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Research paper

Analysis of current aviation biofuel technical production potential in EU28

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ABSTRACT

The significant growth aviation has been observing is increasing the sector's pressure on the environment; in the EU28, passengers travelling by air in 2016 increased of 5.9% compared to 2015. The aviation industry voluntarily committed to significant aspirational goals, and identified bio-based aviation fuels as a potential means to improve its environmental performance. Despite of that, the market penetration of aviation biofuels in EU28 is almost negligible. In this paper, an assessment of the likely aviation biofuels demand has been carried out, under a baseline scenario of increasing total fuel consumption of +3% for 2016–2020 and + 3.5% up to 2030; the CO_2 intensity of this growth has been calculated accordingly. Europe is a World leader in biofuel technologies; the current potential aviation biofuels is based on the HVO/HEFA technology, and the upper limit of the installed capacity can be considered approximately 2.4 Mt y^{-1}. Nevertheless, lower production volumes can be expected as production plants are today optimized for road fuel production, not aviation. By 2025 the situation may change, with a total production capacity of 3.5 Mt y^{-1}, and with an average potential production for aviation biofuels ranging 0.5–2 Mt y^{-1}. The paper shows that even if today's EU nominal capacity appears large enough to support the expected aviation biofuels demand, other bottlenecks may limit the real market uptake: availability of sustainable feedstocks, competition with demand for road transport sector, etc. For this reason, a comparison of the cost for CO_2 saving of other potential solutions to mitigate aviation's climate impact has also been carried out.

1. Introduction

Aviation is the transport mode that is showing a significant, steady and quite rapid growth in the EU. The international aviation segment accounts for 12.8% of energy consumed (1916 PJ), whereas domestic aviation uses only 1.54% (232 PJ) of the energy [1]; in term of fuel quantity, EU market values about 53 Mt y^{-1} and about 280 Mt y^{-1} worldwide in 2017. Forecasts for civil aviation in the coming years are mostly for a steady growth; authors such as Alonso [2] predict a constant 3.5% annual growth rate for the European area, in the period 2021–2030. Figures like these are supported by International Air Transport Association (IATA), which set a 3.7% annual Compound Annual Growth Rate (CAGR) in its 20-year air passenger forecast [3].

In line with these figures, during the last decades, the environmental impact of aviation has been growing: global aircraft CO_{2eq} emissions nearly doubled from 88 to 156 Mt y^{-1} in the period 1990–2005, and increased by a further 5% between 2005 and 2014. Interestingly, the increase in emissions has over the same period been lower than the increase in passenger-km (PKM); this reduction in specific PKM emissions (−19%) has been achieved mainly by technical improvements and fleet renewal [4]. For the future, the aviation industry has set an aspirational goal of carbon neutral growth (CNG) from 2020 [5]. The main measures intended to achieve this goal are: technical engine and aircraft aerodynamic and materials improvements; increased fuel efficiency; better air traffic management [6] and the utilization of low-carbon fuels. In contrast to other modes of transport (i.e. road or marine), aviation has a lower flexibility with respect to the use of alternative solutions for fuel; alternative propulsion options, like liquid natural gas, hydrogen, hybrid systems, etc., have been proposed and several solutions already tested, but the most attractive short-to-medium term options for the air transport industry still remains to continue to operate existing engines with lower impacting liquid fuels [7,8]. As aviation industry has significant environmental and energy challenges to address in near future, but less options than other sectors for alternatives (i.e. electrification, H_2, etc.): the sector recognizes biofuels as a potential means to improve environmental performance and reduce oil dependency [9].

International Civil Aviation Organization (ICAO) provides a broad definition of Aviation Alternative Fuel (AAF), and, within this group, alternative fuels which actually have the potential to be sustainably

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Abbreviations

ABP	Animal By-Product
ARA	Amsterdam-Rotterdam-Antwerp area
ASTM	American Society for Testing and Material
ATJ	Alcohol-to-jet
CAAFI	Commercial Aviation Alternative Fuels Initiative
CATJ-SKA	Catalytic ATJ-synthetic kerosene with aromatics
CBJ	Current Bio Jet case
CCS-APR	Catalytic conversion of sugars by aqueous phase reforming
CH	Catalytic Hydrotreating
CIC	Current Installed Capacity
CIF	Cost, Insurance and Freight
CNG	Carbon Neutral Growth
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
FRL	Fuel Readiness Level
FT	Fischer-Tropsch
HBJ	High Bio Jet case
HDCJ	Pyrolysis - hydrotreated depolymerized cellulosic jet
HEFA	Hydrotreated Esters of Fatty Acids
HVO	Hydrogenated Vegetable Oil
ICAO	International Civil Aviation Organization
MSW	Municipal Solid Waste
SIP	Synthetic Iso-Paraffinic
SPK	Synthetic Paraffinic Kerosene
TRL	Technology Readiness Levels
UCO	Used Cooking Oil

produced - supporting aviation footprint reduction – are called Sustainable Aviation Fuel (SAF) [10]. The definition of the sustainability criteria for Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) differs compared to the European context: at European level, the current Renewable Energy Directive [11] as well as its recently agreed Recast (RED II) [12,13] set criteria which a biofuel must meet in order to be considered sustainable. European directives define minimum GHG savings, which biofuels must achieve: for the new RED II, sustainable biofuels (made in facilities beginning operation after 2020) will have to achieve GHG savings of at least 65% respect to the fossil fuel comparator. Other sustainability criteria in the RED require that the biofuel feedstock has not been grown in areas converted from land with previously high carbon stock; and does not come from land which has high biodiversity. Beyond these criteria, the RED also includes non-mandatory socio-economic sustainability criteria on the impacts of biofuels production. CORSIA – at least in its inception phase - limits the definition of sustainability to minimum GHG emission reduction threshold and to carbon stock concerns [10]; accordingly to several studies (i.e. [14]), the criteria today set for CORSIA may not be sufficient to guarantee a real sustainability of the aviation biofuels productions.

In order to assess a potential for the penetration of biofuels in aviation, this has to be considered alongside biofuel demand generated in the road sector, where mandates for alternative fuels uptake are implemented. The RED II includes aviation as an opt-in at the discretion of EU Member States and defines no mandates for this transport mode, while indicating a report to be completed by 2021 on the possible use of biofuels in aviation; RED II annexes currently do no define any default/typical values for AF nor a jet-specific fuel comparator to benchmark against. The RED II foresees that eligible biofuels used in aviation can count 1.2 times their energy content towards the mandated renewable energy target. These differences between road transport and aviation are expected to influence the availability and therefore the market uptake of biofuels in the respective modes in the short-medium term.

The present study aims to investigate the EU current aviation biofuel production sector, and to bring forward the discussion on the availability of sustainable feedstocks, which could potentially cover the EU-domestic demand in the aviation sector.

2. Material and methods

In this paper the current available conversion technologies, for producing alternative fuels for aviation, have been identified by a survey carried out by means of a review of the available scientific literature as well as on other publicly available sources. Beside the assessment of the current technical potential, an appraisal of the maturity level of the various production pathways has been carried out. All these information have been summarised in a database, which JRC constantly updates (a summary of an extract of the interesting data from the database is available as annex).

2.1. Definition of aviation biofuels pathways

In order to be considered as a real alternative to fossil jet, a biofuel has to respect specific quality characteristics. The American Society for Testing and Materials (ASTM) issued two technical norms regulating the sector: ASTM D4054 (Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives), which describes the qualification process for an alternative fuel to be considered compliant for use in ASTM D7566 – 17a (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons). The procedure does not describe the required quality of the fuel itself but the pathway needed for its production. Currently six production pathways are already fully certified for blending with fossil aviation jet. These aviation biofuels are drop-in fuels: they can be directly blended with fossil (ASTM D1655: Specification for Aviation Turbine Fuels) but with differing blend limits:

- **FT-SPK** (Fischer-Tropsch Synthetic Paraffinic Kerosene). Biomass is converted into syngas and then in aviation biofuels fuel, by the FT process. The pathway was approved by ASTM in 2009, and UK MOD DefStan (91-91). FT-SPK aviation biofuels can be blended up to 50% on volume base with fossil jet fuel.
- **HEFA** (Hydroprocessed Fatty Acid Esters and Free Fatty Acid). Lipid feedstocks, such as vegetable oils, used cooking oils, tallow, etc. are converted using Hydrogen into green diesel, which can be further isomerized and separated to obtain a jet fraction. The pathway was approved in 2011 to be blended at 50% percent with fossil jet fuel.
- **HFS–SIP** (Hydroprocessing of Fermented Sugars - Synthetic Iso-Paraffinic kerosene) was approved by ASTM in 2014. Using modified yeasts, sugars can be converted to hydrocarbons, specifically the existing approved process produces a C-15 hydrocarbon molecule called farnesene. The resulting aviation biofuels can be blended with fossil jet up to a 10%.
- **FT-SPK/A** is a variation of FT-SPK, where alkylation of light aromatics creates a hydrocarbon blend, which includes an aromatic part. This process was approved in 2015, for a maximum blending rate of 50%.

- **ATJ-SPK** (Alcohol-to-Jet- Synthetic Paraffinic Kerosene) was approved in 2016. Dehydration, oligomerization and hydroprocessing are used to convert alcohols, such as iso-butanol, into hydrocarbon. The certified aviation biofuels is allowed for blending of 50% maximum.
- **Co-processing** This pathway has been approved in April 2018, and it is now recognised in Annex A1 of ASTM D1655. Lipid feedstock of biological origin (fats, oils and other residues) can be mixed up to 5% by volume with fossil crude for supplying the refining process, and the resulting product is allowed to contain up to the 5% of the bio-component.

There are additional pathways in the pipeline for ASTM certification [15,16] but today they are not contributing to the definition of a commercial production potential:

- **CCS-APR** (Catalytic conversion of sugars by aqueous phase reforming).
- **CH** (Catalytic Hydrotreating of lipids to jet fuels) [17].
- **CATJ-SKA** (Catalytic upgrading of alcohol intermediates - catalytic ATJ-synthetic kerosene with aromatics).
- **ATJ-SPK expansion** (Catalytic upgrading of ethanol).
- **HEFA expansion** (**HEFA +**) (direct use of a wider cut of HEFA with renewable diesel).
- **HDCJ** (Pyrolysis - hydrotreated depolymerized cellulosic jet).

2.2. Definition of the share of aviation biofuels

Europe can today be recognised as a World leader in biofuel production technologies, with a significant number of commercial plants in operation, able to produce ASTM-compliant aviation biofuels. The current most important technology, in terms of installed nominal capacity, is the HEFA/HVO process. HEFA is obtained from Hydrogenated Vegetable Oil (HVO), basically by adding other process steps such as fractionation and isomerization. The refineries, operating with biomass feedstocks, are typically optimized to produce a middle distillate, which is an alternative diesel-like drop-in fuel in road transport. When road fuels are the main desired output, the typical share of ASTM-certified aviation biofuels results in the range of 15% by volume. Maximising the aviation biofuel output is possible, but tends to reduce the overall refinery outcome, in the range of middle distillate. Studies from authors such as Pearlson [18] and Staples [19] suggest that the maximum for the HEFA process can be considered up to 55–60% of the total refinery output. Similarly, also for the other production pathways, a technical maximum yield in aviation cut has to be considered: 32% for Fischer–Tropsch and 85% for Alcohol-To-Jet, respectively [20–23].

In this study these ranges have been used to define to different EU28 production potentials for aviation biofuels, based on the current installed capacity (CIC): the first one considering the current share of aviation fuel in the refinery output (defined as Current Bio Jet - CBJ), and a second one where the production of aviation cut is maximised (defined as High Bio Jet – HBJ).

3. Results

3.1. Definition of maturity level for aviation biofuels pathways

Defining the maturity level of the available aviation biofuels production pathways, either from a technological or from a commercial point of view, is challenging and, despite the great dynamism of the sector, hardly any ASTM certified aviation biofuels batches are supplied at commercial scale today.

The technological maturity of a production pathway can be described through the Technology Readiness Levels (TRLs) [24]. TRL is typically represented by a figure ranging from TRL 1 to TRL 9: TRL 9 is used to define a process actually proven in operational environment, TRL 7 is for demonstration initiatives and TRL 6 is for a technology demonstrated in relevant environment. Among the ASTM certified pathways, HEFA process has the highest TRL, as there is a relevant amount of production potential already installed and the plants are in operation, supplying fuel for flights [25]. More debatable is the maturity level definition of the Fischer-Tropsch pathway that, despite being the first to get ASTM certification, is today not yet fully commercial. There are significant initiatives across the globe that are proving the potential of the FT process from biomass, nonetheless the expectations of the aviation sector appear today to be unsatisfied. The production of aviation biofuels from sugars is a promising pathway and pilot plants are already supporting scale-up initiatives. For Alcohol to Jet, despite scientific literature defining a TRL of about 6–7 [22], the supply of aviation biofuels for commercial flights already occurred [26] demonstrating a higher maturity level for this technology.

Other international initiatives (CAAFI [17]) use the Fuel Readiness Level (FRL) scale: it includes descriptions that are customized to fuel research and certification events and includes specific items, including required fuel quantities; the scale rates ASTM-certified fuels at FRL7 or higher [8]; while for the other still non-certified pathways the FRL ranges from four to six. Table 1 shows the main outcomes of the performed evaluation.

Table 1
TRL and FRL of the five ASTM-Certified pathways.

Process		TRL	FRL
Fischer-Tropsch Synthetic Paraffinic Kerosene	**FT-SPK**	6–8	6-7
Hydroprocessed Fatty Acid Esters and Free Fatty Acid	**HEFA**	9	9
Hydroprocessing of Fermented Sugars - Synthetic Iso-Paraffinic kerosene	**HFS–SIP**	7–8	5–7
Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics	**FT-SPK/A**	6–8	6-7
Alcohol-to-Jet- Synthetic Paraffinic Kerosene	**ATJ-SPK**	7–8	7

3.2. Current EU production potential

Based on the available data and information, it is possible to define an EU28 Current Installed Capacity (CIC), which represents the overall (jet and middle distillate) production capacity of the refineries suitable for obtaining alternative aviation fuels. As shown in Table 2, today this potential - in terms of installed capacity - accounts for about 2.4 Mt y^{-1}; this values is in good agreement with other sources (i.e. [27–29]).

Considering the typical share of aviation fuel cut, obtainable from refineries - currently optimized for road fuel production – the EU potential drops to 355 kt y^{-1} (Current Bio Jet - CBJ). Under a scenario of high demand for aviation, technically the aviation biofuels share can be increased up to 1.4 Mt y^{-1} (High Bio Jet – HBJ in Table 2).

Despite this technical possibility, the market today seems to be still stably oriented to road fuel production. In coming years, co-processing of alternative feedstock (fats and oils) with crude oil - recently certified by ASTM within the limit of 5% - could significantly contribute to the EU overall aviation biofuels production potential. Additionally, by 2020 the situation may significantly change, with the possibility to use a larger portion of the current production potential, as well as because of new plants and technologies entering into operation (e.g. TOTAL is

Table 2
Estimated EU aviation biofuels potential
(CIC: current installed capacity; CBJ: current biojet capacity, HBJ: capacity with refineries optimized to maximize aviation output).

Mt y^{-1}	CIC	CBJ	HBJ
2018	2.37	0.36	1.42
2025	3.52	0.55	2.08

planning to reach commercial state for its demo plants, achieving a potential of 200 kt y^{-1} for the Thermochemical pathways [30]). For instance, with so-called HEFA+ (or HEFA extension) comes the possibility to use a wider cut of HVO, at low blend levels, as a drop-in aviation biofuels (this pathway is currently in the pipeline for ASTM-certification).

The current analysis has been carried out at EU scale as, considering the global scope of the aviation industry, it is more likely the final products will be utilised in airport close to the places of production, rather than transported across the globe (although feedstocks could be traded if, or once, demand for aviation biofuel supports larger production volumes). Nevertheless, in this current scenario of market uncertainty, significant investments in other ASTM-certified pathways (e.g. ATJ and SIP) do not appear to be a priority for major industrial players in Europe.

It is worth noting that, on the production side, there is still room to improve capacity in existing plants, which might reduce the midterm demand-supply mismatching effect of today's lack of significant investments.

3.3. Appraisal of the potential EU aviation demand for aviation biofuels

Defining a potential for EU aviation biofuel demand is challenging, as the sector does not have to comply with specific mandates and only voluntary targets are currently set by industry in Europe. The market penetration of aviation biofuels is increasing slightly [10], but the overall use of biofuels remains low [4]. De Jong [31] production volumes of aviation biofuels up to 2015 as being negligible, mainly due to high impact of feedstock on the final production costs, which are at least twice as much as fossil based jet fuel (commercially known as Jet A1), and to the absence of an external incentive.

Forecasts for sector growth are considered here in order to identify a reasonable volume for the overall demand of jet fuel and therefore for aviation biofuels substitution potential. In EU28 (plus Iceland, Liechtenstein, Norway and Switzerland), Jet A1 consumption reached 55 Mt in 2018. According to previous studies [2,4,5], a baseline scenario can be defined which considers an increase in fuel consumption of about +3% for 2016–2020 and + 3.5% for 2020–2030.

As presented before, the aviation industry set an aspirational goal of carbon neutral growth from 2020 onwards; the evaluation of the fuel demand can be performed by coupling the expected increment in passengers with considerations about the efficiency improvements allowed by fleet renewal; in this case the IATA 1.5% yearly coefficient has been considered [2]. The carbon intensity of this growth can be calculated accordingly. In 2021, the fuel needed for covering the expected growth in aviation demand will account for 1.87 Mt of Jet A1, with a consequent emission of 5.70 Mt of CO_2.

In order to estimate a future potential for aviation biofuels penetration, it is worth considering that the current market is dominated by HEFA from lipid feedstocks, and the appearance of significant alternative pathways by 2021 is unlikely. Based on the sector's aspiration for neutral growth from 2020 onward, CO_2 growth is balanced by HEFA. According to previous studies [19,32], the GHG saving of HVO from Used Cooking Oil (UCO) [12] - to which a stage of isomerization is added - ranges from 81 to 87%, respect to fossil derived fuels. Assuming the lower value of this range (81%), the consequent emission reduction accounts for 2.56 kg of CO_2 per kg of aviation biofuel produced from UCO. In order to balance the estimated emissions from the expected growth in 2021, the theoretically required volume of HEFA from Used Cooking Oil would result in 2.3 Mt y^{-1}; representing approximately the 3.8% of the total Jet A1 consumption in EU28. Interestingly, this value is practically equivalent to the current European current installed production capacity (CIC), and well aligned with the target set by EU flightpath for 2020 [33].

4. Discussion on aviation biofuels market penetration

Even if the EU nominal plant capacity appears today to be large enough to support the potential aviation biofuels demand, concerns arise on the availability of sustainable feedstocks and competition with their demand in road transport. The defined potential for aviation biofuels relies on the possibility to use a larger cut of the current refineries production for aviation, but this approach can be considered only in the unlikely scenario of a strong reduction in road transport demand in favour of aviation. It is more realistic to anticipate that a lower share of aviation biofuels compared to the maximum potential will in fact become available. In order to estimate the potential competition between the two sectors, it may worth considering that, according to Ref. [28], the estimated aviation biofuels required for achieving the sector neutral growth, is equal to 16% of the current total biofuel consumption.

The current aviation biofuels production potential it is based on HVO/HEFA cut from hydrogenation of lipid feedstocks; as described in previous paragraphs, the amount of the HEFA can vary for different plant settings, which in turn is a function of the relative opportunity of producing more aviation over road biofuels.

The technical potential has also to consider the likely availability of sustainable feedstock, as HEFA will remain the main actor on the scene, the lipid feedstock technical availability is expected to constitute a limiting factor, especially in light of the sustainability aspects.

4.1. Availability of sustainable feedstocks

The current demand of feedstock for biofuel production is significant. Concerns about the sustainability of feedstocks used for biofuels have arisen in the RED [12] where the EU re-thought its biofuel policy and defined a set of criteria aimed at ensuring the sustainable use of biofuels (transport) and bioliquids (used for electricity and heating). Outside Europe, international aviation has recently agreed on a set of criteria for defining an alternative fuel as sustainable. Within the ICAO CORSIA scheme, the life-cycle emissions of alternative jet fuels have to demonstrate a minimum GHG saving of 10% - encompassing direct and indirect (ILUC) emissions, according to CORSIA methodology - compared to fossil kerosene. Moreover, sustainable biofuels should not be produced from biomass obtained from land converted after 2009 [34]. Defining feedstock sustainability is certainly debatable, as many different aspects can be taken into consideration and no overarching agreement on a definition exists neither at scientific nor political levels. At international level, the definition of what constitutes a sustainable aviation biofuel has been significantly simplified, certainly in comparison to Europe and the discussion of biofuels sustainability in the current RED Recast, as well as the surrounding safeguards provided by the broader regulatory context. Moreover, several feedstocks are perceived as having a better sustainability performance than others; in this study, feedstock suitable for aviation have been considered the non-food oil crops, waste cooking oil and other lipidic residues. Feedstock sourcing and processing are ongoing challenges for industry, as their composition is strongly variable, requiring constant plant adaptation. In order to mitigate this issue, practically all the industrial players of the sector have announced the installation of pre-treatment units for their plants [35].

Lipid feedstocks used for the production of HEFA aviation biofuels are today mainly based on palm oil and palm industry co-products (e.g. Palm Fatty Acid Distillate (PFAD), Palm Kernel Oil (PKO), etc.), nevertheless their sustainability is widely debated and their importance is expected to reduce in medium term.

Among oil bearing crops that are alternative to traditional varieties used for human and animal food, several options have been explored in recent years, but most of them with low market impacts: i.e. Jatropha, cotton oil soapstock [36 [36]], tobacco oil [37], etc. An interesting work has been carried out in the framework of the FP7 EU supported project ITAKA [38,39] on Camelina oil (*Camelina sativa* L. Crantz). New projects are trying to demonstrate these potentials by means of larger production, i.e. BIO4A [40].

Used Cooking Oil (UCO) is also widely considered a promising feedstock for aviation biofuels production. An accurate estimation of the UCO potential in the EU is complicated both by a shortage of available data and by the reliability of reported numbers, where ranges are considerable. Available volumes in EU are predominantly estimates based on volumes collected from the commercial sector, as the collection of UCO is regulated by EU law; the potential resources of used cooking oil collected per capita varies considerably between countries. By 2017, the volume of UCO collected from households in the EU was estimated to have grown to just under 48 kt y^{-1}, while the total possible UCO volume theoretically available from households was estimated as being 854 kt y^{-1} [41]; USDA [29] reports a total use (including imports) for 2018 of about 2.8 Mt y^{-1} in EU.

Animal fat (or tallow), is one of the two main products from rendering animal by-products (ABPs); the other being solid protein. Tallow is a potential feedstock for aviation biofuels production although almost all the volumes of this material – at least in the EU - are already in use. Just under 2.8 Mt of tallow was produced in the EU in 2016 according to the European Fat Processors and Renderers Association (EFPRA) [42]. The EU categorizes ABPs as Cat 1, 2 or 3 depending on the risk they pose to public and animal health (Regulation (EC) 1069/2009); with Cat 1 material having the highest risk. Tallows have varying existing uses depending on the category they belong to, in 2016 approximately 620 kt of Cat 1 and 2 fats and 500 kt of Cat 3 fats were used as fuels (principally for biodiesel manufacture and a smaller fraction used for direct combustion) with the rest mainly being used by the animal feed and oleo-chemical industries [42].

Aviation fuel could also be made from the estimated annual EU crude tall oil (CTO) resource of 650 kt [43], or more likely distilled tall oil fraction of CTO, as crude tall oil is said to contain impurities which damage the hydrotreating catalysts [44]. Tall oil was described as a 'biomass fraction of wastes and residues from forestry and forest-based industries' and was added in 2015 to the list of materials from which biofuels could be made and which would 'count double' towards a Member State renewable energy target; however real availability of this feedstock is debated [43].

The price volatility of the lipid feedstock is a quite relevant issue for industry, for instance animal fat (cat 1 and 3) and palm oil had, in 2016, an average price increase of 30%–40% [35]. In 2017, the average price for UCO changed from 560 € CIF Europe to 615 € t-1 and Tallow Methyl Ester (TME) from 886 to 915 € t-1 FOB ARA.

Lipid feedstock are not the only option for the sector, technologies like FT can be supplied by lignocellulosic materials; US DOE reported that the USA produces 1.18 Gt of dry lignocellulosic biomass per year [15], with 933 million tonnes y^{-1} of agricultural residues and 368 Mt y^{-1} of forestry residues [45,46]. However, questions remain whether lignocellulosic biomass could be available in sufficient quantities to cover the demand for materials, animal feed, and other applications such as biofuel production and bio-based chemicals [47]. After a study lasting two years, JRC presented the results on biomass flow, supply and demand on a long-term basis for the European context [48]. Total EU28 domestic biomass production from land-based sectors (agriculture and forestry) in 2013 accounted for 1.4 Gt of above ground dry matter, with agriculture the biggest supply sector providing 65% of the total, followed by forestry with 34%. In agriculture, the crop economic production is almost entirely harvested and marketed (514 Mt y^{-1}), while the residues that amount to 442 Mt y^{-1} are used only used at a rate of 23%. Part of the uncollected potential could be removed to produce bio-based materials and energy, while the other part should be left to preserve the soil structure and fertility and maintain ecosystem services including soil organic carbon levels or preventing soil erosion. The study also investigated the EU28 wood potential, estimating an average annual harvest level of 271 Mt y^{-1} (of which 224 Mt y^{-1} are removed from forests); similarly to the agricultural sector, part of the residue potential could be removed for bioenergy or bio-based materials. At EU level, reported data indicate that energy accounts for nearly half (48%) of the total use of woody biomass, the remaining 52% being material uses. JRC also reported that, as a whole, the EU28 uses more than 1 Gt of biomass dry matter, with more than 60% used in the feed and food sector, followed by bioenergy (19.1%) and biomaterials (18.8%). This figure is quite close to the overall production potential, thus suggesting that with the current market and price structure only a minor share of residual biomass potential is available for new uses (e.g. biofuels for aviation), with competition among sectors likely to occur in an increased demand scenario.

Apart from feedstock specifically produced for biofuels, the utilization of the organic part of municipal solid wastes for the production of biofuels is considered as an interesting approach for improving EU's energy security, limiting the pollution associated with waste production, thus allowing societal improvements [49]. Two main companies are working at commercial scale for producing biofuels from MSW: Enerkem [50] and Fulcrum [51], with an announced capacity of 100 kt y^{-1} and 175 kt y^{-1} of input respectively. The benefits of shifting municipal waste in the hierarchy of waste management is not limited to better resource use but also offers a way to positively impact the sector's GHG balance. In 2014, the total waste generated in the EU28, by all economic activities and households, amounted to 2.5 Gt y^{-1} and, excluding major mineral wastes, to 891 Mt y^{-1} [52]. The amount of collected recyclables and bio-waste materials varies widely across European countries, and significant differences are also a function of the collection system used (e.g. door-to-door, civic amenity sites, etc.). Only the 19% of generated municipal waste is collected separately in large cities in the EU28 [53] and it explains the reason behind considering MSW as a potential feedstock of specific interest for biofuel production.

The S2Biom project estimated a European bio-waste potential based on the definition of the Waste Framework Directive (which excludes paper waste), of 89 Mt y^{-1} (dry basis) by 2030 [54]. Searle and Malins [55] assumed a biogenic fraction of household waste of 63%, estimating a sustainable EU potential of 63 Mt y^{-1} on dry basis.

4.1.1. Conclusions regarding the aviation biofuels target

Regarding the calculated amount of feedstock required for achieving the aviation target of GHG neutrality, despite the large differences in the estimation of ligno-cellulosic residues, the potential for feedstock availability seems to be technically available for FT; also taking into consideration the low current production potential of these pathways. Similar conclusions can be drawn for MSW pathway. Conversely, HEFA production relies on feedstocks, which can be considered to be more limited in availability, especially when competition is assumed, with existing demand from other sectors. It is worth to remark that recent report on commercial experiences confirm that costs and real availability of these kind of feedstocks strong bottlenecks [38].

4.2. CO_2 reduction cost driven scenario

Market-based measures are recognised by the sector as a necessary instrument to achieve long-lasting reductions in aviation emissions [56] and biofuels are not the only potential solution to tackle expected increases in aviation GHG emissions. Since 2012, the European aviation sector has been included in the Emissions Trading System: EU ETS.

The 39th session of ICAO Assembly (2016), following three years of negotiations, found an agreement on a Global Market Based Measure (GMBM) to address international aviation emissions. The goal is to offset emissions exceeding 2020 levels by investment in green projects and programs. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) will start with a pilot and voluntary phase in 2021 and is expected to become compulsory from 2027, whereas emissions data should be collected already from 2019. After the 2016 ICAO decision, the European Commission approved legislation extending the current intra-European scope of the EU ETS for aviation (flights in the European Economic Area) beyond 2017, and provide for a new review once there is more clarity on CORSIA rules and implementation by non-EU countries. The derogation for extra-European Economic Area (EEA) flights will be prolonged until 31 December 2023, when the mandatory first phase of CORSIA will begin.

Under the EU ETS, all airlines are required to monitor, report and verify their emissions and they receive tradeable allowances, covering a certain level of emissions from their flights per year. At present, the allowances are distributed as follows: 82% are granted for free to aircraft operators, 15% are auctioned, and 3% are held in a special reserve for later distribution to fast-growing aircraft operators and new entrants in the market [57]. The current value of the allowances suggests a cost of the CO_2 mitigation strategy within ETS is of about 25 € t^{-1} of saved CO_2 [58].

The same calculations, about the specific cost of saving a tonne of CO_2, can be performed for aviation biofuels. JRC has been developing its own database of the likely production costs; considering an average feedstock value of about 600 € t^{-1} for European sourced Used Cooking Oil, hydrotreated and isomerized in industrial scale plant, the final aviation biofuels cost ranges from 950 to 1012 € t^{-1} (a value is in agreement with recent literature works [19,32,59]). With a CO_2 intensity of 0.595 t of CO_2 emitted per tonne of aviation biofuels used, this allows mitigating 2.56 tonne CO_2 per tonne of fuel, when compared to fossil option. With a cost of 1000 € t^{-1} aviation biofuels, the resulting cost per tonne of CO_2 saved is thus 390 € t^{-1}. When compared to ETS allowances, the order of magnitude of the difference in the economic effectiveness of these options, appears evident; with the result that the cost of CO_2 saving is not the driver for a short-term aviation biofuels uptake.

4.3. Mandate driven scenario

A dedicated mandate for aviation is often perceived as the only effective tool to ensure a real market penetration of aviation biofuels. Internationally, several countries have claim to intend to adopt specific mandates for aviation sector: the Indonesian Ministry of Energy and Mineral Resources set a mandate for the use of biofuels in air transport with a blending target of 2% in 2016 and 5% by 2025 [60]; likely, other countries will follow.

In EU, the Directive 1513/2015 allows biofuels used in aviation to count towards Member States' renewable energy targets as within the Renewable Energy Directive. Aviation biofuels meeting RED sustainability criteria result in exemptions from EU ETS obligations, therefore potentially contributing to the additional target set by the European Fuel Quality Directive to cut the GHG intensity of transportation fossil fuels supplied in the EU by 6% in 2020 [4]. While all the Member States can incentivize specific biofuels through national schemes, to date only the Netherlands has reported aviation biofuels as a means to contribute to their transport target. For the time being only few countries, such as Norway, Sweden, Spain and France have been proposing a specific target for aviation.

In this framework, a dedicated mandate for aviation could contribute to speed up the use of biofuels in the sector; nevertheless, introducing mandates has the potential risk of creating distortions in the overall EU transport market, as it is likely to cause harmful interactions with the road sector. On the other hand, it is also likely that if the aviation biofuels have lower sustainability requirements, more feedstocks which the road sector cannot use will leak into aviation.

5. Conclusions

The aviation sector set a voluntary, ambitious carbon-neutral growth from 2021 onwards; this might stimulate the biofuel industry that today is more focused on the established road biofuel market. The production potential in EU is supported by several plants but appraisals often do not take into account limiting factors; our estimated potential for 2025 accounts for an overall installed capacity of 3.5 Mt y^{-1}, but with a technical potential for aviation biofuels ranging between 0.5 and 2 Mt y^{-1}. Despite the target, the current aviation biofuels penetration is low, mainly because of the constraints of high costs, where feedstock costs represent the lion's share, and availability of sustainable feedstocks.

If the production potential appears to be able to support the demand, questions about availability of sustainable feedstock exist. Despite some studies affirm that EU Member States have sufficient amount of feedstocks to meet the advanced biofuel targets, production today - which is based on HEFA technology - counts on a comparatively lower availability and a feedstock basket, which is also subject to high competition with road. Price volatility of lipid feedstocks is quite a relevant issue for industry and increasing pressure on their demand will likely increase their price, with competition among sectors expected: the estimated aviation biofuels - required for balancing the emissions from aviation growth and meeting the sector voluntary target - accounts for 2.4 Mt, which is equal to the 16% of the current EU biofuels consumption.

As the wide use of biofuels have some drawbacks, other solutions can be considered to tackle the expected aviation GHG emissions: since 2012, the European aviation sector has been included in the emission trading system. Comparing the costs of saving CO_2, by means of using biofuels or with ETS allowances, suggests that the current market prices will tend to favour the latter. Eventually, it is worth noticing that mandates could contribute to stimulate aviation biofuels market uptake, but at the same time, they may induce harmful interactions between aviation and road sectors.

Disclaimer

The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

Annex I

Current Installed Capacity - **CIC**				
Technologies	Country	Feedstock	2018	2020
			kt y-1	*kt y-1*
FT	Finland	Wood	0	115
HEFA	Italy	oils, fats	0	310
HEFA	Italy	oils, fats	0	530
HEFA	Spain	oils, fats	80	80
HEFA	Italy	oils, fats	360	360
HEFA	Finland	oils, fats	190	190
HEFA	Finland	oils, fats	190	190
HEFA	The Netherland	oils, fats	800	800
HEFA	Sweden	oils, fats	100	100
HEFA	France	oils, fats	500	500
Co-processing	Spain	oils, fats	0	180
Co-processing	Spain	oils, fats	48	60
HEFA	Lapperanta	CTO	100	100
		Total	**2368**	**3515**

Aviation Fuel Share		
	CBJ	HBJ
HEFA	15%	60%
FT	32%	32%

Production capacity			
kt y-1	CIC	CBJ	HBJ
2018	2368	355	1421
2020	3515	547	2077

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