Social costs and benefits of advanced aviation fuels

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Content

Summary

Background

As part of the Horizon 2020 research project JETSCREEN, Airbus is interested in the social, economic and environmental impacts of a shift to low-sulphur, low-aromatics, low-naphthalene aviation fuels to reduce the pollutant and GHG emissions of aviation. In order to assess these impacts in a structured way, CE Delft has carried out a social cost-benefit analysis (SCBA) of applying these alternative aviation fuels instead of the regular JET A1 kerosene.

Baseline and project scenarios

In the baseline scenario considered in this study we assumed that all airplanes worldwide make use of JET A-1 as fuel. Some relevant specifications of this type of kerosene is given in Table 1. The three types of low-sulphur, low-low-aromatic, low-naphthalene aviation fuels considered in this study are presented in Table 1 as well. These fuels can be produced by hydro-treatment of the straight run kerosene. For the purpose of this study, we have assumed that no structural changes to the refineries nor any extension of the refinery capacity is required to produce these alternative fuels.

Table 1 - Specifications of the baseline kerosene and the three types of alternative aviation fuels

	Regular JET A1	JET A1 HT1	JET A1 HT2	JET A1 HT3
Specific energy content (MJ/kg)	43,266	43.31	43.37	43.58
Aromatics (% v/v)	16.8	16	15.6	7.1
Total sulphur (mg/kg)	300	45.4	6.2	13.6
Naphthalene (% v/v)	1.81	0.7	<0.1	<0.1

Results of the SCBA

An overview of the main results of the SCBA is given in Table 2. All costs and benefits are presented as annual figures for the year 2018 (price level 2018).

Table 2 - Overview SCBA results (compared to the baseline scenario, mln €, 2018 price level)

Type of effects	Specific effects	HT1	HT2	HT3
Direct effects	Additional costs of advanced aviation fuels	192	322	2,966
	Fuel costs savings	-209	-494	-1,484
	Maintenance costs	- PM	- PM	- PM
	Retrofit costs	+ PM	+ PM	+ PM
Indirect effects	Change in consumer surplus	0.04	0.11	9.00
	Change in producer surplus	0	0	0
External effects	Air pollution	-73	-85	-91
	GHG emissions	-687	-677	-1,224
	Emissions from fuel production	0.00	0.00	0.01
Net results	**Costs minus benefits**	**-778 +/- PM**	**-934 +/- PM**	**177 +/- PM**

From Table 2 it becomes clear that both the use of alternative fuels HT1 and HT2 results in net social benefits, particularly due to significant fuel cost savings (as the alternative aviation fuels have a higher energy intensity than the regular A-1 kerosene) and reductions in GHG emissions. These benefits are highest for the HT2 fuel, which is mainly because the use of this fuel results in significantly higher fuel cost savings than using the HT1 fuel. The use of the alternative fuel HT3 results in additional social costs. This is mainly caused by the high additional costs of the extra removal of aromatics required to produce this fuel. These additional production costs are considerably higher than the additional fuel cost savings and GHG emission reductions achieved by using this type of fuel.

Another conclusion that can be drawn from Table 2 is that the alternative fuels HT1 and HT2 results in net benefits from a business perspective as well. The fuel cost savings that could be achieved by using these fuels are higher than the additional costs of producing them. However, it should be noticed that particularly for HT1 the additional production costs and the fuel cost savings are in the same order of magnitude, such that including the maintenance and retrofit costs into the quantitative analysis may change this conclusion.

Robustness of the conclusions

In order to test the robustness of the conclusions drawn from the SCBA, we have carried out some sensitivity analyses to see to what extent the results change in case we apply some other input values or assumptions. The following sensitivity analyses have been carried out:

- *A higher and lower natural gas price*; as the natural gas price is an important determinant of the additional production costs of the alternative fuels, this sensitivity analysis provides information on the impact of changes in the production costs on the results of the SCBA.
- *The reduction in fuel use because of lower demand for air transport*; a switch to hydro-treated fuels may result in a reduction in demand for air transport (because of the higher fuel costs ticket prices may be increased). As a results of this drop in demand, airlines are likely to reduce their fuel consumption applying operational measures like cutting routes or frequency of flights. In the main analysis, we were not able to take this effect into account and therefore a sensitivity analysis on this issue has been carried out.
- *The black carbon content of the alternative aviation fuels*; in the main analysis we have considered a conservative estimate of the reduction in black carbon content of the alternative aviation fuels. In this sensitivity analysis the impact of a more substantial reduction in black carbon emissions have been assessed.
- *The CO_2 price*; in the scientific literature there is much debate on the CO_2 price to be used in analyses like this one. For that reason, we have performed a sensitivity analysis considering a considerably higher and lower CO_2 price.

The results of the sensitivity analyses show that the conclusions for the alternative fuels HT1 and HT2 are rather robust, i.e. the conclusion that these fuels result in net social benefits are still valid when applying the different assumptions and input values considered in the sensitivity analyses. However, it should be noticed that under these alternative assumptions also the use of HT3 may lead to net social benefits. It is therefore recommended to further study some of the assumptions underlying the analysis for particularly this fuel type.

1 Introduction

1.1 Background

The EU Directive 2009/28/EC requires a 10% share of renewable energy in the transport sector in every Member State by 2020. For 2050, a goal of 75% renewables in the gross energy consumption is set by the EU energy roadmap, which requires a 40% share of low carbon sustainable fuels in aviation (EC, 2011). The latter goal is quite challenging, particularly as global oil demand (and hence CO_2 emissions) of aviation are expected to grow significantly in the coming years. According to IEA's New Policy scenarios, aviation accounts for around 15% of global oil demand up to 2030.

Although there is no specific EU legislation in relation to air pollutant emissions of aviation, the general EU legislation establishing limit values for the concerned pollutants (Directive 2008/50/EC) on ambient air quality and cleaner air for Europe) applies at and around airport as they do everywhere else in the EU. As part of meeting the targets set by the Air Quality Directive the EU has implemented aircraft emission standards, which are in line with the engine certification standards adopted by the Council of ICAO, (2017).

The Horizon 2020 research project 'JETSCREEN' has been initiated to contribute to the achievement of the long-term sustainability goals for aviation. For that purpose, a screening and optimization platform for alternative fuels is developed. This platform integrates knowledge-based screening tools that will assess the risks and benefits and optimise alternative fuels for a maximum energy per kilogram of fuel and a reduction of pollutants emissions. More specifically, the platform should provide to fuel producers, air framers and aero-engine and fuel system OEMS, tools that will:
- streamline the alternative aviation fuel approval process;
- assess the compatibility of fuel composition/properties with respect to the fuel system and the combustion system;
- quantify the added value of alternative fuels;
- optimise fuel formulation in order to attain the full environmental potential of synthetic and conventional fuels.

As part of the JETSCREEN project, Airbus is interested in the social, economic and environmental impacts of a shift to low-sulphur, low-aromatics, low-naphthalene aviation fuels to reduce the pollutant and GHG emissions of aviation. For that purpose, they requested CE Delft to conduct a social cost-benefit analysis of three types of low-sulphur, low-aromatics, low-naphthalene aviation fuels. The methodology applied for and the results of this analysis are presented in this report.

1.2 Objective

The objective of this study is to analyse the economic, environmental and social effects of using low-sulphur, low-aromatic, low-naphthalene fuels in aviation. Three alternative specifications for such advanced jet fuels are considered and compared to a jet fuel applying to the current fuel standards.

In order to present these effects in a structured manner, we have set up a Social Cost-Benefit Analysis (SCBA). It aims to reveal all the effects of the use of advanced aviation fuels, even those of non-financial nature. Valuation methods are used to give these non-financial effects a price.

1.3 Scope

In this SCBA, the following basic principles are applied:

- The analysis has a global scale, which means that all impacts of the switch to low-sulphur, low-aromatic, low-naphthalene fuels in aviation are taken into account (independent of where they take place).
- In our analysis we assume that no additional refinery capacity have to be build neither that structural changes to the existing refineries have to be made to produce the alternative aviation fuels. In reality this may not be the case, as EASA, (2010) states that there is insufficient hydroprocessing capacity in most refineries to desulpharise all jet fuel, gasoline and diesel. However, also the global scale of the appliance of these alternative fuels (the previous bullet) may be considered hypothetical. Therefore, this assumption seems valid for the purposes of this study.
- The year 2018 is used as base year. All costs and benefits will be expressed in annual values for 2018 in order to make them comparable.
- All monetarised figures are converted to 2018 prices, expressed in Euros.

1.4 Methodology

In this study, we carry out a Social Cost-Benefit Analysis (SCBA) to investigate the costs and effects of various alternative specifications for fuels in aviation. A SCBA is an evaluation method that provides an integral assessment of the (positive and negative) impacts of policy decisions. This assessment compares the costs and benefits of one or more project alternatives with a so-called baseline or business-as-usual scenario. The baseline scenario is the most likely development that will occur when no policy decision is taken.

An SCBA typically comprises five steps:

1. Definition of the baseline and project scenarios.
2. Identification of the relevant effects (both costs and benefits) of the project.
3. Quantification of the various (physical) effects.
4. Monetarising the various effects.
5. Assessing the main uncertainties in the SCBA by applying relevant sensitivity analyses.

As a SCBA is based on a broad definition of the term welfare, not only financial/tangible costs and benefits are taken into account, but also intangible effects are considered. The welfare effects are categorized into direct, indirect and external effects:

- *Direct effects* are impacts that are a direct consequence of the project. In case of the switch to advanced aviation fuels, it concerns most notably the additional production costs of these fuels and potential fuel cost savings (due to the higher energy intensity of the advanced fuels).
- *Indirect effects* are a carry-over effect from some of the direct effects. For example, the increased fuel cost (direct effect) may lead to increased ticket prices and hence lower demand for aviation, which may have negative welfare impacts for air travellers (indirect effect).
- Finally, *external effects* relate to unintended changes in the welfare of third parties due to a certain action or change in policy for which no compensation is received. These often concern environmental impacts.

In order to make all effects comparable, the effects are quantified and monetarised as much as possible. The value of external effects is for instance determined in monetary terms (if possible) through specific valuation techniques, as no market prices are readily available. In this way, all effects of the project can be compared and an integral evaluation of its contribution to social welfare can be made.

In this SCBA, for all relevant costs and benefits annual values can be estimated. Therefore, it is possible to compare the costs and benefits for just one year (2018).

1.5 Outline of the report

In Chapter 2, we present the baseline scenario and the three project scenarios that are considered in this study. Chapter 3 identifies the relevant effects to be considered in the analysis. Furthermore, these effects will be assessed and monetarised if possible.
The overall results of these analyses are presented and discussed in Chapter 4. In this chapter, we also carry out some sensitivity analyses in order to test the robustness of the results. Finally, the conclusions of the study are presented in Chapter 5

2 Scenarios

2.1 Introduction

In this chapter we present the baseline and project scenarios that are considered in the SCBA. The baseline scenario is discussed in Section 2.2, while the three project scenarios are presented in Section 2.3.

2.2 Baseline scenario

In the baseline scenario it is assumed that all airplanes worldwide make use of JET A-1 as fuel. It is the most commonly used aviation fuel, which is produced to standardised international specifications. The main specifications of JET A-1 are presented in Table 3.

Table 3 - Specifications of the baseline aviation fuel

Specifications	Value
Name	ETS CR JET A1
Analysis facility	Haltermann
Specific Energy content (MJ/kg)	43,266
Freezing Point (°C)	-57
Flash Point (°C)	42
Density at 15°C (kg/m^3)	791.7
Initial Boiling Point (°C)	151.7
Aromatics (% v/v)	16.8
Total Sulphur (mg/kg)	300
Mercaptan Sulphur (mg/kg)	9
Naphthalene (% v/v)	1.81

The base year for this study is 2018. In 2018, nearly 39 million flights were flown globally (ICCT, 2019). The total CO_2 emissions from all commercial passenger and freight operations were 918 million metric tons (ICCT, 2019). Of this 918 million metric tons, 747 million metric tons of CO_2 were caused by passenger operations, and 171 million metric tons of CO_2 were caused by freight operations (ICCT, 2019). If we convert the CO_2 emissions back to fuel burned, the global fuel use from commercial passenger and freight aviation in 2018 was 363,035 million litres.

2.3 Project scenarios

In this section we consider three project scenarios, distinguishing three types of low-sulphur, low-low-aromatic, low-naphthalene aviation fuels. In the remainder of this study, we will refer to these three fuels as alternative aviation fuels. The specifications of these three fuel types are shown in Table 4. In all project scenarios, it is assumed that the use of the baseline fuel is fully replaced by the alternative fuel.

Any differences in the demand for air traffic, aviation fuel use and CO_2 emissions of aviation compared to the baseline scenario are assumed to be part of the effects of the switch to the alternative aviation fuels. These effects are discussed in detail in Chapter 3.

Table 4 – Specifications of the three alternative aviation fuels

	JET A1 HT1	JET A1 HT2	JET A1 HT3
Analysis facility	CERTH	CERTH	CERTH
Specific energy content (MJ/kg)	43.31	43.37	43.58
Freezing point (°C)	-56	-56	-56
Flash point (°C)	42	39	36
Density at 15°C (kg/m^3)	792.9	790.8	785.3
Initial boiling point (°C)	150.9	147.9	147.1
Aromatics (% v/v)	16	15.6	7.1
Total sulphur (mg/kg)	45.4	6.2	13.6
Mercaptan sulphur (mg/kg)	4	<3	<3
Naphthalene (% v/v)	0.7	<0.1	<0.1

The required reductions in sulphur, aromatics and naphthalene compared to the baseline jet fuel in order to meet the specifications as given in Table 4, are presented in Table 5.

Table 5 - Required reduction of sulphur, aromatics and naphthalene to meet the specifications of the three alternative aviation fuels

Compounds	JET A1.1	JET A1.2	JET A1.3
Total sulphur reduction (mg/kg)	244.6	293.2	286.4
Mercaptan sulphur reduction (mg/kg)	5	>6	>6
Aromatics reduction (% v/v)	0.8	1.2	9.7
Naphthalene reduction (% v/v)	1.11	>1.71	>1.71

3 Effects

3.1 Introduction

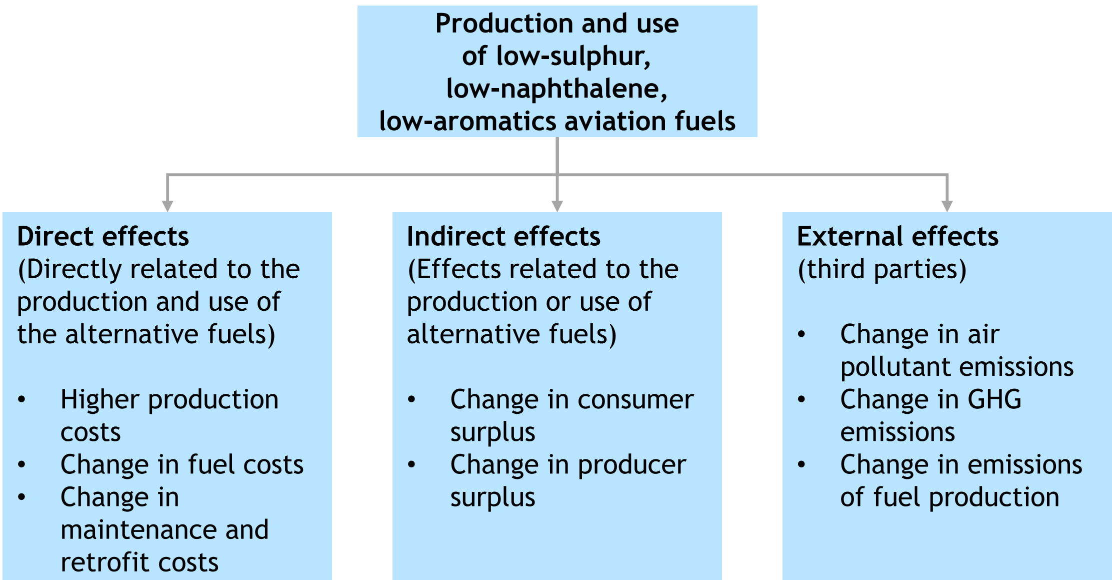
In this chapter the various effects of using the alternative aviation fuels are identified and assessed. Where possible, these effects are quantified and monetarised. This is done for both the baseline scenario and the three project scenarios.

In Section 3.2, we first briefly introduce the various effects that are considered in this SCBA. Next, the various direct, indirect and external effects are assessed in Sections 3.3 through 3.5.

3.2 Considered effects

An overview of the effects of the production and use of the alternative aviation fuels is given in Figure 1.

Figure 1 - Overview of welfare effects of the production and use of the alternative aviation fuels



Three types of effects are distinguished in this study:
- *Direct effects* are impacts that are direct consequences of the productions and/or use of the alternative aviation fuels. It includes the additional production costs of these fuels as well as changes in fuel costs (due to differences in energy intensity between the baseline fuel type and the alternative fuels).
- *Indirect effects* are all welfare impacts induced by the direct impacts. The higher production costs (or change in fuel costs) may affect the air ticket prices and hence may results in welfare impacts for air travellers (consumers) and airlines (producers).
- *External effects* are unintended changes in the welfare of third parties (due to the production and use of the alternative aviation fuels) for which no compensation is

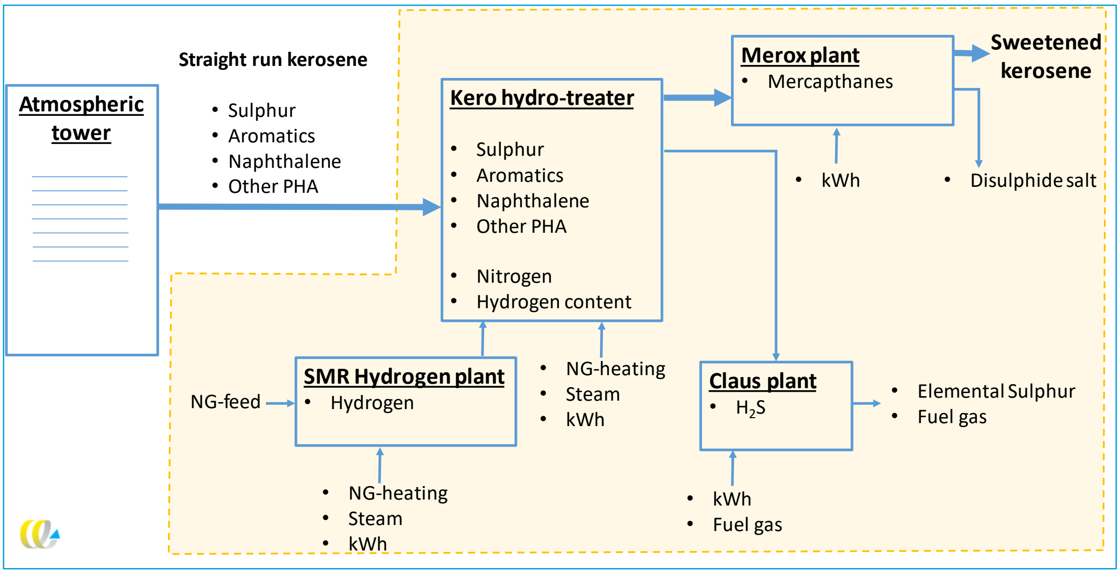
received or fee is paid. These are mainly related to environmental impacts, such as the effects on air pollutant emissions, GHG emissions and emissions of fuel production.

3.3 Direct effects

3.3.1 Additional costs of the alternative aviation fuels

To produce the alternative (low-sulphur, low-aromatics, low-naphthalene) aviation fuels additional processes are required compared to the conventional production process for straight run kerosene. An overview of these additional processes are shown in Figure 2.

Figure 2 - Process to remove sulphur, aromatics and naphthalene from kerosene



Source: Based on (Abella, et al., 2019).

In general, the process to remove sulphur, aromatics and naphthalene consists of the following four steps:

— *Hydro-treatment*; this is a process of removing unwanted impurities/inorganic components (including sulphur, aromatics and naphthalene) by processing it at high temperature and pressure in the presence of hydrogen and a catalyst. In this process hydrogen reacts with the sulphur in the fuel to form gaseous hydrogen sulphide, which is then separated from the fuel. Also for naphthalene and aromatics hydro-treating is considered the most common method for removal. In an industrial refinery, hydro-treatment takes place in a fixed bed reactor at elevated temperatures ranging from 300 °C to 400 °C and elevated pressures ranging from 30 to 100 kPa, in the presence of a catalyst consisting of an alumina base impregnated with cobalt and molybdenum.

— *Hydrogen production;* as input for the hydro-treatment hydrogen is required. The most common method to produce hydrogen is by steam methane reforming (SMR). In this method high-temperature steam (700 °C to 1,000 °C) is used to produce hydrogen from a methane source, such as natural gas (NG). Under pressure, the methane reacts with steam in the presence of a catalyst to produce hydrogen, carbon monoxide and carbon dioxide. In a next step, the carbon monoxide and steam are reacted using a catalyst to

produce carbon dioxide and more hydrogen. In a final step, carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen.
- *Merox (sweetening);* this is a process of removing a particular class of sulphur containing compounds called mercaptans[1] from jet fuel. This is done by oxidising the mercaptans in an alkaline environment.
- *Claus process*; the gaseous hydrogen sulphide resulting from the hydro-treatment process is further processed in the Claus plant. The Claus process consists of a thermal stage (combustion chamber, waste heat boiler) and some catalytic reaction stages (reheater, reactor and condenser). The main products of this process are elemental sulphur and fuel gas.

As indicated in Figure 2, specific inputs (e.g. natural gas, electricity) and intermediate products (H_2) are required in each of these four process steps. The use of these inputs and intermediate products result in additional production costs. The amounts of natural gas, electricity, steam and hydrogen that are required in each step of sulphur, aromatics, and naphthalene removal are taken from the detailed refinery model PRELIM 1.3 (Abella, et al., 2019). The following assumptions are used in this respect:
- We consider the marginal increase of primary resources for additional hydro-treatment (compared to the conventional production process of Jet A.1 fuel) in an existing refinery assuming linearity versus removal.
- As indicated in Section 1.3, we assume that no new refinery capacity will be developed and hence no additional OPEX nor CAPEX effects are included in the assessment. This also implies that the hydrogen used is coming from existing Steam Methane Reformers (SMR).
- Cost increase exclusively by extra primary energy sources: natural gas and grid power.
- Steam of SMR is used elsewhere in the refinery and equivalent distracted from the natural gas consumption.
- Hydrogen consumption for H_2S to enable processing in Claus is included in the assessment.
- Claus process with its input and output energy streams is included.
- Refinery gas for steam of Claus is used elsewhere in the refinery and equivalent distracted from the natural gas consumption.
- Heat, steam and power consumption of hydro-treatment is allocated by the amount of hydrogen consumed per component (sulphur, Claus H_2S and aromatics).
- Constant added power for Merox is assumed per amount of kerosene, independent of absolute mercaptan reduction level for polishing.
- The yield and sale of additional elemental Sulphur production is deducted from the cost per ton kerosene.

Based on these assumptions, the amounts of inputs and intermediate products have been estimated by using the PRELIM 1.3 refinery model. The results of this assessment are given in Table 6.

[1] Mecraptans have a sulphur atom bonded to a hydrocarbon group and a hydrogen atom.

Table 6 - Overview of the amounts of inputs and intermediate products required in the various steps of the process to remove sulphur, aromatics and naphthalene per ton kerosene

	Natural gas-feed (m^3NG/kgH_2)	Hydrogen (kgH_2/- or m^3NG /ton.m% X reduced)	Natural gas-for heating (m^3NG/kgH_2 or -/ton.m% X reduced)	kWh (kWh/kgH_2 or -/ton. m% X reduced)	Steam (kg/kgH_2)	Steam (m^3NG/kgH_2 or -/ton.m% X reduced)
1. Steam methane reforming	3.5		0.38	0.31	-4.1	-0.39
2. Hydrotreatment:						
a- Sulphur conversion		0.63 2.2	0.69 0.44	0.48	0.58	0.056 0.12
b- Sulphur conversion to H_2S for Claus		0.63 2.2	0.69 0.44	0.48	0.58	0.056 0.12
c- Aromatics		6.9 24 (as m^3NG/ton. m% H increased)	3.9 27	2.7	3.3	0.32 0.69
d- Naphthalene		0.94 3.3 (as m^3NG/ton.m% Naphthalene reduced)				
3. Merox				0.78 kWh/ton kero-out		
4. Claus				0.99	-29	-2.8

Based on the information from the PRELIM 1.3 model, as presented in Table 6, and the required reductions in sulphur, aromatics and naphthalene to meet the restrictions of the alternative aviation fuels (see Section 2.3), the additional amounts of natural gas and electricity required to produce one ton of alternative fuel is presented in Table 7.

Table 7 - Additional amount of natural gas and electricity required to produce one ton of the three types of alternative aviation fuels (compared to the baseline fuel)

Process steps		**Natural gas (m^3/ton kerosene)**			**Electricity (kWh/ton)**
		Hydrogen feed	**Heating**	**Steam**	
Jet A.1 HT1					
Hydro-treatment (incl. SMR)	Sulphur conversion	0.53	0.11	0.030	0.12
	Sulphur conversion to H_2S for Claus	0.53	0.11	0.030	0.12
	Aromatics removal	1.6	1.8	0.046	1.4
	- Naphthalene removal	0.33[a]			
Merox		-	-	-	0.029
Claus		-	-	-0.68	0.24
Total				**4.1**	**2.7**

Process steps		Natural gas (m^3/ton kerosene)			Electricity (kWh/ton)
		Hydrogen feed	Heating	Steam	
Jet A.1 HT2					
Hydro-treatment (incl. SMR)	Sulphur conversion	0.64	0.13	0.036	0.15
	Sulphur conversion to H_2S for Claus	0.64	0.13	0.036	0.15
	Aromatics removal	2.4	2.7	0.069	2.1
	-Naphthalene removal	0.34[a]			
Merox		-	-	-	0.031
Claus		-	-	-0.82	0.29
Total				**6.0**	**3.5**
Jet A.1 HT3					
Hydro-treatment (incl. SMR)	Sulphur conversion	0.63	0.12	0.035	0.14
	Sulphur conversion to H_2S for Claus	0.63	0.12	0.035	0.14
	Aromatics removal	19	22	0.56	17
	-Naphthalene removal	0.34[a]			
Merox		-	-	-	0.78
Claus		-	-	-0.80	0.28
Total				**43**	**18**

[a] The level of reduction of aromatics is considered including naphthalene. Therefore, the amount of natural gas used to produce hydrogen to remove aromatics is assumed to include the removal of naphthalene as well.

To estimate the additional costs of the alternative aviation fuels, the additional amounts of natural gas and electricity are multiplied by the respective energy prices (see Table 8). The average energy prices are based on the average prices in the US and the EU. The global variance in natural gas and electricity prices is, however, rather large and hence may differ significantly based on the location of the refinery where the alternative aviation fuels will be produced. For that reason, we will conduct some sensitivity analyses to assess the impact of the assumed energy prices on the results of the social cost-benefit analysis.
In addition to the costs of additional use of natural gas and electricity, the process also results in some elemental sulphur which has a market value. This benefit is monetarised by using an average global price for sulphur of € 162 per MT.

Table 8 - Energy and Sulphur prices

Primary energy sources	US	EU	Average
Natural gas (€/m^3)	0.13	0.33	0.23
Electricity (€/kWh)	0.06	0.04	0.05
Elemental Sulphur (€/MT)			-162

Sources: EIA, (2019), Eurostat, (ongoing-b).

The additional costs of the three alternative aviation fuels is presented in Table 9.
The total additional fuel costs are calculated based on the worldwide fuel use from commercial passenger and freight aviation in 2018. As mentioned in Section 2.2, the total worldwide fuel in 2018 was 363,035 million litres. However, note that due to the fact that the hydro-treated fuels have a higher specific energy, less fuel is required. Hence, we use a fuel consumption of 362,666; 362,164; and 360,419 million litres for the HT1, HT2 and HT3

fuels respectively (for more detail on this see Section 2.3)[2]. In total, the additional costs of a global switch from Jet A-1 fuel to hydro-treated fuels are € 192, € 322 and € 2,966 million for each of the three hydro-treated fuels respectively.

Table 9 – Average additional costs of primary energy for the three alternative aviation fuels

	Jet A1 HT1	Jet A1 HT2	Jet A1 HT3
Natural gas (€/ton kerosene)	0.88	1.4	10
Power from grid (€/ton kerosene)	0.17	0.17	0.92
Elemental Sulphur (€/tonne kerosene)	-0.40	-0.47	-0.46
Total cost (€/ton kerosene)	0.7	1.1	10
Total cost (€ct/litre kerosene)	0.053	0.089	0.823
Total additional fuel cost (mln €)	**192**	**322**	**2,966**

3.3.2 Fuel cost savings

The use of the alternative fuels may also lead to cost savings. There are three ways in which this might work: through changes in fuel use, changes in maintenance costs and changes in retrofit costs. The first one (changes in fuel use) is discussed in this subsection, while the latter two are discussed in the next subsection.

By hydro treating fuels to remove sulphur, naphthalene and aromatics from the fuels, more room for extra carbon atoms is created. As a result, the alternative fuels considered in this study have a higher specific energy than conventional Jet A-1 fuel. The fuel flow to the engine is scaled in proportion to the energy content of the fuel, therefore less fuel needs to be used if the specific energy content of the fuel is higher.

The baseline energy content for Jet A-1 fuel used in this project is 43.266 J/kg. The three different grades of low-sulphur, low-naphthalene and low-aromatics fuels each have a higher specific energy content of 43.31 M/kg for Jet A-1 HT1, 43.37 J/kg for Jet A-1 HT2 and 43.58 J/kg for Jet A-1 HT3 (see Table 10). From the specific energy content of the fuels we can calculate the reduction factor in fuel use. E.g. for the A1 HT3 fuel the reduction factor would be 43.266/43.58 = 0.993. This would imply that global fuel use could be reduced by 0.7%.

From Section 2.2 we know that global fuel use from commercial passenger and freight aviation in 2018 is 363,035 million litres. IATA's Jet A-1 fuel price in 2018 was $ 0.67 per litre (IATA, ongoing), which can be converted to € 0.57 per litre using Eurostat's exchange rate[3]. This in turn can be used to calculate the fuel cost savings.

Table 10 provides an overview of the steps in the calculation of the fuel cost savings as a result of the higher energy density of the alternative fuels. Fuel cost savings amount to € 209 million, € 494 million and € 1,484 million HT1, HT2 and HT3 respectively.

2 As is explained in Section 3.4.2, these total fuel consumption figures are probably a slight overestimation of the actual figures, as the reduction in fuel consumption due to less demand for air transport (because of the increased costs of aviation) are not included in these figures. In Section 4.3.2 we have carried out a sensitivity analysis to assess the impact of this omission on the final results of the SCBA.

3 The €:$ exchange rate according to Eurostat was 1:1.1810 in 2018 (Eurostat, ongoing-a).

Table 10 – Overview of changes in fuel use

	Jet A-1	HT 1	HT 2	HT 3
Specific energy (MJ/kg)	43,266	43.31	43.37	43.58
Ratio of specific energy compared to Jet A-1		0.999	0.998	0.993
Fuel use reduction factor		0.001	0.002	0.007
Fuel use reduction factor (%)		0.1%	0.2%	0.7%
Global fuel use (million l)	363,035	362,666	362,164	360,419
Price of Jet A-1 fuel (€/l)	0.57			
Fuel use reduction (million l)	0	369	871	2,616
Fuel cost savings (million €)	**0**	**209**	**494**	**1,484**

It is important to note that the fuel cost savings in this section are only calculated based on the fact that the specific energy content of the hydro-treated fuels is higher than for Jet A-1 fuel. However, due to the fact that the costs of hydro-treated fuels is higher than the cost of conventional Jet A-1 fuel, one can also expect a drop in passengers (see Section 3.4.2). Unfortunately, as there is no data about where these passengers fly to, and the responses of airlines to a drop in passenger numbers, we are unable to translate this drop in passenger numbers to the total amount of fuel saved.[4] Therefore, the figures presented in this section are likely to be an underestimate of the true fuel cost savings. In Section 4.3.2 we have performed a sensitivity analysis to assess the impact of this omission on the fuel cost savings and the overall results of the SCBA.

3.3.3 Maintenance and retrofit costs

Maintenance and retrofit costs are likely to be affected if a large scale switch to low-sulphur, low-naphthalene and low-aromatics fuels takes place. Fuels with a lower sulphur-content, and a resulting higher specific energy content, reduce engine wear, which may imply less frequent maintenance (University of Antwerp & Transport & Mobility Leuven, 2010). However, retrofit costs may increase. For instance, the aromatics in the fuel keep O-rings flexible, and removing aromatics from the fuel will imply less flexible O-rings, which will have to be retrofitted and replaced more often.

In general, there is not enough research on the size of a possible increase or decrease of maintenance and retrofit costs as a result of the use of alternative fuels. Therefore, in this study we have currently placed the change in maintenance and retrofit costs as a PM post.

3.4 Indirect effects

3.4.1 Change in producer surplus

The producer surplus of airlines may be affected by the large scale switch to low-sulphur, low-naphthalene and low-aromatics fuels, depending on the extent of cost pass-through and the shape of the supply curve.

Cost pass-through rates in aviation are very much dependent on the market and the type of competition in the market, and there is disagreement on the rates in the literature.

4 Airlines could, for instance, cancel certain flights or continue to fly the regular flights with a lower occupancy rate. In both cases fuel is saved either because of the cancellation of the whole flight, or due to reduced weight in the aircraft. However, due to data limitations, we do not know how airlines will react and can hence not estimate the impact of reduced passenger numbers on fuel saved.

Koopmans and Lieshout (VU university et al., 2014) argue based on theoretical considerations and the assumption that aviation markets are Cournot-type oligopolies that the pass-through rate for airline-specific cost increases is less than 50%, whereas the pass-through rate for industry-wide cost increases is more than 50%. Vivid Economics, (2007) argue that, depending on the elasticity of demand, and also assuming that aviation markets are Cournot-type oligopolies, pass through rates of more than 100% are possible. CE Delft, (2007) argues that aviation markets show characteristics of Bertrand-type oligopolies (the profit margins do not suggest large oligopoly rents) and that therefore, the cost pass-through will be 100%.

As this study investigates the adaptation of low-sulphur, low-naphthalene and low-aromatics fuel on a global scale, it is most likely that airlines will be able to pass-through 100% of the increased costs they face, because all competing airlines are faced with the same increase.

The second aspect that needs to be investigated to determine the change in producer surplus is the shape of the supply curve. As we are looking at the global market, one could argue that the supply curve of aviation is horizontal. At the current equilibrium price, there is an infinite supply of aviation. There will always be a company willing to offer aviation services at the equilibrium price. The price of aviation services is the marginal cost price, and hence, there is no producer surplus. If the price is then collectively raised, because all airlines in the world are faced with the same cost increase, the combination of a 100% cost pass-through rate and this horizontal supply curve implies that a new equilibrium is reached where services are offered at the marginal cost price. This implies there is no change in the producer surplus.

3.4.2 Change in consumer surplus

If we assume, based on the reasoning in the previous subsection, that the higher cost price of the alternative fuels are passed on to consumers in the form of higher prices, this switch in fuel leads to a reduction in the demand for aviation. This in turn implies that the consumer surplus also decreases. There are certain travellers or goods that would have used aviation in absence of the switch to the alternative fuels, but that don't now. As a result, their welfare decreases. We divide the consumer surplus into two parts: consumer surplus for passenger aviation and consumer surplus for freight aviation.

Consumer surplus for passenger aviation

The change in consumer surplus for passenger aviation can be measured as the sum of the welfare loss of the individual travellers. However, the shape and slope of the demand curve is unknown. In this study we assume that the demand curve is linear, and that the consumer surplus can be calculated using the rule of half: the reduction in the number of passengers multiplied by half of the average cost price increase of the ticket price (due to the higher fuel costs). The intuition behind this rule is that the maximum welfare loss is equal to the height of the ticket price increase (due to the fuel cost increase), whereas the minimum welfare loss is just above zero. With a linear demand curve this means that the average welfare loss is equal to half of the ticket price increase.

From Section 3.3.1 we know that the increase in the fuel cost price from the use of the three alternative fuels is 0.053, 0.089 and 0.823 €ct per litre of fuel respectively. The price of Jet A-1 fuel is € 0.57 (see Table 10), which implies the three alternative fuels are priced 0.1, 0.2 and 1.5% higher than Jet A-1 fuel. As the aviation market is highly competitive, we assume that the entire fuel cost price increase is passed on to air travellers by increasing the ticket prices.

In 2018, fuel costs were 23.5% of expenditures for airlines (Statista, ongoing). If we assume that this ratio is also represented in the price of tickets, we can calculate the percentage change in the price of aviation. For instance, for the HT1 fuel, the total price increase would be 23.5% * 0.1% = 0.02%. For the HT2 fuel and HT3 fuel this implies that the percentage change in ticket prices is 0.04 and 0.34%.

To calculate the reduction in the number of passengers we need to know how sensitive passengers are to increases in ticket prices. This is defined as the price elasticity of demand: the percentage change in quantity demanded divided by the percentage change in price.

$$Price\ elasticity\ of\ demand = \frac{\%\ change\ in\ quantity\ demanded}{\%\ change\ in\ price}$$

The price elasticity is highly dependent on the scope (e.g. route/national or pan-national level), the geographic aviation market and the length of the flight (e.g. short-haul vs. long-haul). We use the methodology developed by (InterVISTAS, 2007) to calculate the price elasticity.[5] In this context the relevant price elasticity of demand that we use to calculate the change in consumer surplus is -0.6. This implies that the demand for aviation is inelastic, as a 1% increase in the price of aviation will lead to a -0.6% decrease in quantity demanded.

Table 11 provides an overview of the steps in the calculation of the change in consumer surplus as a result of the higher cost price of the alternative fuels. To transform the percentage change in demand to absolute number we use the fact that 4.3 billion passengers were carried on scheduled services in 2018 according to ICAO, (2019) (see Section 2.2) and that the global average ticket price is equal to € 600 (eTN, 2019). The change in consumer surplus amounts to € -0.04 million, € -0.11 million and € -9 million for HT1, HT2 and HT3 respectively.

5 InterVISTAS provides a methodology to calculate the relevant price elasticity that should be used in a specific context. This methodology is composed of three components: base elasticity, specific markets and short- vs. long-haul. The base elasticity relates to the geographic scope. As the geographic scope is global, we use a base elasticity of -0.6. When looking at specific countries or routes the base elasticity becomes more negative (e.g. -0.8 and -1.4 respectively). When looking at specific aviation markets, a multiplier is used to adjust for difference in income (e.g. is aviation a luxury good) between regions and aviation market structure (e.g. presence of many low cost carriers). The multipliers vary from 0.6 (e.g. transpacific flights or intra Sub-Saharan Africa flights) to 1.4 (e.g. intra-European flights). As the scope of this project is global, we do not use a multiplier to control for the geographic aviation market in this context. Lastly, because of this global scope, we also do not need a short-haul adjustment multiplier (1.1). This leaves us with merely the base elasticity of -0.6 which we use in this study.

Table 11 – Overview of changes in consumer surplus

	Jet A-1	HT 1	HT 2	HT 3
Price of fuel (€/l)	0.57			
Additional price (€/l)		0.00053	0.00089	0.00823
Total fuel price (€/l)	0.57	0.57053	0.57089	0.57823
% change in fuel price compared to Jet A-1		0.1%	0.2%	1.5%
% of fuel costs in ticket price	23.5%	23.5%	23.5%	23.5%
% change in total ticket price		0.02%	0.04%	0.34%
Average ticket price (€)	600	600.13	600.22	602.05
Price elasticity of demand		-0.6	-0.6	-0.6
% change in demand		-0.01%	-0.02%	-0.20%
Passengers carried in 2018 (billion)	4.3	4.3	4.3	4.3
Change in passengers (million)		-0.57	-0.95	-8.80
Change in consumer surplus (million €)		**-0.04**	**-0.11**	**-9.00**

Second order consumer surplus effects

Next to these first order consumer surplus effects, there are also potential second order effects on consumer surplus. These second order effects arise from airline supply reactions and are frequently not taken into account in analyses (Burghouwt, 2016). The increased costs of the alternative aviation fuels leads to a decrease in demand, which may cause the occupancy rate of a flight to drop below the break-even load factor. This in turn could force airlines to cut frequencies or cancel routes, as lumpy seat capacity implies airlines are unable to adjust capacity to demand at short notice (Burghouwt, 2016). These supply side effects may also affect the welfare of consumers, for example, because they have to fly at less preferred times. Although we acknowledge that these second order effects may play a role, we are unable to quantify them here (because of lack of data).

Consumer surplus for freight aviation

In essence, the consumer surplus for freight aviation could be calculated in the same manner as for passenger aviation, i.e. using the rule of half. However, there is a lot less data about freight. For instance, to our knowledge there is no data about the price elasticity of demand for freight, and hence we do not know how responsive clients in the cargo sector are to higher prices. If such data would be available, the change in consumer surplus for freight aviation could be calculated. However, as this data is not available, we put these costs on PM.

3.5 External effects

3.5.1 Air pollution

The burning of aviation fuel results in the emission of a number of pollutants, such as $PM_{2.5}$, NO_x and SO_2. These pollutants have a notable effect on air pollution levels, which affect human health, biodiversity and crop yields. We quantify the effects of a switch to the alternative fuels on air pollution in this section.

The average damage cost estimates for aviation emissions are given in Table 12. A full description of how these values are calculated is given in Annex B. We use these values to monetise the physical impacts of the change in the fuel used. As is shown by Table 12, the values cover both the human health and other negative impacts of air pollutant emissions, and they consider the differences in the negative impacts of emissions exhausted at the LTO phase and the climb/descent/cruise phase. It should be noticed that the damage cost factors for $PM_{2.5}$ should be considered conservative estimates, as they do not differentiate between $PM_{2.5}$ and ultrafine particles (which are more damaging) and as the various chemical compositions of particulate matter are not taken into account (recent scientific evidence suggests that black carbon is more damaging than other types of particulate matter). For more information on this issue, see Annex B.

Table 12 – Average damage cost estimates for emissions from aviation in €/kg emissions

	$PM_{2.5}$	NO_X	SO_2
Human health			
LTO	40.82	8.76	4.77
Climb, descent, cruise	1.48	0.43	0.30
Non-human health impacts			
LTO	0.00	0.64	0.29
Climb, descent, cruise	0.00	0.17	0.07
All impacts combined			
Global average	6.60	1.75	0.97

Table 13 provides an overview of the steps in the calculation of the effect of a large scale switch to hydro-treated fuels on air pollution. The effect is comprised of the individual effects of three different pollutants, SO_2, $PM_{2.5}$ and NO_x. As a first step, we have taken the global fuel use[6] for each of the scenarios (from Section 3.3.2) and allocated this to the LTO phase and climb, descent and cruise phase based on Owen et al., (2020). In a next step, we estimated the change in SO_2 and $PM_{2.5}$ emission costs using a similar approach. With help of the refinery model PRELIM 1.3, we estimated the SO_2 and $PM_{2.5}$ content of the various types of fuels. Combining this information with data on global fuel use and the relevant damage cost factors, the change in economic costs due to the SO_2 and $PM_{2.5}$ emissions are calculated.

As the hydro-treated fuels have lower emissions of SO_2 compared to conventional Jet A-1 fuel, this results in a net benefit in the social cost-benefit analysis. The first two types of hydro-treated fuels have black carbon emissions that are identical to the black carbon emissions in conventional Jet A-1 fuel. The third hydro-treated fuel (HT3) however, has lower black carbon emissions compared to Jet A-1 fuel, implying a net benefit in the social cost-benefit analysis. For NO_x, there does not appear to be consensus in the scientific world as to what happens to the NO_x emissions of hydro-treated fuels. Some measurements report higher NO_x emissions for hydro-treated fuels compared to conventional Jet A-1 fuel, whereas others report a decrease. As there is no consensus in the scientific literature, we have therefore chosen to assume that there is no difference in the NO_x emissions of the hydro-treated fuels compared to the conventional Jet A-1 fuel.

[6] As explained in Section 3.3.2, the fact that global fuel consumption is reduced because of a drop in demand for air transport (due to higher ticket prices resulting from higher fuel costs) is not taken into account in the various project scenarios. The impact of this assumption is assessed by a sensitivity analysis in Section 4.3.2.

Table 13 – Overview of changes in air pollution

		HT1	HT2	HT3
Global fuel use in the various scenarios (allocated to flight phases)				
Global fuel use (million l)	363,035	362,666	362,164	360,419
Global fuel use - LTO (million l)	47,195	47,147	47,081	46,855
Global fuel use - Climb, descent and cruise (million l)	315,840	315,520	315,083	313,565
Estimation of the change in SO_2 emissions costs				
SO_2 (g per litre of fuel)	0.2432	0.0368	0.0050	0.0111
Global SO_2 emissions (tons) - LTO	11,478	1,737	236	519
Difference in global SO_2 emissions (tons) - LTO (Compared to Jet A-1)		-9,741	-11,242	-10,959
Difference in global SO_2 emissions (mln €) - LTO (Compared to Jet A-1)		-49	-57	-55
Global SO_2 emissions (tons) - Climb, descent and cruise	76,815	11,625	1,578	3,471
Difference in global SO_2 emissions (tons) - Climb, descent and cruise (Compared to Jet A-1)		-65,190	-75,236	-73,344
Difference in global SO_2 emissions (mln €) - Climb, descent and cruise (Compared to Jet A-1)		-24	-28	-27
Total difference in global SO_2 emission costs (mln €) (Compared to Jet A-1)		**-73**	**-85**	**-83**
Estimation of the change in $PM_{2.5}$ emissions costs				
$PM_{2.5}$ (g per litre of fuel)	0.024	0.024	0.024	0.021
Global $PM_{2.5}$ emissions (tons) - LTO	1,144	1,143	1,141	984
Difference in global $PM_{2.5}$ emissions (tons) - LTO (Compared to Jet A-1)		-1	-3	-160
Difference in global $PM_{2.5}$ emissions (mln €) - LTO (Compared to Jet A-1)		-0.05	-0.11	-7
Global $PM_{2.5}$ emissions (tons) - Climb, descent and cruise	7,656	7,648	7,638	6,587
Difference in global $PM_{2.5}$ emissions (tons) - Climb, descent and cruise (Compared to Jet A-1		-8	-18	-1,069
Difference in global $PM_{2.5}$ emissions (mln €) - Climb, descent and cruise (Compared to Jet A-1)		-0.01	-0.03	-2
Total difference in global $PM_{2.5}$ emission costs (mln €) (Compared to Jet A-1)		**-0.06**	**-0.14**	**-8**
Estimated total change in air pollutant costs				
Total impact on air pollution costs (mln €)		**-73**	**-85**	**-91**

In total, the net benefits of hydro-treated fuels on air pollution levels amount to € 73 million, € 85 million and € 91 million for HT1, HT2 and HT3 respectively. The monetary benefits of lower sulphur emissions is the largest component.

3.5.2 GHG emissions

The climate impact of aviation is determined by both CO_2 and non-CO_2 emissions. The CO_2 emissions from aviation have a long term warming impact. Non-CO_2 emissions tend to have a shorter term impact that may be warming or cooling. To calculate the climate change impacts from a global switch to low-sulphur, low-naphthalene and low-aromatics fuels we need to know the change in emissions (for each type of emissions)and the global warming potential (GWP_{100}) of each type of emissions. The global warming potential measures the radiative forcing of a pulse emission of a gas, integrated over 100 years, relative to the radiative forcing of a pulse emission of carbon dioxide integrated over 100 years (the latter is set to 1) (Fuglestvedt et al., 2010). Based on their GWP compared to the GWP of CO_2, we can then monetise the various emissions with the CO_2 price. We treat each greenhouse gas individually in the next sections.

Carbon dioxide

The GWP_{100} of CO_2 is 1 according to Lee et al., (2010) and the level of scientific understanding around it is high. Based on the carbon content of conventional Jet A-1 fuel, under full combustion 2.59 kilo of CO_2 per litre kerosene is emitted. For the hydro-treated fuels, 2.55 ton of CO_2 is emitted per litre of kerosene (based on the PRELIM 1.3 model). Using a CO_2 price of € 104 per tonne (CE Delft et al., 2019) and the global fuel use as provided in Section 3.3.2, the total change in the costs of CO_2 emissions are estimated (see Table 14).

Table 14 - Overview of changes in carbon dioxide

	Jet A-1	HT1	HT2	HT3
Global fuel use (million l)	363,035	362,666	362,164	360,419
Kg of CO_2 emitted per litre of kerosene	2.59	2.55	2.55	2.55
Global CO_2 emissions (Mton)	942	926	925	920
Difference in global CO_2 emissions compared to Jet A-1 (Mton)		-16	-17	-21
CO_2 price (€/ton)[7]		104	104	104
Total impact on CO_2 emissions (mln €)		**-1,618**	**-1,750**	**-2,212**

Sulphate particles

As we have seen in Section 3.5.1, the use of the alternative fuels leads to lower sulphur emissions. We assume that each atom of sulphur emitted turns into SO_4, which has a GWP_{100} of -40 according to Lee et al., (2010). Sulphur therefore has a global cooling potential. Reducing the sulphur content of the fuel leads to warming and is hence considered a cost in the social cost-benefit analysis.

The monetary impact of the change in sulphur emissions is calculated according to the following formula:

$$\begin{aligned} &Impact\ of\ sulphate\ (€) \\ &\quad = \Delta\ Global\ sulphur\ emissions\ (ton) \times \frac{molecular\ mass\ of\ sulphate}{atomic\ weight\ of\ sulphur} \\ &\quad \times GWP_{100}SO_4 \times CO_2\ price \end{aligned}$$

where:
- the change in global sulphur emissions follows from the calculations in Section 3.5.1;
- the molecular mass of sulphate is 96.06;
- the atomic weight of sulphur is 32.065;
- the GWP_{100} of SO_4 is -40;
- the price of CO_2 is € 104 per ton.

7 For more information on the CO_2 price, please see Section 3.5.3.

Table 15 provides an overview of the steps used in the calculation. In the last line of Table 15 the additional climate costs due to the reduced sulphate emissions are shown.

Table 15 – Overview of changes in sulphate particles

	Jet A-1	HT1	HT2	HT3
Difference in total global SO_2 emissions (kton) - Compared to Jet A-1[8]	0	-75	-86	-84
CO_2-eq. (kton)		2,997	3,459	3,372
CO_2 price (€/ton)		104	104	104
Total impact on sulphate particles (mln €)		**931**	**1,074**	**1,047**

Black carbon particles

Black carbon is a component of fine particulate matter ($PM_{2.5}$). All aviation related $PM_{2.5}$ is black carbon. As we have seen in Section 3.5.1 the use of hydro-treated fuels leads to the same levels of $PM_{2.5}$ emissions for the first two types of hydro-treated fuels (hence identical black carbon emissions). The third type of hydro-treated fuel has lower black carbon emissions than Jet A-1 fuel. As the GWP_{100} of black carbon particles is 460 (Lee et al., 2010), the use of hydro-treated fuels has a global cooling effect and is hence considered a benefit in the social cost-benefit analysis.

The monetary impact of the change in black carbon emissions is calculated as follows.

$$\begin{aligned} &Impact\ of\ black\ carbon\ (€) \\ &\qquad = \Delta\ Global\ black\ carbon\ emissions\ (ton) \times GWP_{100}BC \times CO_2\ price \end{aligned}$$

Where:
- the change in global black carbon emissions follows from the calculations in Section 3.5.1, under the assumption that all emitted $PM_{2.5}$ is black carbon;
- the GWP_{100} of black carbon is 460;
- the price of CO_2 is € 104 per ton.

Table 16 provides an overview of the steps in the calculation. Again, the additional climate benefits due to the lower black carbon emissions are shown in the last row of the table.

Table 16 - Overview of changes in black carbon emissions

	Jet A-1	HT1	HT2	HT3
Difference in total global $PM_{2.5}$ emissions (kton) - Compared to Jet A-1[9]	0	0	0	-1
CO_2-eq. (kton)		-4	-10	-565
CO_2 price (€/ton)		104	104	104
Total impact on sulphate particles (mln €)		**0**	**-1**	**-59**

[8] These follow from the calculations in Section 3.5.1.

[9] These follow from the calculations in Section 3.5.1.

NO_x

As we have outlined in Section 3.5.1 there is no scientific consensus on whether the NO_x emissions from hydro-treated fuels are higher or lower than from conventional Jet A-1 fuel. We have therefore chosen to assume that there is no difference in the NO_x emissions of the hydro-treated fuels compared to the conventional Jet A-1 fuel.

Furthermore, the level of scientific understanding on the global warming potential of NO_x is very low. Estimates for the GWP_{100} of NO_x ranges from -2.1 in the low to 71 in the high scenario according to Lee et al., (2010). Hence, even if there was information on the emissions of NO_x from hydro-treated fuels, any estimate of the climatic and monetary impact of NO_x would be highly uncertain.

H_2O

The carbon to hydrogen ratio of the hydro-treated fuels is different than for conventional Jet A-1 fuel. Therefore, there will also be a change in the emissions of water vapour. However, the magnitude of this effect is not well characterised in the scientific literature. In addition, the direct radiative effect of water vapour in the atmosphere is very small. (according to Lee et al., (2010) the GWP_{100} of H_2O is 0.14). We therefore assume there are no effects on water vapour emissions associated with a switch to hydro-treated fuels.

Aviation-induced cloudiness

Aviation-induced cloudiness is the umbrella term for contrails and contrail cirrus. Condensation trails (contrails) are line-shaped ice clouds generated by jet aircraft cruising in the upper troposphere at 8–13 km altitude. The GWP_{100} of aviation-induced cloudiness is 0.63 according to Lee et al., (2010). The level of scientific understanding of this phenomenon is very low, and there are only few studies that investigate the effect of reductions in aromatics, naphthalene and sulphur content of fuels on aviation-induced cirrus. One of these studies revealed that a reduction in the number of soot particles (black carbon or $PM_{2.5}$) emitted by aircraft engines decreases the number of ice crystals in contrails, which in turn reduced the climate impact of contrail cirrus. A reduction in the soot number emissions of 50% decreases the radiative forcing by approximately 15% (Bock & Burkhardt, 2019). This relationship is non-linear when very low numbers of soot are considered. However, in this study the maximum reduction in $PM_{2.5}$ emissions is 13% for HT3, hence we use the relationship that each percentage point reduction in soot emissions leads to 0.3% reduction in radiative forcing.

Based on discussions with climate experts we have concluded that the best way to identify the impacts of a large-scale switch to hydro-treated fuels is to scale down the GWP of aviation-induced cloudiness mentioned in Lee et al., (2010) based on the relationship identified by Bock & Burkhardt, (2019).

Table 17 provides an overview of the steps in the calculation. The additional climate benefits due to the lower black carbon emissions are shown in the last line of the table.

Table 17 – Overview of changes in aviation-induced cloudiness

	Jet A-1	HT1	HT2	HT3
% difference in PM emissions	0%	0%	0%	-13%
% reduction in radiative forcing		0	0	-4%
Adjusted GWP for AIC	0.63	0.63	0.63	0.6048
Difference in total global BC emissions (kton) - Compared to Jet A-1		0	0	-1
CO_2-eq. (kton)		-0.01	-0.01	-0.74
CO_2 price (€/ton)		104	104	104
Total impact on contrails (mln €)		**0.0**	**0.0**	**-0.1**

Total climate impact

The total climate impact is summarised in Table 18.

Table 18 - Overview of total climate impact

	Jet A-1	HT1	HT2	HT3
Total CO_2 impact (mln €)	0	-1,618	-1,750	-2,212
Total impact of sulphate particles (mln €)	0	931	1,074	1,047
Total BC impact (mln €)	0	0	-1	-59
Total impact on contrails (mln €)	0	0.0	0.0	-0.1
Total climate impact (mln €)	**0**	**-687**	**-677**	**-1,224**

3.5.3 Emissions from fuel production

As shown in Section 3.3.1, the hydro-treatment of the three types of alternative aviation fuels requires additional amounts of natural gas and electricity, resulting in additional emissions related to the production of the fuels. In this subsection, we quantify and monetise the extra amount of CO_2 emissions due to the hydro-treatment of the fuels. This process also results in additional air pollutant emissions. However, the damage caused by these emissions depends heavily on the location of the refinery and as we don't know these locations we are not able to quantify this damage[10].

To monetise the additional CO_2 emissions from the hydro-treatment of the fuels, we start with the amounts of natural gas and electricity required per ton of kerosene. We have summarised this in the first two rows of Table 20 (see Section 3.3.1 for more details). To monetise the environmental impact of hydro-treating the fuel, we first need to translate the additional electricity and natural gas used to the extra amount of CO_2 used. This is done using the CO_2-equivalent emission factors detailed in Table 19.

Table 19 - CO_2-equivalent emission factors of electricity and natural gas

Primary resource	CO_2-eq. emission factors
Electricity (NG gas plant)	548.8 g CO_2-eq./kWh
Natural gas	2,372 g CO_2-eq./m^3

10 We expect this effect to be very small and hence not taking it into account in the SCBA will not significantly affect the results of the overall analysis.

The emission factor for electricity is taken from the refinery model PRELIM 1.3.
The emission factor for natural gas is composed of a well-to-tank (WTT) part and a tank-to-wheel (TTW) part. The WTT part is taken from the EcoInvent database (EcoInvent, ongoing), and the TTW part from list of energy carriers by the Netherlands Enterprise Agency (RVO, 2018). This was done due to data limitations: there is no emission factor for the global average natural gas. It is thus important to note that the TTW part is based on Dutch gas, which is low calorific gas. This implies that the estimate of the CO_2-equivalent emissions from the additional natural gas used is a conservative estimate.

By combining the additional amounts of electricity and natural gas used in the production of the three fuels with the CO_2-equivalent emission factors one reaches the total additional CO_2-equivalent emissions per ton of fuel produced. Using the density of kerosene of 0.808 kg/l we can convert the additional CO_2-equivalent emissions per ton of fuel to the additional CO_2-equivalent emissions per litre of fuel. To reach the global total additional CO_2-equivalent emissions, we multiply the emissions per litre of fuel with the global fuel use from Table 10. These figures take into account the fact that less fuel is needed globally if a transition to these three types of fuel takes place (because of the higher energy intensity of the alternative fuels compared to the regular JET A.1 fuel.

The last step involves translating the global total additional CO_2-equivalent emissions from mass units into monetary units. This is done using a global CO_2 price, which we take from the European Commission's Handbook of External Costs of Transport (CE Delft et al., 2019). This price is set at € 100 per ton of CO_2-equivalents (2016 prices). Updating the price level to 2018 implies a CO_2 price of € 104.

Table 20 – Overview of the emissions from fuel production

	HT1	HT2	HT3
Additional electricity used per ton of fuel (kWh)	2.7	3.5	18
Additional natural gas used per ton of fuel (m^3)	4.1	6.0	43
CO_2-eq. emissions from additional electricity used per ton of fuel (kg)	1.48	1.92	9.88
CO_2-eq. emissions from additional natural gas used per ton of fuel (kg)	9.72	14.23	101.98
Total additional CO_2-eq. emissions (kg) per ton of fuel	11.21	16.15	111.86
Total additional CO_2-eq. emissions (kg) per litre of fuel	0.014	0.020	0.138
Global total additional CO_2-eq. emissions (kg)	5,030	7,239	49,896
Global total additional CO_2-eq. emissions (mln €)	0.0005	0.0008	0.0052

4 Results

4.1 Introduction

This chapter gives an overview of the results of the social cost-benefit analysis. A comparison of the various costs and benefits, as discussed in Chapter 3, is made in Section 4.2. To test the robustness of these results, some sensitivity analyses are carried out in Section 4.3.

4.2 Overview of results

An overview of the results of the social cost-benefit analysis is presented in Table 21. The results are presented as additional annual costs for the year 2018 (price level 2018).

Table 21 - Overview SCBA results (compared to the baseline scenario, mln €, 2018 price level)

Type of effects	Specific effects	HT1	HT2	HT3
Direct effects	Additional costs of advanced aviation fuels	192	322	2,966
	Fuel costs savings	-209	-494	-1,484
	Maintenance costs	- PM	- PM	- PM
	Retrofit costs	+ PM	+ PM	+ PM
Indirect effects	Change in consumer surplus	0.04	0.11	9.00
	Change in producer surplus	0	0	0
External effects	Air pollution	-73	-85	-91
	GHG emissions	-687	-677	-1,224
	Emissions from fuel production	0.00	0.00	0.01
Net results	**Costs minus benefits**	**-778 +/- PM**	**-934 +/- PM**	**177 +/- PM**

From Table 21 it becomes clear that both the use of alternative fuels HT1 and HT2 results in net social benefits, particularly due to significant fuel cost savings and reductions in GHG emissions. These benefits are highest for the HT2 fuel, which is mainly because the use of this fuel results in significantly higher fuel cost savings than using the HT1 fuel. The use of the alternative fuel HT3 results in additional social costs, which is mainly caused by the high additional costs of the extra removal of aromatics required to produce this fuel. These additional production costs are considerably higher than the additional fuel cost savings and GHG emission reductions achieved by using this fuel.

In this project we have not been able to quantify (and monetise)the impact of the use of the alternative aviation fuels on the maintenance and retrofit costs. For that reason, both the change in maintenance and retrofit costs are considered as a (respectively negative and positive) PM post in this SCBA. We do, however, expect that these effects will not change the sign of the net results (i.e. costs minus benefits) of the three scenarios.

An important conclusion that can be drawn from Table 21 is that even from a business perspective, the alternative fuels HT1 and HT2 results in net benefits compared to the regular JET A1 fuel. The fuel cost savings that could be achieved by using these fuels do more than compensate for the additional costs of producing these fuels. However, it should be noticed that particularly for HT1 the additional production costs and the fuel cost savings are in the same order of magnitude, such that including the maintenance and retrofit costs into the quantitative analysis may change the conclusions (from the business perspective).

Finally, Table 22 presents the net results of the SCBA in terms of €ct per litre of fuel and as share of the price of JET A.1 fuel. This way of presenting the final results of the analysis shows that the net social benefits/costs of the three alternative aviation fuels are relatively small.

Table 22 – Net results in €ct/litre fuel and as share of the price of JET A.1 fuel (compared to baseline scenario, 2018 price level

	HT1	HT2	HT3
Net results (in €ct/litre of fuel)	-0.2 +/- PM	-0.3 +/- PM	0.05 +/- PM
Net results as share of price of reference JET A.1 fuel	-0.4%	-0.4%	0.1%

4.3 Sensitivity analyses

The results of the SCBA presented in the previous section rely on a number of assumptions, which are subject to some extent of uncertainty. In order to test the robustness of the SCBA (in particular, whether the conclusions drawn are significantly altered by departures from these assumptions) some sensitivity analyses have been carried out, i.e. for:
- the natural gas price;
- the reduction in fuel use because of lower demand for air transport;
- the black carbon content of the alternative aviation fuels;
- the CO_2 price.

4.3.1 Natural gas price

As was shown in Section 3.3.1, the additional production costs of the alternative aviation fuels consists in the end of the additional costs of natural gas and electricity required for the hydro-treatment. For both natural gas and electricity we have estimated the additional costs by using an average price for both the EU and the US. Particularly for natural gas the average price differs significantly between the US and the EU. In the US the average natural gas price is equal to € 0.13 per m^3, while in the EU this is € 0.33 per m^3. In our analysis we have used an average for both the EU and the US of € 0.23 per m^3. In this sensitivity analysis we assess the impact of applying both the US and EU average natural gas price on the results of the SCBA.

The results of the sensitivity analysis are presented in Table 23. It becomes clear that the natural gas price has a significant impact on the additional production costs of the alternative aviation fuels. Applying the US natural gas price lowers the production costs by 40 to 60%, while applying the EU natural gas price results in 40 to 60% higher production costs. These relatively large impacts on the production cost also significantly affect the net results of the analysis. But only in the case of HT3 it also affects the conclusions drawn as in case of a low natural gas price the use of HT3 fuel results in net social benefits. As for the scenarios with HT1 and HT2 fuels, the conclusions are robust with respect to the natural gas price.

Table 23 – Results sensitivity analysis natural gas price (compared to the baseline scenario, mln €, 2018 price level)

Cost item	Sensitivity analysis	HT1	HT2	HT3
Additional costs of advanced aviation fuels	Natural gas price from main analysis (0.23 €/m^3)	192	322	2,966
	US natural gas price (0.13 €/m^3)	76	144	1,731
	EU natural gas price (0.33 €/m^3)	308	500	4,200
Net results	Natural gas price from main analysis (0.23 €/m^3)	-778	-934	177
	US natural gas price (0.13 €/m^3)	-894	-1,112	-1,088
	EU natural gas price (0.33 €/m^3)	-662	-756	1,411

4.3.2 Reduction in fuel use because of lower demand for air transport

In the main analysis we have identified that one of the effects from a switch to hydro-treated fuels is a reduction in demand for air transport. This effect is treated in Section 3.4.2. However, as a result of this drop in demand, airlines are also likely to reduce their fuel consumption (either because they will cut routes or frequency or because planes are less full). As airlines' responses to higher fuel costs are difficult to estimate, without in-depth knowledge of company strategy, we have assumed no change in fuel consumption in the main analysis. However, for the sensitivity analysis we have assumed that the percentage reduction in passengers corresponds to the percentage reduction in fuel use. This is 0.01, 0.02 and 0.2% reduction for HT1, HT2 and HT3 respectively. It would be clear that this assumption leads to an overestimation of the reduction of fuel consumption, as the fuel consumption will very probably decrease less than linearly with a drop in demand for air transport. However, it gives a first indication of the impact this effect may have on the results of the SCBA. The results of this sensitivity analysis are shown in Table 24.

Table 24 - Results sensitivity analysis fuel use reduction from lower demand (compared to the baseline scenario, mln €, 2018 price level)

Cost item	Sensitivity analysis	HT1	HT2	HT3
Additional costs of advanced aviation fuels	No fuel use reduction from lower demand	192	322	2,966
	Fuel use reduction from lower demand	192	322	2,960
Fuel cost savings	No fuel use reduction from lower demand	-209	-494	-1,484
	Fuel use reduction from lower demand	-236	-539	-1,902
Air pollution	No fuel use reduction from lower demand	-73	-85	-91
	Fuel use reduction from lower demand	-73	-85	-91
GHG emissions	No fuel use reduction from lower demand	-687	-677	-1,224
	Fuel use reduction from lower demand	-700	-699	-1,419
Emissions from fuel production	No fuel use reduction from lower demand	0.00	0.00	0.01
	Fuel use reduction from lower demand	0.00	0.00	0.01
Net results	No fuel use reduction from lower demand	-778	-934	177
	Fuel use reduction from lower demand	-818	-1,000	-443

As is shown by Table 24 the main conclusions for the HT1 and HT2 fuels are robust for the changes in the assumption on fuel use reduction due to lower demand. As in the main analysis the use of these fuels result in net social benefits. With respect to HT3, the main conclusions do change when using this different assumption on fuel use reduction. While in the main analysis the use of HT3 fuel results in net social costs, in this case its use results in net social benefits.

4.3.3 Black carbon emissions of alternative aviation fuels

In the main analysis we have made the conservative assumption that aircrafts, on average, fly using 30% thrust. At that level of thrust, according to Brem et al., (2015), the reduction in the emission index of black carbon is 0.000286 g/kg per percentage point reduction in the aromatics content of the fuel. The same publication specifies that the mass of black carbon is determined by the aromatics content of the fuel and is independent of the naphthalene content. In the main analysis we have therefore used the black carbon emissions of 0.03 g/kg for HT1 and HT2, and 0.026 g/kg for HT3.

If one were to let go of the conservative assumption that aircrafts, on average, fly at 30% thrust, one could use the figures associated with 65% thrust. In that case the black carbon emissions of the fuel would be 0.03 g/kg, 0.027 g/kg and 0.014 g/kg for HT1, HT2 and HT3 respectively. We have carried out a sensitivity analysis to see the impact of these lower black carbon emissions. The results are shown in Table 25.

Table 25 - Results sensitivity analysis black carbon emissions (compared to the baseline scenario, mln €, 2018 price level)

Cost item	Sensitivity analysis	HT1	HT2	HT3
Air pollution	BC emissions at 30% thrust	-73	-85	-91
	BC emissions at 65% thrust	-73	-91	-114
GHG emissions	BC emissions at 30% thrust	-687	-677	-1,224
	BC emissions at 65% thrust	-687	-719	-1,391
Net results	BC emissions at 30% thrust	-778	-934	177
	BC emissions at 65% thrust	-778	-981	-13

As for the previous sensitivity analyses, it is shown that the main conclusions for the HT1 and HT2 scenarios are rather robust. In all cases, these scenarios result in net social benefits. The larger air pollution and GHG emission benefits result in net social benefits for the HT3 scenario as well (in contrast to the main analysis, where net social costs were found for this scenario).

4.3.4 CO_2 price

In the main analysis the changes in GHG emissions are monetised by using the recommended central CO_2 price from the European Handbook on external costs of transport (CE Delft et al., 2019). This CO_2 price was based on an extensive literature review on the avoidance cost of CO_2 emissions. This review also shows that the range of avoidance cost values is rather large and hence it was recommended to apply sensitivity analyses using a lower and higher value for the CO_2 price. The recommended CO_2 prices by the Handbook are presented in Table 26.

Table 26 - Recommended CO_2 prices (€/tonne) for the short and medium term (up to 2030)

Base year	Low	Central	High
2016	60	100	189
2018	64	104	193

In order to assess the impact of the CO_2 price on the SCBA, we have carried out two sensitivity analyses: one applying a lower CO_2 price of € 64 per tonne, and one applying a higher CO_2 price of € 193 per tonne. The results of this sensitivity analysis are shown in Table 27. They show that the overall conclusions on HT1 and HT2 are rather robust with respect to the level of CO_2 price applied. However, with respect to HT3, using a higher CO_2 price of € 193 per tonne results in net social benefits (where in the in the main analysis using HT3 results in net social costs).

Table 27 - Results sensitivity analysis CO_2 price (compared to the baseline scenario, mln €, 2018 price level)

Cost item	Sensitivity analysis	HT1	HT2	HT3
GHG emissions	Central CO_2 price (€ 104 per tonne)	-687	-677	-1,224
	Low CO_2 price (€ 64 per tonne)	-422	-416	-751
	High CO_2 price (€ 193 per tonne)	-1,278	-1,259	-2,257
Emissions from fuel production	Central CO_2 price (€ 104 per tonne)	0.00	0.00	0.01
	Low CO_2 price (€ 64 per tonne)	0.00	0.00	0.00
	High CO_2 price (€ 193 per tonne)	0.00	0.00	0.01
Net results	Central CO_2 price (€ 104 per tonne)	-778	-934	177
	Low CO_2 price (€ 64 per tonne)	-513	-672	649
	High CO_2 price (€ 193 per tonne)	-1,368	-1,515	-874

5 Conclusions

5.1 Main conclusions of the SCBA

The social cost-benefit analysis carried out in this study provides evidence that from a social perspective the use of low-sulphur, low-naphthalene fuels (HT1 and HT2) in aviation is preferred to the use of the regular JET A.1 kerosene. The higher production costs of these fuels are outweighed by particularly lower fuel costs (due to the higher energy intensity of these fuels) and lower costs of GHG emissions. These findings seem to be robust under various alternative assumptions made in the analysis.

The use of a low-sulphur, low-aromatics, low-naphthalene fuel (HT3) results in higher social costs compared to the regular JET A.1 kerosene. This is because the removal of the aromatics from the fuel requires a lot of additional natural gas and electricity in the refinery and hence results in relatively high production costs. Under the assumptions made in the SCBA, these additional production costs are not compensated for by the fuel cost savings and the various environmental benefits. However, it should be noticed that the various sensitivity analyses carried out in this study show that under alternative assumptions (e.g. a lower natural gas price, a higher CO_2 price) also the use of a low-sulphur, low-aromatics, low-naphthalene fuel may lead to net social benefits. It is therefore recommended to further study some of the assumptions underlying the analysis for this fuel type before drawing any final conclusions.

An interesting result from the assessments carried out in the previous chapters is that the low-sulphur, low naphthalene fuels (HT1 and HT2) seems not only to be preferred to the regular JET A.1 kerosene from a social perspective, but also from a business perspective. The fuel cost savings that could be achieved by using these fuels do more than compensate for the additional costs of producing these fuels. However, it should be noticed that not all operational costs of using these fuels have been quantified (i.e. maintenance and retrofit costs) and that adding these cost items to the calculation may alter the conclusions on this issue.

5.2 Recommendations

This study provides a social cost-benefit analysis of using low-sulphur, low-aromatic, low-naphthalene fuels in aviation. The assessments carried out are based on solid scientific grounds and — within the scope of the study — the best available data has been used to quantify and monetise the various impacts. However, there may be several options to improve or elaborate the analysis:

— *Additional research on the production capacity of alternative aviation fuels*.
  As mentioned in Section 1.3, we have assumed that no additional refinery capacity have to be build neither that structural changes to the existing refineries have to be made to produce the alternative aviation fuels. Although this assumption seems valid for the purpose of this study (i.e. comparing the costs and benefits of alternative aviation fuels with the regular JET A.1 kerosene), it would be interesting to study the capacity that is currently available in existing refineries for the hydro-treatment of fuels. This would provide an indication of the volume of alternative aviation fuels that could be produced for the production costs assumed in this study.

- *Additional research on the additional production costs of alternative aviation fuels.* In this study, the additional production costs are estimated by the refinery model PRELIM 1.3. However, all refineries differ in their structures and the type of processes that are applied and hence in the costs that are related to the hydro-treatment of the fuels. For that reason, it would be very interesting to study in more detail for some existing refineries which processes have to be applied to desulpharise jet fuel and what are the costs of these processes. As the additional production costs are an important cost item in the SCBA, this would be a good option to further improve the robustness of the SCBA.
- *Additional research on the impact of changes in demand for air transport on total fuel consumption.* A switch to hydro-treated fuels may result in a reduction in demand for air transport (because of the higher fuel costs ticket prices may be increased). As a results of this drop in demand, airlines are likely to reduce their fuel consumption applying operational measures like cutting routes or frequency of flights. As mentioned in Section 3.3.2, we were not able to quantify this impact on total fuel consumption, although it may have a significant effect on the results of the SCBA (see Section 4.3.2). Therefore it is recommended to assess this impact in more detail, e.g. by applying a global aviation model.
- *Additional research on the maintenance and retrofit costs.* In the current SCBA we have placed these cost items as PM post in the analysis. Additional research on these cost items would be recommended in order to be able to quantify them.
- *Additional research on the damage costs of air pollution.* In this study we have applied rather sophisticated damage cost factors to monetise the air pollution impacts. However, there is still some room to improve these factors, e.g. by differentiating between $PM_{2.5}$ and ultrafine particles and by taking the specific chemical composition of particulate matter of aviation into account. Also a further breakdown of damage cost factor to the various stages of the flight cycle may be an option to further improve the analysis.
- *Additional research on the global warming potential of non-CO_2 emissions;* as already discussed briefly in Section 3.5.2, there is still quite some discussion in the scientific literature on the impact of non-CO_2 emissions of aviation on climate change. More research on this issue is therefore recommended.

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A Overview of key figures used

Table 28 – Overview of key figures used in this study

Figure	Value	Source
Global fuel use in 2018 (million litres)	363,035	ICCT, (2019)
Passengers carried in 2018 (billion)	4.3	ICAO, (2019)
Density of kerosene (kg/l)	0.808	PRELIM Model 1.3
Price of Jet A-1 fuel (€/l)	0.57	IATA, (ongoing)
Central CO_2 price ($€_{2018}$/ton CO_2-equivalent)	103.63	CE Delft et al., (2019) updated to 2018 prices
Low CO_2 price ($€_{2018}$/ton CO_2-equivalent)	63.63	CE Delft et al., (2019) updated to 2018 prices
High CO_2 price ($€_{2018}$/ton CO_2-equivalent)	192.63	CE Delft et al., (2019) updated to 2018 prices

B Air pollution damage costs for aviation

B.1 Introduction

In this Annex we discuss the way the environmental prices used to monetise the air pollution impacts of the shift to alternative aviation fuels have been determined. We start in Annex B.2 by briefly discussing the concept of environmental prices. The aim and scope of the analyses carried out in this Annex is presented in Annex B.3. In Annex B.4 we briefly explain the methodology that has been applied to calculate the specific environmental prices for this study. The assessments done and the results of these assessments are discussed in Annexes B.5 to B.7. Finally, in Annex B.8 an overview of the environmental prices used in the SCBA is given.

B.2 Environmental prices for air pollution

Environmental prices are prices for the social cost of pollution, expressed in Euros per kilogram pollutant. Environmental prices indicate the loss of economic welfare that occurs when one additional kilogram of the pollutant finds its way into the environment. The loss in human health, ecosystem services and quality of buildings and materials that is caused by pollution is captured in a single monetary unit that can be used in social cost-benefit analysis, environmental profit and loss accounts and as a weighting factor in lifecycle analysis.

In the Handbook Environmental Prices (CE Delft, 2018), CE Delft presents environmental prices for over 2,000 pollutants in the EU28. The calculation of these environmental prices was based on a spatial dispersion model that was used in the NEEDS project ((Desaigues et al., 2007). Concentration Response Functions (CRFs) that are derived from the WHO HRAPIE project (WHO, 2013) plus a case-specific valuation that is based on the literature.

For the classical air pollutants ($PM_{2.5}$, PM_{10}, NO_x, SO_2, NH_3, NMVOC) three sets of prices have been developed:
- national averages;
- transport emissions (from stacks at ambient level);
- high stack (>100 metre) emissions.

However, these values cannot be used directly for the current project for two reasons:
1. Emissions from aviation typically occur at higher altitudes and for these altitudes no damage cost estimates are available yet.
2. Emissions from aviation do not just occur in the EU28, but in all the countries in the world, and these countries differ in terms of wealth (GDP), population density and climatological circumstances. Of these, differences in GDP and population density would have the biggest impact on differences in valuation.

B.3 Aim and delineation

The present annex aims to estimate a global average damage cost estimates for emissions of $PM_{2.5}$, NO_x and SO_2 from aviation. For this we will use the estimates of the Handbook Environmental Prices (CE Delft, 2018) as starting point and adapt them to the altitude of exhaust of emissions of aviation and the differences in GDP and population density in the countries where these emissions result in an increase in concentrations.

The Handbook Environmental Prices follows the WHO, (2013) recommendation on including impacts of air pollution in cost-benefit analysis. WHO, (2013) does not differentiate health damage between $PM_{2.5}$ and ultrafine particles (e.g. particles with a diameter less than 1 micrometre). Even though recent scientific advances have suggested that ultrafine particles are more damaging (and aviation produces relatively more ultrafine particles), this has not been taken into account. We also have not taken into account the chemical composition of particulate matter. Even though recent scientific advances have suggested that black carbon is much more damaging than other types of particulate matter (see e.g. (WHO, 2012)), our study has not differentiated damage costs for the various chemical compositions of particulate matter. For these reasons, the damage cost factors used for $PM_{2.5}$ emissions in this study should be considered conservative estimates.

Endpoints included in the damage costs

The damage costs of pollutants contain the following impacts:
- human health;
- ecosystems (natural capital);
- buildings and materials (human capital).

Of these, human health impacts are most important for all classical pollutants.

Table 29 takes the average values of the Environmental Prices Handbook for classical pollutants in the EU28 and shows which proportion of the total damage costs has been caused by human health.

Table 29 - EU28 environmental price, total, and the price related to human health. Prices for an average emission in the EU28, €/kg emissions

Emissions	Total environmental price			of which Human Health		
	Low	**Central**	High	Low	**Central**	High
$PM_{2.5}$	27.7	**38.7**	59.5	27.7	**38.7**	59.3
NO_x	10.0	**14.8**	22.1	9.5	**13.3**	20.3
SO_2	8.3	**11.5**	17.9	7.7	**10.8**	16.5

These prices form the basis for our recalculations. Hereafter, we will only consider the central estimates.

B.4 Method

Starting points

Starting point of the calculation is the division between domestic and international flights for CO_2 emissions from ICCT, (2019) that divides for over 100 countries the CO_2 emissions into emissions originating from domestic flights and international flights. We assume for this calculation that all emissions are linear to fuel use.

For our calculation we will develop environmental prices for LTO emissions and cruise emissions. For domestic flights we assume that the full LTO-emissions take place within the national territory. For international flights we assume that half of the LTO emissions take place within the national territory.[11]

According to Owen et al., (2020) the literature suggests that worldwide fuel use is differentiated as in Table 30.

Table 30 - Share of global aviation fuel use to different stages of the flight

Stage	Percentage	Altitude
LTO	13%	0-914 metres
Climb	17%	914-7,000 metres
Descent	3%	914-7,000 metres
Cruise	67%	>7,000 metres

For the calculation of the damage costs of classical pollutants we only take the division between emissions lower than 900 metres and higher than 914 metres into account. Currently our models cannot differentiate in the impacts of substances emitted at a level higher than 900 metres. That is why we have to assume that the impacts of climb and descent are similar to the impacts of cruise emissions. We assume furthermore for our calculation of a global average environmental price that the emissions are linear to fuel use.

In this research we have differed the environmental prices for human health, ecosystems and buildings for every country in the ICCT database in order to come up with a global average. For emissions to ecosystems and buildings we only differentiate them according to GDP. One should notice that these constitute under 10% in the total damage costs for all pollutants, that is why we see no reason to differentiate these to altitude of emissions as the differences in valuation between countries for other factors than relative income is very small. Even emissions emitted at high altitude during cruise may affect natural capital as these emissions in the end will deposit to the earth surface through wet and dry deposition. For human health we will differentiate according to GDP, population density and altitude of emissions.

[11] The remaining LTO emissions will be valued with a global average.

Adjusting for GDP

According to Worldbank GDP in the EU28 was equivalent to $ 43,737 in the year 2018. In the same year the value for the world was equivalent to $ 17,948. In the Handbook of External Costs for DG Move (CE Delft et al., 2019) it has been argued that differences in GDP will lead to differences in the valuation of external costs: partly because such costs are tangible costs such as the days that people are unable to work because of illness due to air pollution and partly because people express their willingness to pay in terms of their purchasing power. The study uses an income elasticity of 0.8. Using this income elasticity one can argue that the valuation of impacts in the EU is about a factor 2 higher than globally. Or, in other words, the valuation of the world impacts is 49% of that of the EU.

This is an important adjustment to the figures given in Table 29. For non-human health impacts this is the only adjustment that is being made in this study (see Annex B.7). However, for the important human health-impacts more adjustments are needed. These adjustments are discussed in more detail in Annexes B.5 and B.6.

B.5 Human health: Damage costs for emissions >914 metres

High altitude emissions tend to spread over a large area. Atmospheric chemistry is a complex subject where removal of the pollutants from the atmosphere through dry and wet deposition becomes important. Atmospheric dispersion can be subdivided into local-scale dispersions (up to 50 kms from the source) and regional-scale dispersion that can mount to several thousands of kilometres. Emissions at high altitude are primarily regionally dispersed and in this research we assume that they are for 100% regionally dispersed. For the regional dispersion, chemical interactions between direct emissions and the composition of the air plus the deposition velocities determine the final damage costs. One can distinguish between wet deposition through precipitation and dry deposition through gravity. For human health primarily dry deposition is important as this determines the intake of the pollutant into the human body.[12]

In the modelling of the NEEDS project (Desaigues et al., 2007) part of the emissions that were exhausted at low altitude would move over to the Northern atmospheric layers where transport of emissions over several thousands of kilometres would occur. Table 31 gives the share of damage costs of localized emissions that would cause damage through the Northern atmospheric layers.

Table 31 - Share of damage costs through high altitude atmospheric transport in the NEEDS project for the scenario of emissions in 2010

Emissions	Share of damage costs through high altitude atmospheric transport
NO_x	2.3%
$PM_{2.5}$	0.6%
SO_2	4.6%

Not surprisingly one observes that PM emissions hardly come up to the higher altitudes because of the greater weight of these emissions compared to the other pollutants.

[12] For ecosystem impacts wet deposition is more important.

A first approximation for the damage costs of SO_2 and NO_x would be to assume that vertical atmospheric transport from low to high altitudes would be similar for high to low altitudes assuming that 2-4% of pollutants emitted at high altitudes would cause damage at low altitudes. However, this approximation is for various reasons unsatisfactory: e.g. it neglects the influence from gravity.

Another approach can be found by reference to the literature. Yim et al., (2015) have used a hybrid model to calculate the increase on global emissions from emissions on aviation. They only look at the human health impact from primary and secondary aerosols ($PM_{2.5}$). They conclude that aviation emissions globally increase by 6.2 ng/m^3 for all-altitude emissions and 0.5 ng/m^3 for LTO emissions. This implies that non-LTO emissions would result in an increase of 5.7 ng/m^3.

This increase can be imported in the impact tables that have been used in the Environmental Prices Handbook (CE Delft, 2018) and the Handbook of External Costs of transport (CE Delft et al., 2019) that define the human health costs from air pollution. We have corrected the valuation with a factor 0.49 to reflect the differences in GDP using an income elasticity of 0.8 (see Paragraph 2.2.).[13] The results give the valuation for the $PM_{2.5}$ impacts from emissions at high altitude.

Table 32 - Global damage costs for impacts from primary and secondary aerosols from high altitude aviation on human health

Emissions	€/kg emissions
$PM_{2.5}$	1.48
NO_x^	0.33
SO_2^	0.30

^ Only impacts on human health from secondary aerosols have been taken into account. NO_x emissions may also result in higher smog and NO_2 concentrations. These impacts have not been quantified.

NO_x and SO_2 result in other impacts on human health as well. NO_x results in higher NO_2 concentrations which has direct health costs. SO_2 results in smog formation as well. In our models (using the lifetables as presented in the Annex), we can observe that the health costs for NO_2 is about 33% of the contribution of NO_x to secondary aerosols. For SO_2, our models indicate that the damage of the contribution to smog formation is about 1% of the contribution to human health due to secondary aerosols. Therefore we would suggest that the final value of NO_x from cruise emissions would be fixed at € 0.44/kg while that for SO_2 would remain unaffected.

B.6 Human health: damage costs for emissions <914 metres

Lower altitude emissions tend to be much more damaging than high altitude emissions because they are often located nearby airports and airports are located in relatively densely populated areas when taking into account grid cells of 50 x 50 km^2 in which most of the impacts of air pollution occur.

13 Furthermore, we have used characterization factors from Goedkoop et al., (2013) to reflect the share of emissions of SO_2 and NO_x that turn into secondary particles. We have assumed that this share is similar for PM_{10} and $PM_{2.5}$ emissions.

We have seen in Annex B.4 that 13% of emissions stem from LTO emissions. LTO emissions fall apart in four categories: Taxiing, starting, climbing to 3,000 feet (914 metres) and descending. Based on TNO, (2017) we take that the division between fuel use in the various stages of the LTO in the Netherlands are divided as shown in Table 33.

Table 33 – Share of aviation fuel use during LTO and altitude where emissions take place

	%	Altitude (metres)
Taxiing (idle)	35%	0-10
Take-off (start)	13%	0-10
Climb-out	27%	10-914
Descent	20%	10-941
APU	5%	0-10

From this table we take that 53% of emissions will take place at an altitude below 10 metres and 47% at an altitude higher than 10 metres. We have valued both in a different manner.

Valuation of emissions to 10 metres

For emissions at the height of 0-10 metres we would stick for EU28 countries to the estimations that have provided in the Handbook of External Costs of Transport (CE Delft et al., 2019). This Handbook gives estimates for transport emissions for $PM_{2.5}$ for rural areas, cities and metropolitan areas. Most of these impacts occur in a small range (e.g. <5 km from the exhaust). It is unclear which value one should use for airports. On the one hand, airports are often not surrounded by houses due to noise which would plea for using the value for rural areas. On the other hand, the amount of passengers every day make airports much more crowded than rural areas. Therefore, we have opted to use here an average of the city and rural values provided in the Handbook of External Costs of Transport.

This is the case for all countries for which the Handbook has provided values (EU28 + a few major economies). For cities in other countries, we had to calculate the values. Most important variables in this context are the level of GDP and population density. As with respect to the level of GDP we use the income elasticity for the income levels in purchasing power parities of 0.8. For population density we apply an elasticity taken from an updated version of CE Delft's Benefito model (2011), which gives an elasticity of 0.43 with respect to population density and a constant of 2.697.

We have used this information to recalculate a damage costs for each and every country in the ICTT database where we have assumed that for domestic flights all emissions under 914 metres fall within the country and for international flights 67% (namely only departure). Table 34 gives an estimated damage costs for major economies for $PM_{2.5}$ in €/kg emissions. We have subsequently multiplied these damage figures with the share of fuel use in the domestic territory from ICCT, (2019). This resulted in a weighted average damage costs globally of € 72.2/kg $PM_{2.5}$, also presented in Table 34.

Table 34 – Damage costs from emissions from aviation at a height of 0-10 metres

Country/region	$PM_{2.5}$ damage costs in €/kg
USA	113.7
China	32.0*
UK	93.5
Japan	106.7
Germany	118.5
India	25.4*
European Union	96.5
Weighted global average	72.2*

* Values obtained through Benefito model without taking into account differences in dispersion and atmospheric conditions.

For NO_x and SO_2 we undertook similar recalculations, where for NO_2 we have taken the values for cities because airports are often located nearby cities and NO_2 emissions travel longer distances causing increases in NO_2 concentrations. Both pollutants have been adjusted for population density and GDP/capita in PPP using the equations from the updated Benefito model and weighted with the share of fuel used in domestic LTO. The global outcomes are presented in Table 35.

Table 35 - Damage costs for human health from emissions from aviation at a height 0-10 metres in €/kg

Country/region	NO_x	SO_2
USA	25.1	12.8
China	5.9	3.9
UK	13.6	10.0
Germany	36.8	16.5
India	4.8	2.6
European Union	21.3	10.9
Weighted global average	15.3	8.3

Valuation of emissions 10-914 metres

Emissions at higher altitude tend to spread over a larger area. The damage costs decrease with the height of emissions. The following table indicatively gives the range of damage costs of the Handbook Environmental Prices according to the height of stack.

Table 36 - Indicative values for damage costs at different height of stacks in the EU28 €/kg

Height of stacks	Height of emission	€/kg $PM_{2.5}$
Ultra high stacks	~280	7-10
Electricity generation	~120	16-19
Average	~10-20	38.7
Transport	~1	123

Note: Based on CE Delft, (2018).

Without further analysis one cannot state with absolute certainty what the damage costs of the emissions would be. We have taken here an average value for the EU28 of € 6/kg $PM_{2.5}$ representing the average of the points known from Table 36 and extrapolating the trends.

We assume that the damage values of NO_x and SO_2 similarly decrease. Table 37 gives the values used in this research.

Table 37 – Indicative values for damage costs of 10-914 metres, in €/kg

	$PM_{2.5}$	NO_x	SO_2
EU28	6.0	1.8	0.9
Global weighted average	4.5	1.3	0.7

B.7 Non-health impacts

In the central values, there are small contribution of the emissions of SO_2 and NO_x to ecosystems. These impacts tend to net out to some extend: the loss in biodiversity tends to be compensated by an increase in crop yields because of the fertilizing effect from both sulphur and nitrogen.[14] However, the net balance in the handbook of Environmental prices is a small negative cost as the valued biodiversity losses outweigh a potential increase in crop yields.

Contrary to human health impacts, biodiversity impacts may occur both from wet and dry deposition and that is why the height of stack is much less important. Model calculations from the NEEDS project (Desaigues et al., 2007) show that the emission-response function barely differs from the height of stack and a fixed rate would be a reasonable assumption. However, impacts tend to be lower for emissions that deposit in the oceans than for emissions that deposit in the land. Model runs in the NEEDS projects show that emissions at the Atlantic ocean would cause for NO_x only 34% damage for ecosystem impacts and for SO_2 22%.[15] We take these values as general values for the difference in impacts above land and above sea.

Within this study we cannot model precisely the share of deposition on land areas and sea areas. Without much further details we have taken the simplifying assumption here that 80% of the LTO emissions and 20% of the cruise emissions are emitted above land and the rest above sea.

Another important aspect is that biodiversity impacts are valued less in non-European countries because of differences in the starting level of biodiversity in countries (people living in countries with little nature tend to value nature higher than people living in countries with abundant biodiversity) and the income level. Here we only correct for the income level. Taking again an income elasticity of demand of 0.8, we obtain at the global non-health impacts from aviation as shown in Table 38.

Table 38 - Damage costs for non-human health impacts from emissions from aviation in €/kg

	NO_x	SO_2
LTO	0.64	0.29
Cruise	0.17	0.07

[14] In countries with worse ambient air, nitrogen can also lead to overfertilization and thus to crop losses.

[15] One should notice here that biodiversity impacts on sea are not explicitly modelled in NEEDS, so this is probably an under estimation of the true impacts.

B.8 Summary and average damage costs

Taking the shares of fuel use, as presented in Table 30 and Table 33, we can now obtain a global average costs of emissions from aviation. These are given in Table 39. These values are used in the SCBA.

Table 39 - Average damage cost estimates for emissions from aviation in €/kg emissions

	$PM_{2.5}$	NO_x	SO_2
Human health			
LTO	40.82	8.76	4.77
Climb, descent, cruise	1.48	0.43	0.30
Non-human health impacts			
LTO	0.00	0.64	0.29
Climb, descent, cruise	0.00	0.17	0.07
All impacts together			
Global average	**6.60**	**1.75**	**0.97**

One should notice that if more information is available on the exact cause or origin of emissions, such average values should not be used but instead be replaced by national specific values.