,8	16,7	15,6	14,6	13,5	12,4	11,3	10,3	9,2	8,1	7,1	6,0

G Production costs (borders around SAF mix), in 2021EUR/GJ

Pathway	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
HEFA UCO	22,9	23,6	24,3	25,0	25,7	26,4	27,1	27,8	28,5	29,2	29,9	30,6	31,2	31,9	32,6
HEFA Jatropha	28,0	28,5	29,0	29,5	30,1	30,6	31,1	31,6	32,1	32,6	33,2	33,7	34,2	34,7	35,2
HEFA Palm Fat	28,7	29,2	29,7	30,2	30,7	31,2	31,7	32,2	32,7	33,2	33,7	34,2	34,7	35,1	35,6
HTL Forest Res	22,3	23,1	23,8	24,5	25,2	25,9	26,6	27,3	28,0	28,8	29,5	30,2	30,9	31,6	32,3
FT Corn Stover	39,0	39,1	39,3	39,4	39,5	39,7	39,8	40,0	40,1	40,2	40,4	40,5	40,6	40,8	40,9
FT Forest Res	40,1	40,2	40,3	40,4	40,5	40,6	40,7	40,8	40,9	41,0	41,1	41,2	41,3	41,4	41,5
PtL DAC	43,0	42,8	42,7	42,5	42,3	42,2	42,0	41,8	41,7	41,5	41,3	41,2	41,0	40,8	40,7
PtL DAC import	43,0	42,3	41,5	40,8	40,0	39,3	38,6	37,8	37,1	36,3	35,6	34,8	34,1	33,4	32,6
Fossil kerosine	10,4	10,6	10,8	11,0	11,2	11,3	11,5	11,7	11,9	12,1	12,3	12,5	12,7	12,9	13,0

Pathway	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
HEFA UCO	33,3	34,0	34,7	35,4	36,1	36,8	37,5	38,2	38,9	39,6	40,3	40,9	41,6	42,3	43,0
HEFA Jatropha	35,7	36,3	36,8	37,3	37,8	38,3	38,9	39,4	39,9	40,4	40,9	41,4	42,0	42,5	43,0
HEFA Palm Fat	36,1	36,6	37,1	37,6	38,1	38,6	39,1	39,6	40,1	40,6	41,1	41,6	42,1	42,5	43,0
HTL Forest Res	33,0	33,8	34,5	35,2	35,9	36,6	37,3	38,0	38,8	39,5	40,2	40,9	41,6	42,3	43,0
FT Corn Stover	41,1	41,2	41,3	41,5	41,6	41,7	41,9	42,0	42,2	42,3	42,4	42,6	42,7	42,9	43,0
FT Forest Res	41,6	41,7	41,8	41,9	42,0	42,1	42,2	42,3	42,4	42,5	42,6	42,7	42,8	42,9	43,0
PtL DAC	40,5	40,4	40,2	40,0	39,9	39,7	39,5	39,4	39,2	39,0	38,9	38,7	38,5	38,4	38,2
PtL DAC import	31,9	31,1	30,4	29,7	28,9	28,2	27,4	26,7	25,9	25,2	24,5	23,7	23,0	22,2	21,5
Fossil kerosine	13,2	13,4	13,6	13,8	14,0	14,2	14,4	14,6	14,8	14,9	15,1	15,3	15,5	15,7	15,9

H Emission reduction, in percentages compared to 1990-levels

Target based on	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
NLR & SEO	5%	-31%	-61%	-78%	-72%	-66%	-60%	-54%	-48%	-41%	-35%	-29%	-23%	-17%	-11%	-5%	1%	7%	13%	19%	25%	31%	38%	44%	50%	56%	62%	68%	74%	80%
EU Green Deal	5%	-31%	-61%	-78%	-71%	-65%	-59%	-52%	-46%	-39%	-33%	-26%	-20%	-13%	-7%	0%	6%	13%	19%	25%	32%	38%	45%	51%	58%	64%	71%	77%	84%	90%
Carbon neutral	5%	-31%	-61%	-78%	-71%	-64%	-57%	-51%	-44%	-37%	-30%	-23%	-16%	-9%	-3%	4%	11%	18%	25%	32%	38%	45%	52%	59%	66%	73%	80%	86%	93%	100%

I Allowed emissions, in Mt CO_2

Target in 2050	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
80% target	80	110	135	149	144	139	134	129	124	119	114	109	104	98	93	88	83	78	73	68	63	58	52	47	42	37	32	27	22	17
90% target	80	110	135	149	144	139	133	128	122	117	111	106	101	95	90	84	79	73	68	63	57	52	46	41	36	30	25	19	14	8
100% target	80	110	135	149	144	138	132	126	121	115	109	103	98	92	86	80	75	69	63	57	52	46	40	34	29	23	17	11	6	0

J Emissions (for fossil kerosene) or abatement (for SAFs), in Mt CO_2

Fuel type	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Fossil-fuelled Kerosene	80	110	135	149	144	139	133	128	122	117	111	106	101	95	90
HEFA with UCO	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3
HEFA with Forest Res	0	0	0	0	4	11	18	24	31	38	45	45	45	45	45
Power-to-Liquid	0	0	0	0	0	0	0	0	0	0	0	7	14	21	28

Fuel type	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Fossil-fuelled Kerosene	84	79	73	68	63	57	52	46	41	36	30	25	19	14	8
HEFA with UCO	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
HEFA with Forest Res	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Power-to-Liquid	35	42	49	56	63	70	77	84	91	98	105	112	119	127	134

K Average abatement costs, in 2021EUR/tCO_2

Average abatement costs	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
PtL import from Middle East	197	206	214	222	229	237	245	252	256	256	255	252	247	242	236	230	223	215	207	199	191	182	173	165	155	146
PtL production in EU	197	206	214	222	229	237	245	261	272	281	286	291	294	295	296	297	296	295	294	293	291	289	287	284	281	279

L Marginal abatement costs, in 2021EUR/CO_2

Marginal abatement costs	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
PtL import from Middle East	200	208	216	223	231	238	246	252	242	231	220	210	199	188	178	167	156	146	135	124	113	103	92	81	71	60
PtL production in EU	200	208	216	223	231	238	246	321	316	312	307	303	298	294	289	285	280	276	271	267	262	258	253	249	244	240

M Total abatement costs, in million 2021EUR

Total abatement costs	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	TOTAL
PtL from ME, 80% target	12,8	26,7	41,7	57,7	74,7	92,8	112	132	151	168	184	198	211	223	233	242	250	256	261	264	266	266	265	263	259	253	**4762**
PtL from ME, 90% target	13,4	28,1	43,8	60,6	78,5	97,4	117	138	158	176	193	208	222	234	245	254	262	269	273	277	279	279	278	276	271	266	**4998**
PtL from ME, 100% target	14	29,4	45,9	63,5	82,2	102	123	145	165	184	202	218	232	245	256	266	275	281	286	290	292	292	291	288	284	278	**5233**
PtL from EU, 80% target	12,8	26,7	41,7	57,7	74,7	92,8	112	136	160	184	207	229	251	272	293	313	332	351	370	388	405	422	438	454	469	483	**6575**
PtL from EU, 90% target	13,4	28,1	43,8	60,6	78,5	97,4	117	143	168	193	217	240	263	285	307	328	349	369	388	407	425	442	459	476	491	506	**6897**
PtL from EU, 100% target	14	29,4	45,9	63,5	82,2	102	123	150	176	202	227	252	276	299	322	344	365	386	406	426	445	463	481	498	514	530	**7220**

N Total prevention costs with MACC internalisation, in billion 2021EUR

Total CO2+abatement costs	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	TOTAL
PtL from ME, 80% target	28,4	28,7	28,7	28,7	28,5	28,3	27,9	27,5	26,6	25,4	23,9	22,4	20,8	19,1	17,4	15,8	14,2	12,6	11,1	9,7	8,3	7,1	5,9	4,7	3,7	2,8	478
PtL from ME, 90% target	28,4	28,5	28,5	28,4	28,1	27,8	27,4	26,9	25,9	24,5	23,0	21,4	19,7	18,0	16,3	14,6	13,0	11,4	9,9	8,4	7,1	5,8	4,6	3,5	2,5	1,5	455
PtL from ME, 100% target	28,3	28,4	28,3	28,1	27,8	27,3	26,8	26,2	25,1	23,7	22,1	20,4	18,7	16,9	15,2	13,5	11,8	10,2	8,6	7,2	5,8	4,5	3,3	2,2	1,2	0,3	432
PtL from EU, 80% target	28,4	28,7	28,7	28,7	28,5	28,3	27,9	28,5	28,3	27,8	26,9	25,9	24,6	23,3	21,9	20,4	18,9	17,4	15,8	14,3	12,7	11,2	9,6	8,1	6,6	5,2	547
PtL from EU, 90% target	28,4	28,5	28,5	28,4	28,1	27,8	27,4	27,8	27,6	26,9	25,9	24,8	23,4	22,0	20,5	18,9	17,3	15,7	14,0	12,4	10,8	9,1	7,5	5,9	4,4	2,8	515
PtL from EU, 100% target	28,3	28,4	28,3	28,1	27,8	27,3	26,8	27,1	26,8	26,0	24,9	23,6	22,2	20,7	19,1	17,4	15,7	14,0	12,2	10,5	8,8	7,1	5,4	3,8	2,1	0,5	483

O Climate and prevention costs of common flight routes, in 2021EUR

Route	Distance	Type flight	Fuel burn	kg CO_2/p	Aviation Economics	CE Delft low	CE Delft high	MAC (2025)	MAC low (2032)	MAC high (2032)
AMS-CDG	398 km	Short-haul	2,750 kg	61	€13,37	€11,42	€13,83	€12,20	€15,37	€19,58
AMS-LIS	1,844 km	Medium-haul	7,929 kg	165	€17,68	€28,50	€40,60	€33,00	€41,58	€52,97
FRA-DXB	4,839 km	Medium/long	59,382 kg	299	€72,72	€57,18	€64,51	€59,80	€75,35	€95,98
CDG-ATL	7,051 km	Long-haul	65,669 kg	389	€105,96	€83,32	€94,00	€77,80	€98,03	€124,87

P Marginal damage and prevention costs, in 2021EUR/tCO_2

Costs per tCO2 in 2021EUR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Low SCC: Nordhaus (4.25%)	33	34	35	36	38	39	40	41	43	44	46	47	49	51	52
Base SCC: Nordhaus (2.5%)	122	124	126	128	130	132	134	136	139	141	143	146	149	151	154
High SCC: Stern Review (1.4%)	237	247	256	267	278	286	294	303	312	322	330	339	347	356	366
MACC: PtL from ME	170	178	185	193	200	208	216	223	231	238	246	252	242	231	220
MACC: PtL from EU	170	178	185	193	200	208	216	223	231	238	246	321	316	312	307

Costs per tCO2 in 2021EUR	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Low SCC: Nordhaus (4.25%)	54	56	58	60	62	64	67	69	71	74	76	79	82	85	88
Base SCC: Nordhaus (2.5%)	157	160	162	165	168	171	175	178	181	184	188	191	194	198	202
High SCC: Stern Review (1.4%)	375	385	395	405	416	427	438	449	461	473	485	498	511	524	538
MACC: PtL from ME	210	199	188	178	167	156	146	135	124	113	103	92	81	71	60
MACC: PtL from EU	303	298	294	289	285	280	276	271	267	262	258	253	249	244	240

Q Total damage and prevention costs, in billion 2021EUR

Total costs in billion 2021EUR	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	TOTAL
PtL from ME, 80% target	14	20	25	29	29	29	29	29	29	28	28	28	25	23	21	19	17	15	13	12	10	9	7	6	5	4	3	2	2	1	509
PtL from ME, 90% target	14	20	25	29	29	29	29	29	28	28	28	27	24	22	20	18	16	14	12	11	9	8	7	5	4	3	3	2	1	1	493
PtL from ME, 100% target	14	20	25	29	29	29	29	28	28	27	27	26	24	21	19	17	15	13	11	10	8	7	6	5	4	3	2	1	1	0	477
PtL from EU, 80% target	14	20	25	29	29	29	29	29	29	28	28	35	33	31	29	27	25	23	21	20	18	16	15	13	12	10	9	7	6	5	641
PtL from EU, 90% target	14	20	25	29	29	29	29	29	28	28	28	34	32	30	28	26	24	22	20	18	16	15	13	11	10	8	7	5	4	3	611
PtL from EU, 100% target	14	20	25	29	29	29	29	28	28	27	27	33	31	29	27	25	23	21	19	17	15	13	11	10	8	6	5	3	2	1	581
Damage costs (low SCC)	3	4	5	5	5	6	6	6	6	7	7	7	8	8	8	9	9	10	10	10	11	11	12	12	13	14	14	15	15	16	272
Damage costs (mid SCC)	10	13	17	19	19	20	20	21	21	22	22	23	24	24	25	26	26	27	28	29	29	30	31	32	33	34	35	36	37	38	770
Damage costs (high SCC)	18	26	33	38	40	42	44	46	47	49	51	53	55	57	59	61	63	66	68	70	73	75	78	81	84	87	90	93	96	100	1844