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Abstract

This paper assesses the costs of policies to promote the uptake of sustainable aviation fuels to reduce the greenhouse gas emissions of aviation in the EU. Different policies for attaining a minimum sustainable aviation fuel share are assessed, taking into account sustainability requirements and the costs and potential of feedstock supply. The cost-effectiveness of these policies are compared to simpler CORSIA-type emission trading schemes, using a model that combines the demand functions for road, rail and maritime transport fuels, the supply functions of the related feedstocks as well as the environmental sustainability characteristics of the fuels. For aviation a distinction is made between fuel demand for intra-EU flights and for incoming and outbound EU flights. It is shown that policies that aim to achieve a minimum share of 3.5 % or 5.25 % sustainable aviation fuels by 2030 in the EU are 5 to 10 times more expensive to reduce greenhouse gas emissions than a simpler emission trading mechanism like CORSIA.

1. Introduction

The EU is aiming to reduce the climate impact of aviation using a basket of measures, including support for R&D on carbon neutral aircraft, improvements in air traffic management and the inclusion of aviation in the EU Emissions Trading System (EU ETS). It is now also considering policies to boost the production and uptake of sustainable aviation fuels (SAF), one of which is a specific blending mandate for sustainable aviation fuels.

A blending mandate for renewable fuels raises three concerns. First, such fuels are not necessarily sustainable in the sense that their net reduction of carbon emissions may be small when considered over their total lifecycle. The second concern is the net effect on land use: beyond possible competition with food crops, the production of fuels may displace existing agricultural production and generate indirect land use change (ILUC), potentially generating large emissions depending on the type of converted land, as well as threatening the biodiversity in the areas concerned. Such concerns have led to specific provisions in the regulatory frameworks for renewable fuels. The third concern is the cost-effectiveness of a blending mandate: requiring a relatively low blending share does not necessarily increase strongly the user price of aviation fuel but it can still be a very costly way for society to reduce the carbon emissions from aviation.

In this paper we assess the cost-effectiveness of the blending mandates for SAF and compare these blending mandates with other policies to reduce greenhouse gas (GHG) emissions in the aviation sector.

This paper contributes to the debate on SAF and their role in climate policy in three ways. Firstly, it computes costs in a comprehensive way by including the effect of the policies on all associated fossil fuel markets but also on the markets of SAF feedstocks. Secondly, it includes in a rigorous way the complex sustainability concerns that are raised for the use of aviation fuels with a biological origin. Thirdly, it compares the costs of blending mandates with the costs of alternative carbon policies for aviation.

The structure of the paper is as follows. Section 2 presents the institutional background. Section 3 discusses the literature. The methodology is discussed in section 4. Next, Section 5 gives more background on the sustainable fuels that are considered in the analysis. Section 6 presents the results of the policy evaluation. The last section summarizes the main conclusions and also points to possible extensions.

2. The institutional context

Carbon policy in aviation requires special attention to the institutional context. Of relevance here are the European Emissions Trading Scheme (ETS) and the world-wide CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) adopted by ICAO (International

Civil Aviation Authority)[1]. In addition there is the current European Renewable Energy Directive. These three institutions need to be taken into account in the design of carbon policies for aviation and make the comparison of alternative carbon policies more complex. Finally, the different trading schemes and regulations also have their own sustainability criteria.

The EU ETS includes aviation since 2012. In its current scope, it applies to aviation within the European Economic Area (EEA). Under the EU ETS, airlines are granted a certain level of emission allowances and need to buy additional permits for each extra tonne of CO_2 emitted by flights departing and landing within the EEA. Flights departing from or arriving from outside the EEA escape the EU ETS obligations and are unregulated. This may change with the CORSIA.

The CORSIA is a scheme situated at world level as it is adopted by ICAO. The scheme obliges airlines to offset the increase of international aviation's CO_2 emissions beyond their baseline level[2]. Airlines can use SAF as offset to fulfil their obligation provided that these fuels meet specified sustainability criteria.

The GHG emissions of aviation are also addressed in an indirect way via the Renewable Energy Directive (recast)(RED II) (Directive (EU) 2018/2001). This imposes a blending mandate for road and rail transport, to which renewable fuels used in maritime transport and aviation may contribute. The extension of the RED directive to aviation including possible minimum requirements for the blending of SAF is a major policy route envisaged to enforce a large role for SAF.

The RED II and the CORSIA present important differences in their approach to sustainability. For the pilot phase of the CORSIA, sustainability criteria are limited to GHG emission reduction requirements and exclusion of land with high carbon stocks for the sourcing of biomass, while additional sustainability requirements may be added in the future phases of the program. The RED II also includes requirements on GHG emission reduction and on the types of land that can be used for sourcing biomass, also considering preservation of biodiversity. However, a key difference is that the RED II has a feedstock prescriptive approach promoting the use of some kinds of feedstock and banning the use of others, whereas the CORSIA is feedstock agnostic. A second major difference is the methodology for accounting GHG emissions and the associated thresholds for the eligibility of the fuels, which makes a fuel not necessarily eligible in both schemes. In fact, these two differences are partly interrelated: whereas the CORSIA accounts for GHG emissions induced by ILUC, the RED II does not, but restricts the use of feedstock that present high risks of ILUC emissions.

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[1] https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

[2] Due to the COVID-19 pandemic the CORSIA baseline, originally calculated as the average of 2019 and 2020 emissions from the aviation sector, has been changed to the value of the 2019 emissions for the CORSIA implementation during the pilot phase from 2021 to 2023 (ICAO, 2020).

The differences in sustainability prescriptions and accounting for GHG emissions of SAF is taken on board in our assessment of the cost-effectiveness of alternative climate policies.

3. Literature review

There are several strands in the literature that are relevant for the analysis.

First, the environmental economics literature gives a theoretical framework for the evaluation of the costs and benefits of different policy instruments in the context of sustainable fuels. While these analyses cover other sectors than the aviation sector, they offer important insights. de Gorter and Just (2009, 2010) find that a quantity-based blending mandate is superior to a biofuel subsidy, in terms of social welfare, and the advantage of the blending mandate increases when the fuel tax is lower than optimal. They also show that a combination of a blending mandate with a biofuel subsidy is suboptimal and that trade barriers (in the form of production subsidies, tariffs, sustainability standards) may offset the benefits of biofuel policies. Chen et al. (2014) analyse the welfare effects for the US of a renewable fuel standard for transportation using an integrated model of the fuel and agricultural sector. They find that the standard reduces carbon emissions and increases US welfare due to terms of trade effects. Greaker et al. (2014) take a world view and find that the renewable fuel standard is a positive climate policy because the extraction of oil is postponed as a consequence of the adoption of the standard. In our medium-term analysis, we take the current technological know-how as given but in the longer term technical progress can change the roles of different technologies. We return to this issue in our conclusions and caveats section.

A second relevant strand in the literature consists of detailed techno-economic analyses of different production processes and feedstock, specifically for SAF. Examples are Bann et al. (2017), de Jong et al. (2015) or Tao et al. (2017). Bann et al. (2017) examine the economic viability of six SAF production pathways, with a representation of technical and economic uncertainty. de Jong et al. (2015) provide both a pioneer plant and n^{th} plant analysis[3] and consider the potential offered by co-production (i.e., adding units or locating additional units close to existing production plants). Tao et al. (2017) also perform a pioneer plant and n^{th} plant analysis for another SAF production pathway. SGAB (2017) presents a technology status for the different pathways as well as a summary of the knowledge on the costs of so-called advanced biofuels, i.e., fuels derived from industrial, forestry and agricultural wastes, including biofuels for aviation. Staples et al. (2018) look at the SAF potential in the very long term (2050). It is generally found that, in the absence of government incentives, none of the SAF production pathways are economically viable at present.

The third strand in the literature concerns the evaluation of the sustainability of renewable fuels. Examples in the case of SAF are Elgowainy et al. (2012), Staples et al. (2014) or Suresh

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[3] A n^{th} plant analysis is an analysis for a mature technology.

(2016). The values used in this paper are based to a large extent on ICAO (2019) which gives the background for the default lifecycle GHG emission values for the fuels that are eligible under the CORSIA and which provides an extensive reference list of underlying studies. Another source is Edwards et al. (2017) who present the input data for the determination of the GHG default emissions from biofuels in EU legislation.

4. Methodology

For the evaluation of the cost-effectiveness of SAF policies, a newly developed partial equilibrium model is used for the road, air and maritime transport fuel markets in Europe and the rest of the world. It allows to model the expected economic effects of a policy change compared to a business as usual scenario. A full description of the model is given in Appendix A.

Before describing the major model assumptions, it is instructive to first explain via a simplified representation the essential mechanisms that are put into place by different policy instruments for the promotion of SAF.

4.1 A simple representation of the different policy instruments

Figure 1 represents a perfectly competitive market for aviation fuel that can be supplied by fossil jet fuel and by sustainable aviation fuels (SAF). It shows how the two fuel types interact on a competitive market when different types of policy instruments are applied. For simplicity Figure 1 assumes that the GHG emissions of SAF fuels are zero, an assumption that will be dropped in the full analysis.

The demand for aviation fuel is the end result of the demand for passenger and freight transport, the supply of seats by aviation companies that select certain routes, air traffic management procedures, flight speed, type of aircraft, flight frequencies and prices. The aggregate demand function for aviation fuel integrates implicitly all levers by which airlines can react to the user price of fuel. The price is a mix of the prices of fossil jet fuel and sustainable fuels, where the mix will be a function of the policy instruments in place. The supply of aviation fuels is a combination of fossil jet fuel – here assumed to be supplied at constant marginal cost, an assumption that will also be dropped in the full analysis – and a supply of SAF at an increasing marginal cost. The SAF supply is assumed to have an increasing cost because the production potential of the primary inputs for SAF is limited – one has to collect and process inputs that become more and more costly.

Figure 1 is used to illustrate the impacts of three policy instruments that can stimulate the reduction of GHG emissions from aviation. First, one can use a simple carbon tax on aviation fuels: this increases the marginal cost of conventional jet fuel from p_0 to p_1. In this case, GHG emissions are reduced through two mechanisms: a reduction in fuel demand (from q_0 to $q_{1,t}$) and an increase in the use of SAF (from q_{0S} to $q_{1S,t}$). The inclusion of aviation fuels in the EU ETS has a similar effect as a tax on fossil fuel for the flights within the EEA.

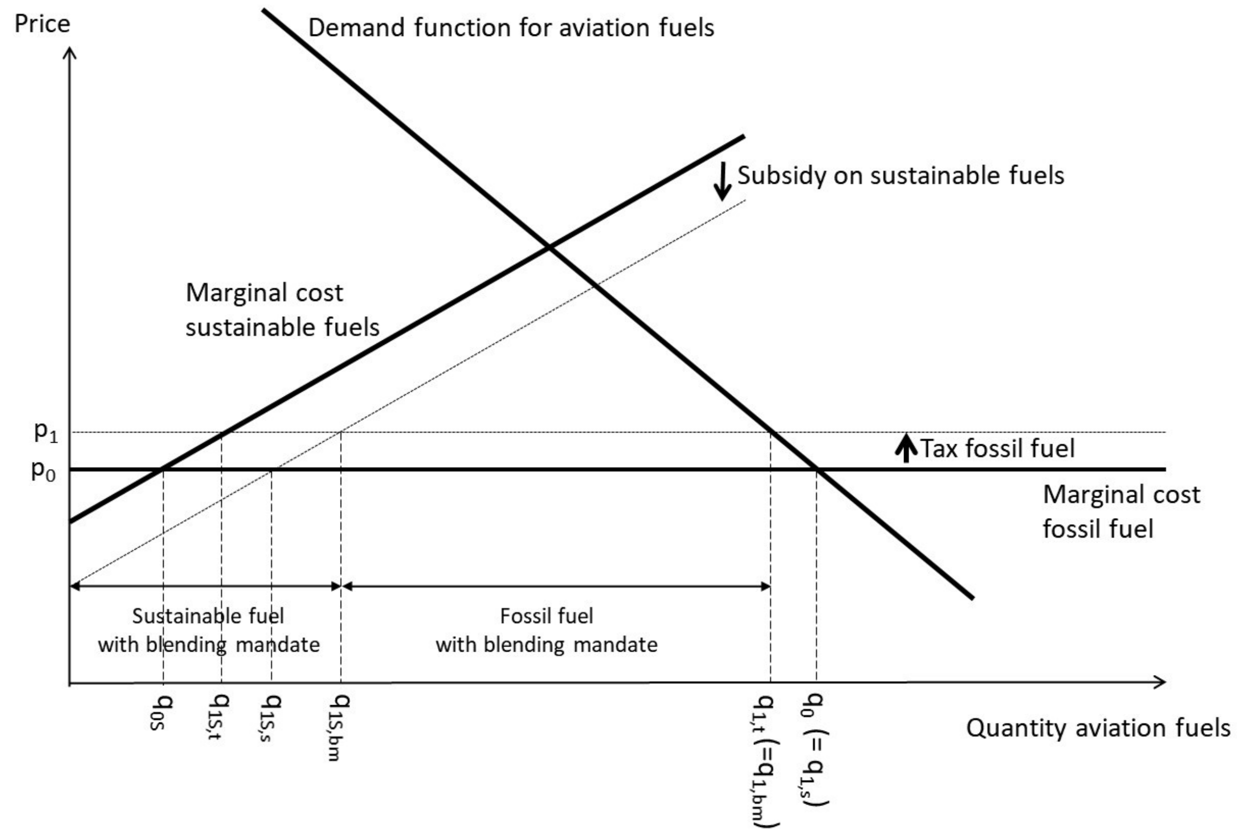

FIGURE 1: SIMPLIFIED REPRESENTATION OF AVIATION FUELS MARKET

The second instrument is a subsidy for SAF. This shifts the supply function for these fuels downwards, and with the subsidy considered in Figure 1, this increases their uptake from q_{0S} to $q_{1S,s}$. However, the total quantity of fuel remains unchanged at q_0 (assuming constant marginal costs for fossil jet fuel). The emission reduction is now due only to the substitution of fuels.

The third instrument is a blending mandate (de Gorter and Just, 2009), an instrument that is intensively used for road fuels and is now also being considered for aviation. In this case the suppliers of aviation fuel, in order to reach the desired mix, have to implicitly “tax” fossil jet fuel and use the revenues to implicitly “subsidize” the production of SAF. Figure 1 shows how the total input of fuels to aviation is reduced (from q_0 to $q_{1,bm}$) while also the combination of aviation fuels becomes more sustainable: the use of sustainable fuels is increased from q_{0S} to $q_{1S,bm}$.

Figure 1 illustrates that the three policy instruments considered have different impacts. The environmental cost-effectiveness of the different instruments cannot be judged from a conceptual analysis as in Figure 1. What will matter is the slope of the SAF supply (production potential and costs), the slope of the demand for aviation fuels (an inelastic demand favours SAF use) and the exact details of the policy implementation.

4.2 A more complete model

Figure 1 has to be extended in four directions. First, a European policy initiative will affect in principle both the market for aviation fuels bought in the EU and fuels bought outside of the EU. Moreover, as the EU ETS only applies to intra-EEA flights, a distinction is also made between fuels for those flights and fuels bought for other flights. Second, sustainable fuels are also used in the rest of the world and blending mandates are in place for European road fuels and potentially also for maritime transport. This competing demand for sustainable fuels has to be considered. Third, there are many alternative pathways to produce sustainable fuels. Their production costs and production potential has to be represented at world scale including the competing demands for feedstocks. For this, the MAGNET model, a general equilibrium model for the world agricultural markets (see Novelli et al., 2019) provides inputs. Finally, the assumption that the GHG emissions associated with SAF are zero is dropped.

Figure 2 gives an overview of the model. A full description of the model can be found in Appendix A. Summarizing, the model endogenously calculates fuel demand by three transport modes: road (non-electric), maritime and air transport. The geographical scope is:

- fuel for EU and non-EU transport for road and maritime transport;
- EU fuel for intra-EU aviation[4], EU fuel for extra-EU aviation and non-EU fuel for extra-EU and non-EU aviation.

The uptake of electric vehicles in road transport and energy consumption by rail transport are taken to be exogenous.

For the EU, the scope of the model is the EU as a whole. The EU Member States are not modelled individually. All non-EU countries are also aggregated into one region.

For each of the transport fuel markets, the model includes a linear aggregate fuel demand function that describes how fuel demand reacts to changes in the fuel price, implicitly integrating all of the levers determining fuel demand. The fuel price differs by market, depending on the policies that are in place.

Fuel demand for road, maritime and air transport can be met by fossil fuels or different types of sustainable fuels, taking into account the energy content of the different fuels, as well as certain technological maximum blending percentages. The different types of sustainable fuels correspond with different combinations of production processes and feedstocks. The model allows for the possibility that some sustainable fuels may be used for two or three transport modes while others are specific for a certain transport mode. The model also takes into account that certain sustainable aviation and road fuels are co-products.

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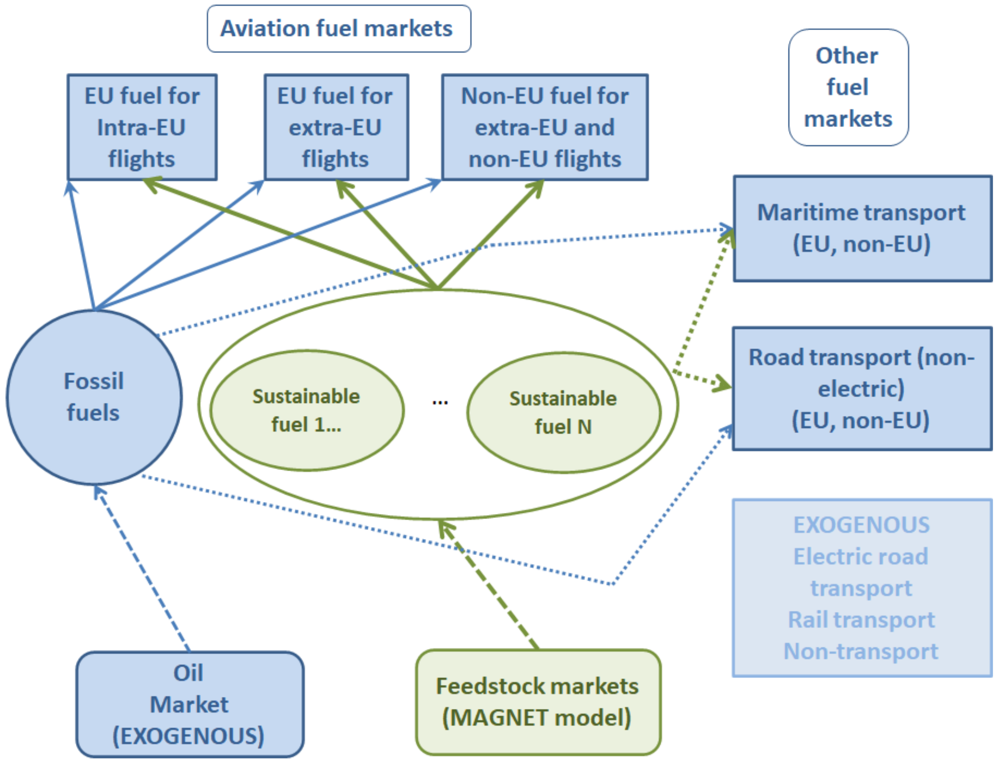
[4] While the EU ETS applies to flights between EEA countries, the model assumes it applies to flights between EU countries (intra-EU flights), which represent the bulk of the flights covered by the EU ETS.

It is assumed that the suppliers of fossil and sustainable fuels are perfectly competitive and sell their output on either the world market or separately in the EU and non-EU. In the first case the pre-tax price for the fuels is determined at world level, while in the second case it is determined at EU and non-EU level separately.



Solid arrows: fuels supplied to aviation sector; Dotted arrows: fuels supplied to other transport sectors; Dashed arrows: feedstocks supplied to fuel producers

FIGURE 2: THE TRANSPORT FUELS MARKET MODEL (TRAFUMA)

The fuel suppliers are assumed to maximize profits. The cost functions take into account that for fuel suppliers producing fuels for several modes, some costs are specific for the mode for which the fuel is supplied, while other costs depend on the total volume of fuels that is supplied to all modes. The cost functions also take into account the price evolution of the feedstocks. The price of crude oil, the feedstock for fossil fuels, is taken to be exogenous.

4.3 The type of aviation carbon policies considered

The evaluation focuses on the SAF uptake, the effect on the user price of aviation fuel, the net GHG emission reduction and the social welfare cost per tonne of CO_{2eq} emission abated. The following policy instruments are considered for the EU:

a) a blending mandate as in the EU RED II, which applies to road and rail transport but to which aviation and maritime transport may contribute;
b) a specific blending mandate for aviation imposing a target share of SAF;
c) a subsidy in the EU for SAF in order to achieve a target share of SAF;
d) a tax on fossil jet fuel in the EU to achieve a target share of SAF.

In addition, three variants of carbon offsets are considered for the aviation sector at world level, as in the CORSIA.

4.4 The baseline scenario

The time horizon of the analysis is 2030. The impacts of the policies for the promotion of SAF are evaluated compared to a baseline that is based on the EU 2016 Reference Scenario (EC, 2016) for the EU and the Reference Scenario of US-EIA (2017) for the rest of the world, assuming that the world economies and transport flows have regained by then the growth path of the pre-COVID-19 period. Table 1 presents the projected fuel demand in millions of tonnes of oil equivalent (Mtoe) in the EU for the different transport fuel markets in the baseline.

The policies in the baseline scenario for the EU include the tax levels in 2015 (assumed to remain constant in real terms) and the share of biofuels in road transport, taking into account the Renewable Energy Directive before its recast as the RED II. In addition, the EU ETS applies. In the baseline the crude oil price in 2030 is taken to be 120 €/barrel and the ETS price equals 35 € per tonne of CO_2, both in line with the EU 2016 Reference Scenario.

	Mtoe	**Ratio compared to 2015 (2015 = 1)**	
	2015	**2025**	**2030**
EU – road	291.70	0.93	0.91
EU – maritime	42.14	1.16	1.24
EU – rail	7.40	1.12	1.17
EU - intra EU aviation	17.76	1.11	1.10
EU - extra-EU aviation	33.53	1.15	1.13

Source: EC (2016); distinction between intra EU and extra EU aviation based on Alonso et al. (2014)

TABLE 1: EU TRANSPORT FUEL CONSUMPTION OUTLOOK ACCORDING TO THE EU 2016 REFERENCE SCENARIO

5. The sustainable fuels included in the analysis

Table 2 gives the complete list of combinations of production processes and feedstocks, which are included in the model for road, maritime and air transport. Note that not all of these combinations can be used in all policy scenarios. The table indicates the mode for which the fuels can be used and whether the model considers co-products in the production of the sustainable fuels[5]. In addition, it presents information on the GHG emissions and on the publications that were used to determine the GHG emissions and supply functions for the sustainable fuels.

For road transport, the model includes the first generation of biofuels, which are currently dominant, as well as a number of advanced biofuels. The first-generation biofuels are bioethanol for gasoline cars and FAME (Fatty Acid Methyl Ester), commonly referred to as biodiesel, for diesel cars. Ethanol is produced from sugar or starchy crops through fermentation, while biodiesel is obtained through esterification of vegetable oils. Both fuels contain oxygen, a component absent from fossil fuels, which results in a lower energy content. These biofuels are blended with fossil gasoline and diesel. Due to the high quality requirements on aircraft fuels, such fuels cannot be used in aviation. For aviation only conversion processes producing pure hydrocarbon can be used. The following processes, already approved for aviation, are included in the analysis:

- Hydroprocessed esters and fatty acids (HEFA)
- Hydrotreated vegetable oils (HVO) also known as HEFA+ in the case of aviation;
- Fischer-Tropsch (FT) fuels that can be produced from gasification of any type of biomass but are more typically used for lignocellullosic biomass and solid waste;
- Synthesized iso-paraffinic fuels (SIP), a particular fermentation process that produces directly hydrocarbons from sugars; and
- Alcohol-to-Jet (ATJ), a process that converts alcohol (ethanol or butanol) into hydrocarbons through dehydration and oligomerisation.

The literature also includes other processes such as hydrothermal liquefaction (HTL), aqueous phase processing, pyrolysis or co-processing. These were not considered in the analysis, either because they are still in early stages or due to lack of cost information.

Processes such as HEFA or Fischer-Tropsch also co-produce diesel and gasoline fuels for road transport, which are considered as “drop-in fuels” as they are better substitutes to fossil fuels for cars than ethanol and FAME and can be blended at much higher ratio. In some cases, there are also co-products for maritime transport. For aviation, the blending ratio is limited to 50 % as chemical differences with kerosene remain. It is worth noting that, combining these conversion processes, all kinds of biomass, i.e. oleaginous, sugar, starchy or lignocellulosic, can be converted into jet fuel and are therefore included in the analysis.

Among the feedstocks incorporated in the model, a number are considered only as an option for the EU: used cooking oils (UCO), animal fats, camelina and sugar beets. This is due to the unavailability of supply functions at the non-EU level.

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[5] The annex presents information on the shares of the different co-products in the production processes as well as the conversion efficiency of the processes.

The associated GHG emissions in Table 2 are expressed in tonne of CO_{2eq} per toe of fuel. The numbers refer to the well-to-wheel/wake (WTW) emissions, on the one hand, for “core life cycle” emissions (i.e. without land use change emissions) and, on the other hand, to WTW emissions including emissions induced by land use change (ILUC). The main sources for the emission factors are Annex V of the RED II and the default values determined by the Committee on Aviation Environmental Protection (CAEP) for the CORSIA (ICAO, 2019a,b). In some cases, sufficient information was not available. For these cases “NA” is mentioned for the emission factors and the model assigns the same emissions as for fossil fuels (3.94 gCO_{2eq}/toe), which is a conservative assumption. However, as will be shown below, the cost characteristics of these fuels are such that they are not selected under the policy scenarios that are considered, making this assumption without consequence for the policy evaluation presented here.

Production process		Feedstocks	Modes	WTW emissions (tonne CO2eq /toe)	WTW emissions with ILUC (tonne CO2eq/toe)	Emission factors based on	Reference used as basis for production costs
FAME	Biodiesel (Fatty Acid Methyl Esther)	Average mix EU 2015[a]	Road	2.21	3.96	Annex V EU RED II and Valin et al. (2015)	UFOP (2015)
Bio-Ethanol	Bioethanol	Average mix EU 2015[a]	Road	1.74	2.26		OECD/FAO (2017)
HEFA	Hydroprocessed esters and fatty acids	UCO (only EU)	Co-products: Air Road	0.58	0.58	ICAO (2019a,b) and Junquera (2015)(Camelina)	Bann et al. (2017) and ITAKA project
		Animal fats (only EU)		0.94	0.94		
		Camelina[b] (only EU)		1.76	1.76		
		Vegetable oils[c]		1.56	2.79		
HVO	Hydrotreated vegetable oil (also known as HEFA+ in the case of air transport)	UCO (only EU)	HVO: Road Maritime HEFA+: Co-products: Air Road	0.58	0.58	Assumption: same emission factors as HEFA	SGAB (2017) and ITAKA project
		Animal fats (only EU)		0.94	0.94		
		Camelina[b] (only EU)		1.76	1.76		
		Vegetable oils[c]		1.56	2.79		
SIP	Synthesized iso-paraffinic fuels (also known as direct sugars to hydrocarbons)	Residues	Co-products: Air Road	NA	NA		De Jong et al. (2015)
FT	Fischer-Tropsch	Woody biomass and energy crops[d]	Co-products: Air Road Maritime	0.47	-0.20	ICAO (2019a,b)	De Jong et al. (2015) Bann et al. (2017)
		Residues[e]		0.33	0.33		
		Municipal solid waste[f] (only EU)		1.36	1.36		
CE	Cellulosic ethanol	Residues[e]	Road	0.59	0.59	Annex VI EU RED II	SGAB (2017)
ATJ	Alcohol-to-jet	Residues[e]	Co-products: Air Road	1.11	1.11	ICAO (2019a,b)	De Jong et al. (2015) Tao et al. (2017)
		Sugar beets (only EU)		NA	NA		
		Sugarcane		1.01	1.34	ICAO (2019a,b)	

[a] feedstock shares based on USDA (2017)

[b] WTW emission factor based on ICAO (2019a,b). The ILUC emissions related to Camelina are taken to be zero, under assumption of certain management practices (Junquera, 2015).

[c] Average emission factor based on ICAO (2019a,b) for corn, canola rapeseed, soybean, palm oil and PFAD (Palm Fatty Acids Distillate).

[d] Average emission factor for short-rotation woody biomass and herbaceous energy crops

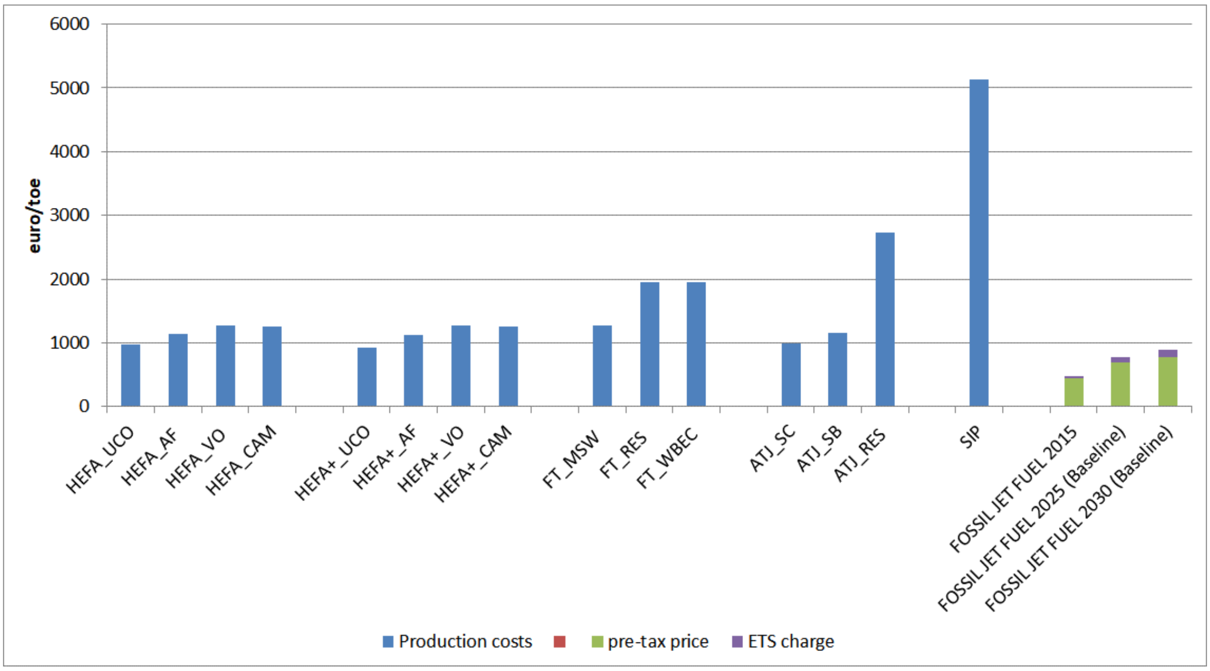
[e] Average emission factor for agricultural and forestry residues

[f] Emission factor calculated assuming a carbon content of 40 % of MSW and a share of 40 % of non-biogenic carbon.

TABLE 2: OVERVIEW OF PRODUCTION PROCESSES AND FEEDSTOCKS INCORPORATED IN THE MODEL

Figure 3 gives an overview of the production costs for different SAF types based on the references summarized in the last column of Table 2. To these costs, the model adds transport, distribution or profit margins for these sustainable fuels (which are already included in the pre-tax price of fossil jet fuel in the figure), which still increases their costs to the buyers. The total of these margins is set at 20 %. The figure does not take account yet of the impact of a higher demand for feedstocks on feedstock prices[6], which will be discussed below. The references in Table 2 already include future cost reductions by upscaling production and technology improvements by 2021-2025. Further improvements of technologies over 2025-2030 are possible but are not included in this analysis as it is assumed that the technology for 2030 is given.

Figure 3 compares the cost information for the SAF with the user cost of fossil jet fuel (including the ETS charge for intra-EU aviation) in the baseline scenario. From the comparison it is clear that without further policy incentives SAF cannot compete with fossil jet fuel. The baseline ETS price (projected to be 35 €/tonne of CO_2 in 2030) is insufficient to make the new fuels competitive for intra-EU aviation. For extra-EU aviation, the difference between the user price of fossil jet fuel and the cost of sustainable fuels is higher than for intra-EU aviation because no ETS charge applies for these flights.



Note: UCO: used cooking oils; AF: animal fats; VO: vegetable oils; MSW: municipal solid waste; RES: residues; WBEC: woody biomass and herbaceous energy crops; SC: sugarcane; SB: sugar beets

Source: own calculations based on Bann et al. (2017), Blanch (2017), De Jong et al. (2015), EC (2016), SGAB (2017), Tao et al. (2017)

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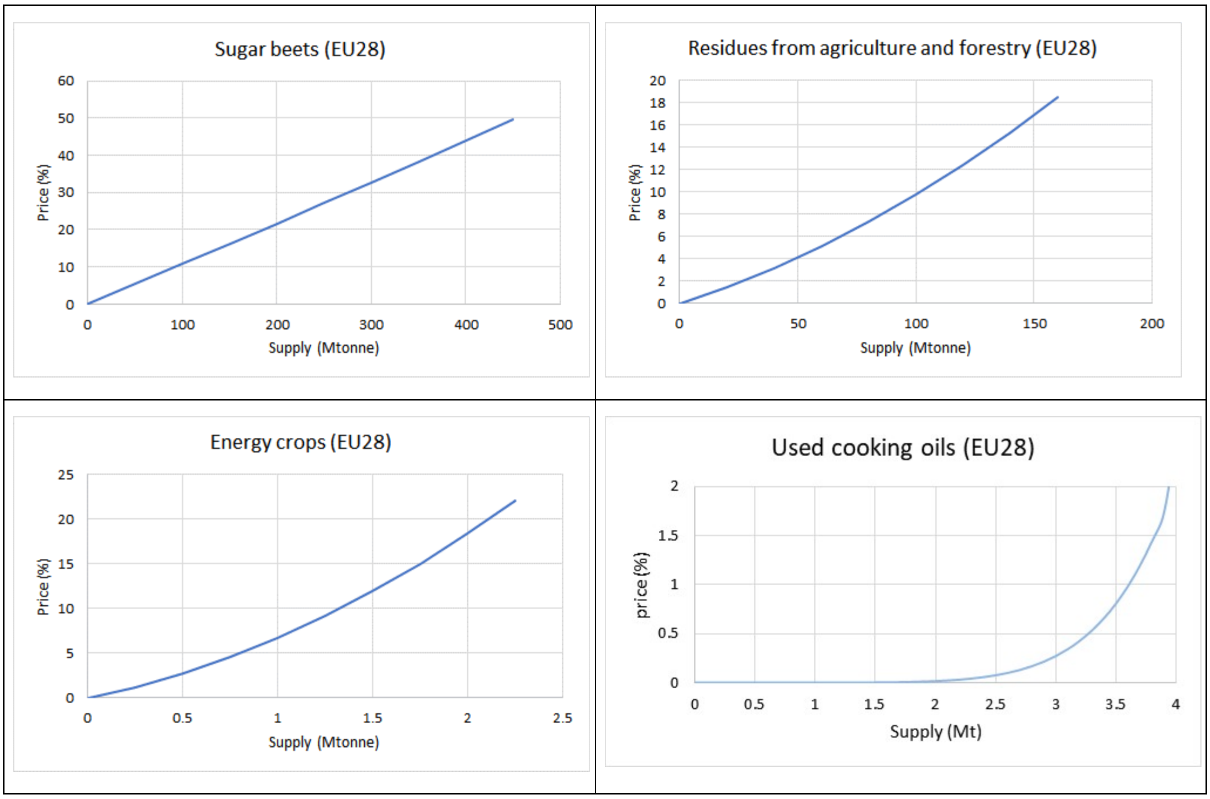
[6] This effect is integrated in the model and is taken into account in the model results that are presented in Section 6.

FIGURE 3: THE COST OF DIFFERENT TYPES OF SAF COMPARED TO FOSSIL JET FUEL

The supply curves for the sustainable fuels' feedstocks are derived with the help of the MAGNET model by analysing the price increases caused by the demand for sustainable fuels in the EU28 and the rest of the world. The feedstock categories considered in the MAGNET model are: vegetable oils, wheat, maize, sugar beet, residues from agriculture and forestry, pellets and energy crops. As an example Figure 4 presents the supply curve for sugar beets, agricultural and forestry residues, energy crops and used cooking oils in the EU28. The vertical axis measures the price change compared to the price development in the absence of large scale use of biofuels in the EU28 and the rest of the world.



Source: based on Novelli et al. (2019)

FIGURE 4: SUPPLY CURVES OF FEEDSTOCK IN THE EU28 – SUGAR BEETS, RESIDUES FROM AGRICULTURE AND FORESTRY, ENERGY CROPS AND USED COOKING OILS

The simulations with the MAGNET model indicate that the use of biofuels from sugar beet and residues from agriculture and forestry (and also maize, vegetable oils and sugar cane (not shown here) have relatively limited price effects, compared to the use of energy crops (and wheat and pellets (not shown here). Energy crops are relatively unattractive feedstocks compared to residues from agriculture and forestry, since the sustainable potential of residues in the EU28 and in the rest of the world is larger than the demand for biofuels and other energy applications and because in the case of energy crops there is competition for land with other applications. For recoverable used cooking oils from the gastronomy sector and households, it is assumed that the supply in the EU of about 3.6 Mtonne (Ecofys, 2013) grows only modestly, by 0.5 % per year. Similarly, the supply curves for animal fats and municipal solid waste take into account an estimate of the maximum available supply in the EU based on data from the literature (Chudziak & Haye, 2016; Searle & Malins, 2013).

6. Results

This section presents the results for five policy scenarios that focus on a minimum SAF share on the EU-market and three scenarios inspired by the CORSIA scheme that focus on the world-wide aviation market.

6.1 SAF policies for EU aviation

6.1.1 Overview of policies

Table 3 summarizes the five policy scenarios that are considered for the EU. Scenario EU-A integrates the specifications of the EU RED II targets for the transport sector. The RED II aims at a renewable energy share of 14 % in 2030 for the transport sector as a whole. The target applies to road and rail transport, but air and maritime transport may contribute to them. The renewable fuel mandate uses so-called "multipliers" to give an extra stimulus to particular fuels. A fuel with a higher multiplier is more attractive because fuel users need a smaller amount of them to reach the target. The RED II imposes a set of complex constraints on the eligible fuels:

- A multiplier of 2 applies to fuels based on certain feedstocks. In addition, a maximum share of 1.7 % applies to fuels based on certain feedstocks, which can be processed with mature technologies, while a minimum share of 3.5 % in 2030 is imposed on fuels using certain other feedstocks, which can only be processed with advanced technologies[7].
- For aviation and maritime transport a multiplier applies, with a value of 1.2; this multiplier can be combined with the previous one.
- By 2030 all food and feed based fuels are phased out[8].

While scenario EU-A does not set a target specific for the aviation sector, the other four scenarios analyse different ways of achieving a target share for aviation. Three of these scenarios aim for a minimum share of SAF of 3.5 %, the level of which is inspired by the EU RED II target in 2030 for fuels produced with advanced technologies. The last scenario considers a minimum share of 5.25 %, which is 50 % higher, in order to investigate how the welfare costs of GHG abatement change with an increasing SAF share. Scenarios EU-B and EU-

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[7] The feedstocks are specified in Annex IX of the RED II.

[8] In the model simulations the following fuels are considered to be food and feed based fuels: biodiesel FAME, bioethanol and sustainable fuels using as feedstock sugarcane, sugar beets and vegetable oils.

E use a blending mandate, scenario EU-C uses a subsidy for SAF[9] and scenario EU-D uses only a tax on fossil fuel. In all of these scenarios it is specified that no feed and food based SAF can be used in the aviation sector. In all of them it also assumed that the RED II applies for road and rail transport. For those sectors a phase out of food and feed based fuels by 2030 is also imposed.

No.	**Scenario**	**Policy instrument aviation**	**Target share SAF by 2030**	**Policy instrument road/rail**
EU-A	EU RED II	SAF multiplier in blending mandate road & rail	None	RED II Blending mandate
EU-B	EU RED II & blending mandate aviation 3.5 %	Blending mandate	3.5%	
EU-C	EU RED II & SAF subsidy	Subsidy SAF (≈ auctioning)		
EU-D	EU RED II & Tax fossil jet fuel	Tax fossil jet fuel		
EU-E	EU RED II & blending mandate aviation 5.25 %	Blending mandate	5.25%	

TABLE 3: SCENARIOS FOR THE PROMOTION OF SUSTAINABLE AVIATION FUELS IN THE EU

We take the minimum shares as given. There is no guarantee that each of the suggested minimum shares is itself optimised.

6.1.2 Impacts and welfare costs of GHG abatement

The results are summarized in Table 4, which presents the impacts and costs of the scenarios compared to the EU 2016 Reference Scenario (baseline). In that scenario the original Renewable Energy Directive has been applied without a phase out of food and feed based fuels.

We report the costs of alternative policy packages under the form of unit costs per tonne of CO_{2eq} emission avoided. The costs equals the sum of consumer and producer surpluses on the road, air and aviation fuel markets plus the net government income.

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[9] Note that this scenario can also be interpreted as an auction system in which the government pays the difference in price with fossil jet fuel to the SAF suppliers that can supply the fuels in the cheapest way. In this variant the same subsidy is paid to all SAF suppliers.

		Baseline	EU-A	EU-B	EU-C	EU-D	EU-E
			EU RED II	EU RED II + blending mandate aviation 3.5 %	EU RED II + SAF subsidy (3.5 % SAF share)	EU RED II + tax fossil jet fuel (3.5 % SAF share)	EU RED II + blending mandate aviation 5.25 %
Fuel consumption							
SAF EU aviation	Mtoe	0	0.6	2.0	2.0	1.0	2.9
	% EU fuel demand aviation	0 %	1.01 %	3.50%	3.50%	3.50%	5.25%
Total fuel demand EU aviation	Mtoe	57.6	57.6	56.3	57.6	27.5	54.7
Renewable energy EU road + rail + aviation	Mtoe	20.4	19.2	21.9	22.0	20.8	22.9
User price fuel		Euro/toe	Change w.r.t. baseline (%)				
Intra-EU aviation		803	-0.05%	4.26%	-0.2%	100%	10%
Extra-EU aviation		696	-0.06%	5.45%	-0.2%	131%	12.36%
Road		1668	1.32 %	1.18%	1.17%	1.30%	1.14%
CO_{2eq} Emissions		Mtonne	Change w.r.t. baseline (Mtonne and %)				
WTW	EU road + aviation	1244	-29.9 (-2.4%)	-35.0 (-2.8%)	-29.8 (-2.4%)	-151.3 (-12.2%)	-44.1 (-3.5%)
WTW with ILUC		1269	-54.6 (-4.3%)	-59.8 (-4.7%)	-54.6 (-4.3%)	-176.1 (-13.9%)	-68.9 (-5.4%)
Impact on EU ETS (CO_{2eq} emissions)			Change w.r.t. baseline (Mtonne)				
TTW	Intra-EU aviation		-1.8	-3.3	-2.0	-29.9	-5.9
TTW	Other EU ETS sectors		+1.8	+3.3	+2.0	+20.8	+5.9
CO_{2eq} emission intensity		gCO_{2eq}/toe					
WTW with ILUC	EU aviation	3.94	3.90	3.84	3.84	3.83	3.78
Welfare cost per tonne of CO_{2eq} avoided (based on worldwide GHG emission reduction of road and aviation)			Euro/tonne CO_{2eq}				
WTW			294	314	369	177	318
WTW with ILUC			159	177	194	149	195
Taking into account impact on emissions on other EU ETS sectors							
WTW			312	350	399	211	373
WTW with ILUC			164	188	202	172	215

TABLE 4: IMPACTS AND COSTS OF FIVE EU POLICY SCENARIOS - 2030

The GHG emission reduction is presented for all fuel use in EU road and aviation: this represents the primary effect of the policy scenarios. A distinction is made between well-to-wheel/wake (WTW) and emissions taking into account indirect land use changes (WTW with ILUC). In all scenarios the change in the second indicator is larger than for the first one (both in absolute and relative terms), as fuels with relatively lower ILUC emissions are used than in the baseline. This is a consequence of the phase out of food and feed based fuels by 2030 under the RED II and the assumption that no such fuels can be used in aviation.

6.1.2.1 Impact on fuel demand, fuel prices and implicit subsidies for SAF

Scenario EU-A has no specific requirement for aviation fuels and has almost no impact on the user price of aviation fuels, while it causes a small increase in the user price of road fuels, as it imposes additional constraints on the fuels that can be used in road transport compared to the baseline. Even a small increase in the cost of road fuels can be costly as the volume of road fuel use is much larger than that for aviation.

As expected, Scenarios EU-B and EU-D have a different impact on the user price of aviation fuel. The blending mandate (Scenario EU-B) increases the user price, but only moderately, while the tax variant (Scenario EU-D) more than doubles the user price for extra-EU aviation and also leads to a doubling of the price for intra-EU aviation fuel. The subsidy variant (Scenario EU-C) keeps the user price almost at the level of the baseline scenario. These results are in line with the intuition we developed in Figure 1.

These three types of policy instrument all achieve the objective of 3.5 % SAF share. But the treatment of SAF is very different (not shown in the table): the blending mandate implies an implicit SAF subsidy for intra-EU aviation of 1007 €/toe of fuel, financed by an implicit tax of 37 €/toe of fuel. In the subsidy policy, the SAF subsidy needed equals 1113 €/toe of fuel for intra-EU aviation. Finally, in the tax scenario, the implicit tax for intra-EU aviation equals only 824 €/toe of fuel because the high tax rate leads to a reduction in the total demand for aviation fuels.

The price changes imply that the blending mandate and especially the tax variant will not only influence the fuels used, but also total fuel demand by aviation. As shown in Table 4 in Scenario EU-D fuel demand is almost halved. In the case of the blending mandate (Scenario EU-B) there is also a decrease in aviation fuel demand, but it is much smaller: -2.2 %. The user price of aviation fuel in Scenario EU-D is of a comparable order of magnitude as the user price of fuel for road transport, while it is substantially lower in the baseline and the other scenarios.

The effect on intra-EU and extra-EU fuel prices is different because for flights with origin or destination outside of the EU, the EU ETS cap and the obligation to buy emission allowances does not apply. We assume that the tax on jet fuel used for extra EU flights can be enforced which may be a heroic assumption given that the EU was not able to enforce the EU-ETS obligation on extra-EU flights.

There are small associated variations in the price of road transport fuels because there is also a blending mandate for road fuels and the policies for the aviation sector have an impact on the costs of road fuels, through the impact on the feedstock prices and the fact that sustainable road and aviation fuels are co-products in a number of cases.

In Scenario EU-E the same mechanisms are at work as in Scenario EU-B. However, as the SAF target share is higher, the impact on the fuel price and fuel demand in the aviation sector is more pronounced. While the target share increases by 50 %, the percentage increase in the fuel price more than doubles. The implicit SAF subsidy for intra-EU aviation increases to 1526 €/toe and the implicit tax on fossil jet fuel to 85 €/toe.

The five policy scenarios lead to a reduction in GHG emissions by road transport and aviation compared to the baseline. Scenarios EU-B to EU-E lead to a larger reduction of GHG emissions for EU road and aviation than Scenario EU-A. In the variants with a blending mandate or subsidy this additional reduction is not very large. However, when a tax is imposed on fossil aviation fuels the reduction is substantial. This is a consequence of the large fall in aviation fuel demand in Scenario EU-D.

Considering the WTW emissions with ILUC from EU road and aviation, the emission reductions with a blending mandate or subsidy are between 54.6 and 68.9 Mtonne in 2030. For the tax variant they are 176 Mtonne in 2030, which is considerably larger. The net emission reductions in road and aviation at world level are somewhat smaller than at EU level because the lower fossil fuel demand on the world fuel markets lead to lower prices and this generates a higher fuel demand outside of the EU (results not shown).

The average CO_{2eq} emission intensity per toe of fuel in the aviation sector falls compared to that in the baseline where no SAF are used and where the emission intensity is that of fossil jet fuel. As can be expected the impact becomes larger with the share of SAF. In scenario EU-A the emission intensity is reduced by approximately 0.8 %, in scenarios EU-B to EU-D by about 2.5 % and in scenario EU-E by 3.9 %.

Table 4 also reports the effects on the tank-to-wheel/wake (TTW) emissions of the sectors in the EU ETS system, including intra-EU aviation. The EU ETS imposes a cap on emissions in the ETS sectors. In the five scenarios, the TTW emissions of intra-EU aviation are reduced. In all scenarios except Scenario EU-D this reduction is completely compensated by an increase in emissions by the other sectors of the EU ETS, keeping the total emissions in the EU ETS constant at the level of the total cap. In scenario EU-D the TTW emissions of intra-EU aviation are reduced below the cap on aviation emissions in the EU ETS. Given the specification at the time of the analysis that the other ETS-sectors could not buy emission allowances from the aviation sector, only the emission reduction of the intra-aviation sector up to the aviation cap is compensated by an increase in the emissions of the other sectors.

6.1.2.3 The welfare cost of the policies

The welfare cost per unit of GHG emissions avoided is the sum of the effects on consumer surplus, government income, transfers to other sectors and producer surplus for the EU (and at world level for the fossil fuel suppliers). This welfare cost per tonne of GHG emission abatement is first presented for the case where the impact on the emissions of road and aviation at world level is considered, but not the impact on the emissions in the other EU ETS sectors. The figures are given both with respect to the reduction in the WTW emissions and WTW with ILUC emissions. In the latter case the costs per tonne are lower as the emission reduction is higher.

In all cases the welfare costs per tonne of GHG emission avoided are substantially higher than the ETS price that is projected for 2030 in the EU 2016 Reference scenario, namely 35 €/tonne CO_{2eq}. The policies considered here are therefore a costly way to reduce GHG emissions in road and aviation, compared to the costs of reductions in the sectors covered by the EU ETS. The reason is simple: the policies considered give strong incentives for using a costly technique (using sustainable transport fuels) to reduce emissions rather than allowing the fossil fuel users the option to use cheaper abatement strategies. The policy instruments like carbon taxes, tradable permits and offset systems do not impose any particular abatement technology and allow to opt for the lowest cost abatement strategies.

Of course, the EU may target much deeper reductions of GHG emissions in the economy and in the aviation sector as the expected climate damage may be much higher than the 35 €/ton CO_{2eq} (see Tol (2012) for a range of damage estimates[10]). But also in that case, sustainable fuels do not appear to be a low cost option.

The comparison between Scenario EU-A on the one hand and Scenarios EU-B, C and E on the other hand indicates that the additional policies for aviation reduce the cost-effectiveness of GHG emission reductions.

In scenario EU-D a tax is introduced and this lowers the welfare cost. In this case a smaller amount of relatively expensive SAF are needed and emissions are reduced relatively more by reducing aviation fuel demand than in the other aviation scenarios. However, also here the welfare cost per tonne of GHG emissions avoided still remains relatively high compared to the costs in other EU sectors, indicating that the tax on fossil fuels in aviation that is set in order to attain a 3.5 % SAF share (rather than a tax that reflects the damage costs of GHG emissions) is a suboptimal policy for decarbonisation at lowest cost.

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[10] Tol (2012) considers a range of values. An important determinant is the social discount factor. He finds a mean valuation of reduced damage of 5 euro/ton CO_{2eq} for a 3 % discount rate and up to 76 euro/ton of CO_{2eq} for a 0 % discount rate.

The last part of the table also indicates that the welfare cost per tonne of GHG emissions avoided would be even 3 to 19 % higher if account is taken of the impact on the GHG emissions in the other EU ETS sectors.

6.1.2.4 Which SAF types would enter the market?

Figure 5 presents more detail on the SAF types that are used in the different scenarios. For the scenarios with the lowest SAF uptake the HEFA/HVO types of fuel are used first, with UCO and animal fats as feedstock and when these become too costly, also Camelina. With higher SAF demand FT-fuels are used, first with MSW as feedstock and next, as the MSW price increases due to the limited supply, with agricultural and forestry residues. Table 5 presents the associated price increases of the feedstocks compared to the baseline scenario. It is noted that these reflect the full policy scenarios that cover also road transport (and therefore also other fuels than the ones included in Figure 5), and not only the policies for aviation. UCO, animal fats and MSW are associated with the largest price increases, reflecting that the available amounts cannot be expanded. The price increases for the MSW feedstock are considerable, but its price is very low to start with in the baseline scenario.

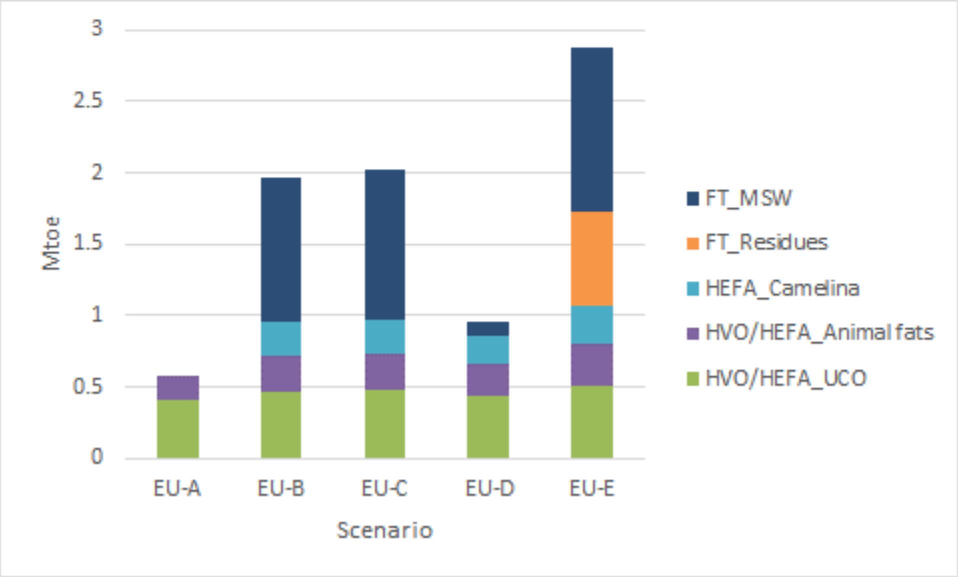

FIGURE 5: SAF DEMAND EU AVIATION – MTOE – 2030

	EU-A	EU-B	EU-C	EU-D	EU-E
	EU RED II	EU RED II (road & rail)			
		blending mandate aviation 3.5 %	SAF subsidy (3.5 % SAF share)	tax fossil jet fuel (3.5 % SAF share)	blending mandate aviation 5.25 %
UCO	+16%	+67%	+75%	+39%	+136%
Animal fats	+3%	+47%	+55%	+23%	+108%
Camelina		+30%	+37%	+8%	+85%
Residues	+6%	+2%	+5%	+5%	+2%
MSW		+512%	+671%		+1804%

TABLE 5: FEEDSTOCK PRICE CHANGE COMPARED TO THE BASELINE SCENARIO

6.1.2.5 Sensitivity analysis

Appendix B tests the sensitivity of the results with higher crude oil prices, higher conversion efficiencies in the production of SAF and a higher share of SAF in the case of joint products. None of these sensitivity studies changes our conclusions.

6.2 What can CORSIA policies bring us?

6.2.1 Assumptions on CORSIA policies

The CORSIA states that offsets need to be bought for CO_{2eq} emissions of international aviation above those in the CORSIA baseline. It is assumed that the emission reductions corresponding with the offsets are certified. As the model does not make a distinction between domestic (i.e. within a country) and international aviation, the CORSIA scenarios are assumed to apply to the whole sector of global aviation. For the year 2030 the number of offsets that needs to be bought for intra-EU, extra-EU and non-EU aviation equals the emissions in these three markets multiplied by the growth factor at world level for aviation in 2030 compared to the CORSIA baseline. Accordingly, the marginal cost of aviation fuels in the three aviation markets is augmented by a CORSIA charge. The CORSIA charge depends on the WTW emissions associated with each fuel as well as the ILUC emissions (see Table 2; all of the fuels in that table meet the CORSIA requirements). These are multiplied by the cost of carbon offsets. At this stage the cost of these offsets is not yet known. Therefore, two values are considered: a value of 10 € per tonne of CO_{2eq} (Scenario CORSIA-A) and a value of 50 € per tonne of CO_{2eq} (scenario CORSIA-B). In these two cases, the CORSIA is assumed to replace the EU ETS system. We also consider the case that for intra-EU aviation the ETS charge of 35 € per tonne of CO_{2eq} is added to the CORSIA charge of 50 € per tonne of CO_{2eq} (scenario CORSIA-C).

6.2.2 Effects of the CORSIA scheme on GHG emissions

Table 6 reports the effects of different CORSIA offset policies on the user cost, the GHG emissions and the welfare per tonne of GHG abatement. Under the CORSIA the emission constraint in the aviation sector can in principle be met by combining three efforts: reducing the demand for aviation fuels, using less carbon intensive sustainable fuels and buying offsets in other sectors.

The first important result is that, for the offset prices considered here, no SAF will enter the market. Fossil jet fuel becomes more expensive but this is insufficient to make SAF competitive. This result is in line with the implicit subsidies for SAF needed to force them in the market: of the order of 1000 €/tonne of SAF. The CORSIA scheme reduces aviation fuel demand by the additional levy as for the remaining emissions above the 2020 levels, offsets have to be bought in other sectors. The additional levies appear in the marginal costs and in the market price of aviation fuels.

Table 6 also presents the impact on the GHG emissions. Since no SAF are used in the three scenarios the impact on the WTW emissions gives the full impact. Scenario CORSIA-A leads to a reduction of aviation GHG emissions at world level by 1.6 % in 2030, while the two other scenarios, which involve a higher offset cost, lead to an emission reduction of about 9 % in aviation. The emission reduction is slightly larger when the EU ETS continues to apply for intra-EU aviation.

Table 6 reports the effects on the emissions of the other sectors in the EU ETS system. In scenarios CORSIA-A and CORSIA-B the EU ETS is assumed not to apply anymore to intra-EU aviation. This means that the non-aviation sectors in the EU-ETS can emit more, as the aviation emissions above the aviation cap do no longer need to be compensated by emission reductions in these sectors. The higher emissions in the other EU ETS sectors equal the difference between the TTW emissions of intra-EU aviation in the baseline and the ETS cap for aviation (or 59.8 – 37.9 = 21.9 Mtonne). In Scenario CORSIA-C the ETS is maintained for intra-EU aviation and the lower TTW emissions for intra-EU aviation compared to the baseline (-5.5 Mtonne CO_{2eq}) are compensated by higher emissions in the other EU ETS sectors. In general the impacts on the emissions of the other EU ETS sectors (and therefore also their impact on the welfare cost of GHG abatement) are however relatively small compared to the total emission reduction that takes place under the CORSIA schemes (considering both the aviation emissions and offsets).

6.2.3 The welfare costs of CORSIA policies

The welfare cost per tonne of GHG emissions avoided is below the value of the offset charge and ETS charge (if applicable). It is lower because we report the average cost of emission reduction rather than the marginal cost. The welfare cost remains much lower than in the case of the policies considered above. The reason is that SAF uptake that was imposed in the previous set of scenarios is a very expensive way to reduce GHG emissions. Reducing emissions by using offsets is 5 to 10 times cheaper.

	Baseline	CORSIA-A (offset cost 10 euro/tonne CO_{2eq})	CORSIA-B (offset cost 50 euro/tonne CO_{2eq})	CORSIA-C offset cost 50 euro/tonne CO_{2eq} and ETS for intra-EU aviation
SAF world aviation	Mtoe			
	0	0	0	0
Aviation fuel demand	Mtoe	% change w.r.t baseline		
Intra-EU + extra-EU	57.6	0.3 %	-7 %	-9.2 %
Non-EU	371.7	-1.9 %	-9.2 %	-9.1 %
User price aviation fuel	Euro/toe	% change w.r.t baseline		
Intra-EU	803	-9.4 %	5.8 %	19.0 %
Extra-EU	696	4.5 %	22.1 %	21.9 %
CO_{2eq} emissions	Mtonne	Change w.r.t baseline (Mtonne and %)		
World aviation (WTW)	1689.0	-27 (-1.6 %)	-150 (-8.9 %)	-154 (-9.1%)
Intra-EU aviation (TTW)	59.7	+2.7 (+4.5%)	-1.7 (-2.7%)	-5.5 (-9.4%)
Other ETS sectors (TTW)		+21.9	+21.9	+5.5
Welfare cost emission reduction		Euro/tonne CO_{2eq}		
World aviation WTW and offsets (in brackets: taking into account emissions other ETS sectors)		7.5 (7.8)	38 (39.8)	39 (39.7)

TABLE 6: IMPACTS AND COSTS OF CORSIA OFFSET POLICIES

7. Policy Implications and caveats

The analysis shows clearly that reducing GHG emissions in the EU aviation sector by imposing an uptake of sustainable aviation fuels is 5 to 10 times more expensive than other options. These welfare costs are not immediately transparent when blending mandates are imposed because the high costs of the SAF that are imposed are hidden in a small increase (4 to 10 %) of the average market price of aviation fuels in the EU. These results hold whatever policy mechanism one uses to guarantee a minimum SAF share: a tax on fossil fuels has a lower (but still a very high) welfare cost per tonne of GHG abated compared to a blending mandate and a SAF subsidy.

The cheapest policy alternatives rely on emission trading with other sectors, either via the EU-ETS or via the CORSIA scheme. This outcome was to be expected as for GHG emissions, the sectoral origin of the emissions does not matter.

What is learnt on the potential of competing SAF even if they are all still very costly? Some of the SAF that qualify as sustainable have a limited potential in terms of supply of feedstock: the HEFA/HVO types of fuel are used first, with UCO and animal fats as feedstock and when these become too costly, also Camelina. With higher SAF demand FT-fuels are used, first with

MSW as feedstock and next, as the MSW price increases due to the limited supply, with agricultural and forestry residues. So SAF may appear relatively affordable when the demand is very limited but encounter quickly supply problems with the tightened sustainability constraints.

This study has used expert estimates for the cost of biofuels. These estimates are valid for the medium term (2020-2030), but costs remain high. In the long term (after 2030) these costs may decrease by learning by doing (scale economies) and by pure R&D (Fischer and Newell, 2008). A possible extension of the study is to consider the long-term effects of the choice of policy instruments. This would also allow to incorporate other fuels types that are in earlier stages of technological development than the ones considered here. Two warnings are important here. First, policy makers tend to believe that a blending mandate or large implementation subsidies would be sufficient to make new fuels cost-effective. Policy makers tend to put too much emphasis on subsidies for learning by doing rather than pure R&D (Zachman, 2015). Second, the imposition of a very stringent renewable fuels standard may not be considered as a credible commitment by industry. Yao (1988) looks into this issue for cars and Dodd et al. (2018) look into the mind-set of the SAF supply industry.

Another extension is to consider the uncertainty about the opportunity cost of sustainable fuels, given that the price of oil, for which sustainable fuels are a substitute, is fluctuating strongly. This influences the choice between price-based versus quantity-based policy instruments, with also the possibility of hybrid policies, in which a quantity-based instrument is combined with price floor and a price ceiling (e.g. Weitzman, 1974; Roberts and Spence, 1976).

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Appendix A: The TRAFUMA model

Policy instruments

The TRAFUMA (Transport Fuel Markets) model is written such that it can take into account the following policy instruments which are relevant for the transport fuel markets considered:

- ad valorem indirect taxes,
- excise type indirect taxes,
- the ETS charge for intra-EU aviation, which is included in the EU Emission Trading System (ETS)
- a carbon offset price for the aviation sector,
- an environmental tax per tonne of emissions,
- a blending mandate, i.e. an exogenously imposed share or target of sustainable fuels in one or more transport markets,
- a subsidy for sustainable fuels in order to reach an exogenously imposed share or target of sustainable fuels,
- a tax on fossil fuels in order to reach an exogenously imposed share or target of sustainable fuels.

In the latter three cases, the model also allows incorporating multipliers that may be used to encourage the use of certain subgroups of sustainable fuels. Additional constraints on the share of specific subgroups of fuels can also be taken into account.

Model equations

The model equations are as follows:

- Total supply of fossil and other fuels to each market should be at least as large as total demand in that market (for road and maritime transport in EU and non-EU; for EU fuels used for intra-EU and extra-EU aviation and for non-EU fuels used for extra-EU and non-EU aviation).
    - Total supply of sustainable fuels consists of different types of sustainable fuels. These sustainable fuels are either the primary product of the production process, or a co-product.
- Each fuel supplier produces until the marginal cost of production equals the value it receives from additional output. This is the basic rule for competitive behaviour. The marginal cost of production is a function of the volume supplied (cf. supra). For fossil fuels and fuels produced with sugarcane as feedstock, a world supplier (and hence also a world price) is assumed. For the other non-fossil fuels a distinction is made between the EU and non-EU suppliers. The different treatment for fuels based on sugarcane and other non-fossil fuels is related to the different availability of supply functions for the feedstocks in the MAGNET model that provides inputs for the TRAFUMA model. For sugarcane the supply function is available at world level, while for the other feedstocks it is available for the EU and non-EU separately.

- For each fuel market, supply should equal demand.
- EU demand for aviation fuels equals demand of EU fuels for intra-EU and extra-EU aviation.
- For each transport market, the user price of each fuel is at least as large as the equilibrium price of fuel in that market. The user price of the fuels includes the pre-tax price and – depending on the policy scenario – the indirect taxes, ETS charge, carbon offset price, environmental taxes and endogenous tax on fossil fuels and/or endogenous subsidy for sustainable fuels.
- For markets for which a blending mandate is imposed, the share of sustainable fuels should be at least as large as that set by the mandate. For some specific fuels, a multiplier may apply.
- For markets for which a target is imposed for the amount of sustainable fuels, the quantity of sustainable fuels should be at least as large as set by the target. For some specific fuels a multiplier may apply.
- For markets for which a blending mandate or a target is imposed, it is operationalised with a combination of a virtual tax of fossil fuels and a virtual subsidy for sustainable fuels. The revenues from the virtual tax on fossil fuels should then cover the amount paid to sustainable fuels in the form of a virtual subsidy[11].
- For each feedstock (except crude oil, for which the price is taken as exogenous), total demand from transport equals demand for the production of the transport fuels. For sugarcane, a world market is assumed. For the other feedstocks, a distinction is made between the EU and non-EU market. The demand for feedstocks is related to the production of sustainable fuels via an exogenous value for the tonnes of feedstock required per toe of fuel.
- The price index for each feedstock depends on the total volume that is used for the production of fuels. This endogenous price index is applied to an exogenous scenario for the feedstock price evolution, which represents the price evolution that would take place without the demand of feedstock required for the production of transport fuels.

The TRAFUMA model is solved using the MCP solver of GAMS[12].

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[11] In practice, the blending mandate functions in two possible ways. In the first case, the same firm produces both the “cheap and dirty” fuel and the “expensive but green” fuel, and then the firm subsidizes internally the production costs of the more expensive fuel. When the two fuels are produced by separate firms, the cheap fuel firms have to pay the expensive fuel firms to reach the right proportion of fuels on the market. This can take the form of “green certificates” sold by the expensive firms to the cheap firm. In both cases the result comes down to a “virtual” tax/ subsidy system that operates between firms and where there is no cost or revenue for the government.

[12] General Algebraic Modeling System (www.gams.com); “MCP” stands for “mixed complementarity problem”.

Model calibration

Supply functions

For fuels sold in the base year (i.e. fossil fuels and the aggregate of biodiesel FAME and bioethanol) the supply functions are calibrated based on values for the base year for quantities supplied and prices as well as assumptions about the price elasticity of supply. The value for the supply elasticity of fossil fuel is based on de Gorter & Just (2009), while that of biofuels of the first generation is based on Hochman et al. (2011), who consider a range of 5 to 20 and for which we use a central value of 10. A supply price elasticity of 10 means that for a price increase of 10 %, producers are ready to supply 100 % more in the medium term.

For the sustainable fuels no information is available on the supply elasticities and an assumption is made based on the values corresponding with a modest price increase per extra toe of fuel (for given feedstock prices). In addition, the impact of changes in demand for sustainable fuels on feedstock prices is taken into account.

For future years, the model takes into account the impact of exogenous changes in crude oil (in accordance with the EU reference scenario) and feedstock costs. The latter are based on a reference scenario derived from the MAGNET model (see Novelli et al., 2019).

Demand functions

For the base year, the linear demand functions are calibrated based on data for fuel demand and fuel prices in the base year, as well as fuel demand elasticities. The data sources for fuel demand and fuel prices in the base year are summarized above. The demand elasticities used for the analysis in this paper are based on the following studies:

- Road transport: Goodwin et al. (2004)
- Maritime transport: IMF & World Bank (2011)
- Aviation: IATA (2008) and Brueckner & Abreu (2017), using data on transport flows from Boeing (2016)

Transport mode	Market	Scenarios for elasticity values		
		CENTRAL	HIGH	LOW
Road transport	EU and non-EU	-0.64	-1.08	-0.2
Maritime transport	EU and non-EU	-0.45	-0.68	-0.23
Aviation	Intra-EU	-0.48	-0.72	-0.24
	Extra-EU	-0.42	-0.62	-0.21
	Non-EU	-0.42	-0.62	-0.21

TABLE A 1: ELASTICITY VALUES FOR FUEL DEMAND BY ROAD, MARITIME AND AIR TRANSPORT

The following assumptions are underlying the elasticity values for aviation:

- Fuel costs have a share of 33 % in operational costs of aviation (IATA, 2016).
- Changes in operational costs are fully reflected in fares.
- The elasticity of travel demand w.r.t. fares ranges from –0.4 to –0.8 depending on the market segment (IATA, 2008). Taking into account the shares of the market segments (based on Boeing, 2016), the fare elasticity of demand would be –0.37 for intra-EU aviation and –0.3 for extra-EU and non-EU air travel.
- The elasticity of fuel efficiency w.r.t. the fuel price is taken to be approximately 0.22. For this we start from the short run fuel price elasticity that has been derived by Brueckner & Abreu (2017) to which we apply the ratio between the long term and short term fuel price elasticity for road transport, as determined in Goodwin et al. (2004).

For future years, the demand side of the model is calibrated such that it follows the long-term outlook of the baseline scenario as described in the main section of this paper.

Production processes

The next two tables present more information on the conversion factors and share of different co-products that are taken into account in the sustainable fuel production functions of the TRAFUMA model.

Fuel type	**Feedstock**	**Ton of feedstock per toe of fuel**	**Reference**
HEFA, HVO/HEFA+	All	1.2	Bann et al. (2017)
SIP	All	13.4	de Jong et al. (2015)
FT	Residues and energy crops	6.5	de Jong et al. (2015)
	MSW	3.7	Bann et al. (2017)
ATJ	Residues	8.6	de Jong et al. (2015)
	Sugarcane	24.3	Calculations based on Tao et al. (2017)
	Sugar beets	19.1	Calculations based on Tao et al. (2017)
CE (Road)	All	5.8	SGAB (2017)

TABLE A 2: CONVERSION EFFICIENCY OF THE PRODUCTION PROCESSES (TON OF FEEDSTOCK PER TOE OF FUEL)

Fuel type	**Feedstock**	**Toe of road fuels per toe of SAF**	**Reference**
HEFA, HEFA+	All	5.4	Bann et al. (2017)
SIP	All	0.2	de Jong et al. (2015)
FT	Residues & energy crops	3	de Jong et al. (2015)
	MSW	6.9	Bann et al. (2017)
ATJ	Residues	0	de Jong et al. (2015)
	Sugarcane or sugar beets	0.3	Calculations based on Tao et al. (2017)

TABLE A 3: CO-PRODUCTS: TOE OF ROAD TRANSPORT FUEL PER TOE OF AVIATION FUEL

Appendix B: Sensitivity analyses

Three sensitivity analyses have been carried out for Scenarios EU-A and EU-B. In the first one also the baseline scenario is affected, while in the two other the baseline remains the same as in the analysis described above (central case).

A crude oil price that is 25 % higher[13]. This leads to a lower fuel demand already in the baseline scenario in which road and air transport fuel demand drops about 3 % compared to the central case. In Scenario EU-A the higher crude oil price leads to a higher reduction in the demand for sustainable fuels than for fossil fuels. If a separate blending mandate is imposed for aviation, as in Scenario EU-B, this is also the case for road transport, but the percentage change in the amount of SAF is by definition equal to that of fossil jet fuel as a target share of SAF is imposed. In both scenarios the total amount of renewable fuels in road and air transport taken together is reduced by 2.4 % to 2.5 % compared to their values in Table 4.

A higher conversion efficiency in the production of SAF (10 % to 25 % less feedstock needed per toe of SAF, depending on the production pathway). In Scenario EU-A this increases the amount of SAF by 0.1 Mtoe (increase by 20 %). The total use of sustainable fuels in aviation and road transport however falls by 0.1 %, because more fuels with a higher RED II multiplier are used. In Scenario EU-B, which imposes a separate target for aviation, the total amount of sustainable fuels is increased by 0.2%, while that in aviation increases by 0.5 %. The higher conversion efficiency makes the fuels cheaper, but not to the extent that their attractiveness increases substantially.

The share of SAF in sustainable fuel production is increased (the amount of co-products for road transport is 50 % lower for HEFA, HVO and FT based on MSW). This leads to a higher use of these fuels in aviation. In Scenario EU-A the higher RED II multiplier for aviation fuels implies that less sustainable fuels should be used in road transport in order to meet the target. This leads to a decrease by 0.4 % in the total demand for sustainable fuels by road and air transport. In Scenario EU-B the lower SAF cost leads to a higher fuel demand, both for fossil and sustainable fuels. More HEFA, but less FT fuels are used. For road transport the higher share of air co-products leads to a slightly higher user price of road fuel and a slightly lower fuel demand (– 0.1 %). The sum of demand for sustainable fuels by road and air transport falls by 0.9 %.

The conclusion from the sensitivity analysis is that the impacts of these three variations are generally relatively small. In addition, with the RED II multiplier for aviation in Scenario EU-A, lower SAF costs can lead to a lower uptake of sustainable fuels when road and air transport are considered together.

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[13] it should be noted that a higher crude oil price will have broad economic impacts with consequences also for transport demand; however, in this case we make abstraction of these broad economic effects and focus on the direct impact of higher crude oil prices for transport. The sensitivity analysis does not consider the impact of the crude oil price change on the production costs of sustainable fuels.