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NOVEL AIRCRAFT PROPULSION AND AVAILABILITY OF ALTERNATIVE, SUSTAINABLE AVIATION FUELS IN 2050

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Abstract

This paper investigates green hydrogen and bio-based sustainable aviation fuels, including their production technology and feedstock, in combination with Clean Sky 2 propulsion technologies and novel hydrogen-powered propulsion technologies. The impact that these alternative aviation fuels and propulsion technologies can have on greenhouse gas emissions is identified and the demand for alternative aviation fuels is compared with their expected availability, both until 2050.

Keywords: aircraft propulsion, sustainable alternative fuel, hydrogen, climate impact, fuel supply

1. Introduction

Mitigation of climate change and other environmental impacts is increasingly globally pursued by governments, international bodies and industry. In 2019, the European Commission through its Green Deal [1] announced the objective of Europe to become the first climate-neutral continent by 2050 – a target that has subsequently been implemented in the legally binding European Climate Law [2]. This further stipulates a reduction of CO_2 emissions of 55% across Europe by 2030, compared to levels in 1990. Policies to achieve this were proposed in the Fit for 55 package.

Specific for aviation, Europe set aviation environmental goals in FlighPath2050 in 2011. Through successive technology research programs (such as Clean Sky [3] and Clean Sky 2 [4]), Europe is accelerating the progress towards the Flightpath 2050 through development of new aircraft and propulsion technologies. Recently, aviation industry's commitments towards net-zero CO_2 have grown, as exemplified in Europe by Destination 2050 [5], the start of Clean Aviation [6], and addressed globally by work of the Air Transport Action Group [7] and the International Air Transport Association [8]. Besides emissions reductions through new aircraft and propulsion technologies, these publications highlight the promise of alternative fuels for aviation. New legislative proposals in the Fit for 55 package, such as ReFuelEU Aviation [9], also aim to stimulate the production and use of such alternative fuels.

Developments in alternative aviation fuels and in novel propulsion give rise to the questions:

- What can these developments contribute to achieving the FlightPath2050 goals and towards reaching climate neutrality of aviation in line with the European Green Deal and Fit for 55?
- How can the most promising developments, on alternative fuels production and propulsion technologies, actually take place on time to achieve these contributions on time?
- And, does aviation's demand of alternative aviation fuel and the demand of other consumers than aviation in the time frame 2030-2050 match with the potential for alternative aviation fuel supply from different feedstocks?

The main options considered in this paper as promising alternatives to conventional fossil jet fuels are drop-in sustainable aviation fuel (SAF) and green hydrogen.

Drop-in SAF is alternative fuel that, presently in blends, is qualified to replace fossil kerosene in current aircraft and existing infrastructure, due to its similarity with fossil kerosene. The qualification is regulated by ASTM. Current drop-in SAFs need to be blended with at least 50% fossil kerosene. Although gross (tailpipe) CO_2 emissions are similar to fossil kerosene, net CO_2 emissions of drop-in SAFs are substantially lower. This is due to the fact that the carbon contained in the fuel is sourced from sustainable biomass – in case of bio-based SAF – or recycled or captured from the air – in case of synthetic SAF (also known as e-fuel or power-to-liquid fuel).

Green hydrogen is hydrogen that is produced in a sustainable way, such as by electrolysis of water that is powered by renewable electricity (e.g., coming from solar and wind power plants). Hydrogen (H_2) is an alternative fuel that cannot be used in current aircraft engines and for which novel propulsion concepts are emerging. Disruptive technologies to enable hydrogen-powered aircraft is one of the three pillars of the aircraft and propulsion technology research and innovation agenda in Clean Aviation [10]. As hydrogen does not contain carbon, the gross CO_2 emissions from hydrogen-powered aircraft are zero.

As H_2 is a necessary 'ingredient' for synthetic SAF, there is an interdependency between these types of alternative fuels: for a given quantity of H_2 available for aviation, more usage by hydrogen-powered aircraft means less is available for producing synthetic SAF.

For propulsion, the paper focuses on novel technology developments for drop-in SAF and green hydrogen powered aircraft, with the potential to reduce fuel consumption (in case of drop-in SAF powered aircraft), and to be successfully integrated in aircraft that enter into service well before 2050. The impact on gaseous emissions and energy consumption during flight are analyzed globally.

For alternative fuels, the paper focuses on fuel availability for flights departing from Europe and UK from technological, economic, environmental, and social perspectives. The paper considers the fuel availability in three cases, which are defined by the use of other alternative fuels than bio-based fuels. For each case multiple scenarios are analyzed.

2. Promising novel propulsion concepts and alternative fuels

2.1 Promising novel propulsion concepts

In a preceding literature study [11], seven classes of propulsion concepts with numerous underlying novel propulsion technologies were identified for potential aircraft applications with entry into service well before 2050. These seven propulsion concepts are defined by two characteristics:

- the energy source that is stored in the aircraft and used for propulsion, which can be drop-in SAF, hydrogen, or chemical energy as stored in a battery;
- the main devices that may be used for conversion of energy from source to mechanical energy in the shaft that is driving the propeller or fan:
    - gas-turbine-based engines that convert the chemical energy from drop-in SAF into mechanical energy,
    - generators that convert mechanical energy from gas-turbine-based engines into electrical energy,
    - fuel cells that convert the chemical energy from hydrogen into electric energy,
    - batteries that convert their chemical energy into electric energy, and
    - electromotors that convert electric energy into mechanical energy.

These seven propulsion concepts are: disruptive gas turbine based propulsion using drop-in SAF for combustion, gas turbine based propulsion using hydrogen for combustion, battery electric propulsion, fuel cell electric propulsion using hydrogen, turbo-electric propulsion based on drop-in SAF, other hybrid-electric propulsion using drop-in SAF, and hybrid-electric propulsion using hydrogen as energy source, see the left column in Table 1.

In the literature study [11], the seven classes of propulsion concepts have been qualitatively evaluated on their impact on volume and weight when integrated into aircraft, while keeping the same range and same number of passengers. In addition, some propulsion concepts have zero CO_2 and/or NO_X emissions during flight. It appears that the zero-gross-emission concepts have higher propulsive system weight and/or volume (from storage to propeller/fan) compared to present propulsion (fossil kerosene gas-turbine-based engine). This negative impact increases with the size of the aircraft in which they are applied, thus limiting their application to the smaller aircraft types, potentially with shorter ranges than presently in operation. Combining these data, the most promising aircraft types for application of the seven classes of propulsion concepts are identified for conventional tube and wing aircraft configuration, as shown in Table 1.

Propulsion concept	Propulsion concept definition		Gross emissions (zero/nonzero)		Aircraft type classes			
	On-board energy source	Energy converting devices	CO_2	NO_x	Small	Regional	Single-aisle; Small twin aisle	Large twin aisle
Drop-in SAF combustion	D	T	X	X		X	X	x
Hydrogen combustion	H	T	0	X			X	
Electric battery	B	B, E	0	0	X			
Electric fuel cell	H	E, F	0	0	X	X		
Turbo-electric	D	E, G, T	X	X		X	X	X
Hybrid-electric SAF	B, D	B, E, G, T	X	X		X	X	X
Hybrid-electric hydrogen	B, H	B, E, F, G, T	0	X		X	X	

Table 1 - Seven propulsion concepts for entry into service well before 2050 with their definition, qualitative evaluation of emissions during operation, and application on aircraft (based on [11], see also [12]). B = battery, D = drop-in SAF, E=electromotor, F=fuel cell, G=generator, H=hydrogen, T=gas-turbine-based engine; 0 = zero emission; x = nonzero emission; applicable aircraft type class.

2.2 Promising alternative fuels

Sustainable aviation fuels are synthesized on the basis of feedstocks which can be categorized into biomass (e.g. used cooking oil, agricultural residues, forestry residues and municipal solid waste) and renewable electricity produced by renewable sources such as wind, solar and hydro. For each feedstock, a variety of conversion processes can be used to reach a fuel that meets current jet fuel specifications. In the literature study [11], technological, economic, and environmental and social performances of alternative fuels have been investigated. Preliminary investigations were shared with experts in a workshop and led to a pre-selection of five alternative fuels with their production routes. Following further literature study, complemented with an online expert survey, the preselection was confirmed with the addition of one fuel [13], see Table 2.

Abbreviation	Group of SAFs production routes	Product	Preselection	Expert agreement	Final selection
HEFA	Hydro-processed Esters and Fatty Acids	Bio-jet fuel	✓	Strongly agree	✓
HFS	Hydro-processed Fermented Sugars	Bio-jet fuel	✗	Strongly agree	✗
FT	Fischer-Tropsch	Bio-jet fuel	✓	Agree	✓
HTL	Hydrothermal Liquefaction	Bio-jet fuel	!	Agree	!
FP	Fast Pyrolysis	Bio-jet fuel	✓	Agree	✓
ATJ	Alcohol to Jet	Bio-jet fuel	!	Disagree	✓
IH^2	Integrated Hydropyrolysis and Hydroconversion	Bio-jet fuel	✗	Agree	✗
PtL	Power-to-Liquid (Fischer-Tropsch)	E-fuel	✓	Strongly agree	✓
BG	Biomass gasification	LH_2	✗	Agree	✗
MEC	Microbial Electrolysis Cell	LH_2	✗	Strongly agree	✗
AE	Alkaline electrolysis	LH_2	✓	Strongly agree	✓
PEM	Proton exchange membrane electrolysis	LH_2	!	Agree	!
SOEC	High-temperature solid oxide electrolyzer cell	LH_2	✗	Agree	✗
TWS	Thermochemical Water Splitting	LH_2	!	Agree	!

Legend: ✓ selected ! some of the performance indicators could be improved ✗ not selected

Table 2 – Alternative fuel production routes preselection and final selection [13]

GHG emissions of each alternative fuel production technology from different biomass residues feedstocks were collected and available in an Ecological Balance Sheet [14].

These six selected routes are explained in more detail together with applicable feedstocks and associated production technologies below. The six pathways are divided into the three main categories of alternative fuels identified in Section 1.

2.2.1 Hydrogen

In order to produce hydrogen, the **alkaline electrolysis** pathway can be performed. In this process hydroxide ions (OH^-) are transferred through the electrolyte from the cathode to the anode using hydrogen that is generated on the cathode side. This production path is technologically mature with relatively low production cost. However, it has technological disadvantages like low current density, limited ability to operate at low loads, and the inability to operate at high pressure [14].

2.2.2 Bio-based drop in SAF

The **Hydro-processed Esters and Fatty Acids** (HEFA), **Fischer-Tropsch** (FT), **Fast Pyrolysis** (FP) and **Alcohol-to-Jet** (ATJ) are the four types of pathways to produce bio-based drop-in SAFs. HEFA is the most mature SAF pathway and it is currently commercially available. The HEFA feedstock groups considered in this paper are forest residue, agricultural residue and municipal solid waste, in line with [16]. These oily feedstocks undergo a deoxygenation reaction where hydrogen is added to the process to break down the compounds into hydrocarbons [17]. Another process FT, where the synthetic gas is converted into ultra-clean fuels and value-added chemicals. To produce the synthetic paraffinic kerosene (SPK), the combination of biomass gasification with FT synthesis and catalytic cracking is used. Feedstocks that are used for FT are lignocellulosic biomass and municipal solid wastes [18] and [17]. The FP pathway uses organic materials which are heated up to 450 – 600 °C in the absence of air in order to produce organic vapors, pyrolysis gases and charcoal. Afterwards, they are condensed to bio-oil [19]. Lastly, the ATJ route can produce SAF from alcohols like methanol, ethanol, butanol, and long-chain fatty alcohols. The two primary alcohol sources are ethanol and butanol, and are formed during the fermentation of sugary, starchy, and lignocellulosic biomass such as sugarcane, corn grain and switchgrass [17].

2.2.3 Synthetic drop in SAF

The pathway to produce synthetic drop-in SAF is **Power-to-Liquid (PtL) Fischer-Tropsch**. This PtL pathway produces liquid hydrocarbons based on electric energy, water, and CO_2. Synthesis gas is synthesized by using hydrogen and CO_2. Hydrogen is produced with electrolysis of water with renewable electricity. In order to produce jet fuel, the Fischer-Tropsch pathway should be used to upgrade the synthetic fuels.

3. Aircraft and fleet level evaluation of hydrogen-powered propulsion

3.1 Aircraft level evaluation of hydrogen-powered propulsion

For three ICAO seat classes, representative in-service aircraft were selected as reference aircraft, see Table 3. Hydrogen-powered variants of these aircraft have been conceptually sized and evaluated on their gaseous emissions and on their hydrogen and energy consumption in [21]. The design payload was kept the same, but the ranges were shortened compared to the reference aircraft. Entry-into-service (EIS) was assumed in line with the Clean Aviation SRIA [10].

Seat class	Reference aircraft	Hydrogen propulsion	Design range	Max. number passengers	Entry-into-service
20-50	ATR42	Fuel cell	1000 km	48	2035
151-176	A320neo	Hybrid	2000 nm	150	2035
211-300	B787-8	Gas turbine	2000 nm	270	2040

Table 3 - Seat class evaluation of hydrogen-powered propulsion on representative aircraft with short design ranges and entry-into-service

Hydrogen technology was introduced on improved variants of the (current technology) reference aircraft, which will be referred to as advanced aircraft. These advanced aircraft take into account other aircraft and propulsion technology developments than hydrogen-based propulsion and are in line with the assumed EIS and with the first assessment of Clean Sky 2 aircraft concepts by the Clean Sky 2 Technology Evaluator [20]. The detailed aircraft level evaluation provides the gaseous emissions and energy consumption for various payload range combinations. These evaluations were used for comparisons against the reference aircraft (of today) and the Clean Sky 2 aircraft concepts, both using kerosene as fuel.

The aircraft level evaluation results in [21] indicate that zero CO_2 emission can be obtained with only a slight increase of energy consumption during flight, compared to the Clean Sky 2 aircraft concepts. Energy consumption and NO_X emissions will reduce with respect to the reference aircraft (of today). H_2O emissions increase consistently with the use of hydrogen as fuel.

For wider application in the fleet level evaluation, the aircraft level evaluation results for the 20-50 seat class were extrapolated: from 20-50 class to the 20-100 seat classes and from the 151-176 class to the 100-210 classes, without change of range and entry-into-service, thus resulting in hydrogen-powered short-range aircraft for the seat classes 20-300.

3.2 Fleet level evaluation

The fleet level evaluation of the hydrogen-powered propulsion aircraft has been carried out using the so-called High and Low global traffic scenarios referred to as the “DLR Clean Sky 2 scenario” [22]. The scenarios are the same for the period until 2035 and mainly differ in terms of growth thereafter: in the ‘Low’ scenario, the number of flights grows from 38 million in 2020 to 56 million in 2050 (+ 48%). In the ‘High’ scenario, the number of flights in 2050 has grown to 62 million (+ 64%). Compound annual growth rates of these scenarios are 1.3 and 1.7%, respectively. Neither scenario includes the impact of COVID-19. Both traffic scenarios have a variant with reference aircraft and a variant with Clean Sky 2 concept aircraft that, from their entry-into-service, are gradually replacing reference aircraft.

Besides a different number of flights, the average aircraft size differs between the scenarios. In the Low scenario, 45% of the total flights in 2050 is flown with aircraft seating up to 210 passengers (81% up to 300 seats); whereas in the High scenario, aircraft seating up to 210 passengers operate 38% of total flights (73% up to 300 seats).

At fleet level, two scenarios for the introduction of the promising SAF-based aircraft and hydrogen propulsion concepts in the future fleet have been addressed. The scenario without hydrogen-powered propulsion involves the promising drop-in-SAF-based aircraft that are obtained by powering the advanced aircraft by drop-in SAF rather than kerosene. During the evaluation period 2035-2050, promising SAF-based aircraft are gradually entering the fleet consistent with [20][22]. In the scenario with hydrogen-powered propulsion, the promising drop-in-SAF-based aircraft in the preceding scenario that are in the seat classes 20-300 and carry out short-range flights are replaced by the short-range hydrogen-powered aircraft.

The scenario with hydrogen-powered propulsion leads to a reduction of 20% (low traffic scenario) and 16% (high traffic scenario) in global gross CO_2 emissions in 2050 at fleet level compared to the scenario without hydrogen-powered propulsion, whereas global gross energy consumption slightly increases and H_2O emission increases significantly at fleet level – by 26% (high traffic scenario) to 32% (low traffic scenario). Further non-CO_2 climate effects were not studied. The number of flights operated by hydrogen-powered aircraft by 2050 varies from 35% (high traffic scenario) to 38% (low traffic scenario).

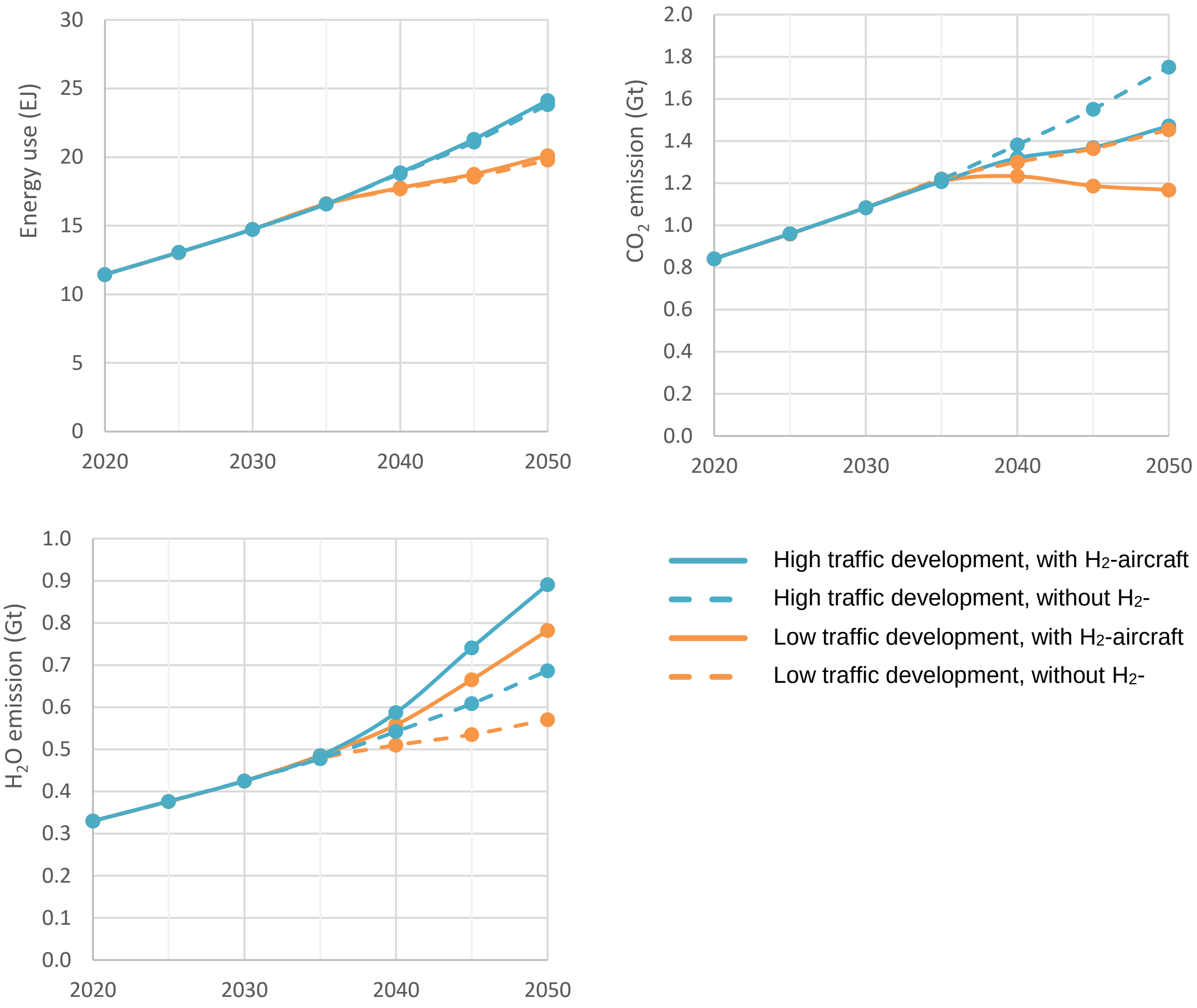


Figure 1 - Global aircraft energy use and gross emissions at fleet level in **high** or **low** traffic scenarios, both with (solid lines) and without (dashed lines) hydrogen-powered aircraft in the fleet

4. European availability of alternative fuels versus demand

The European availability of alternative fuels has been analyzed for three cases of fleet scenarios and fuel supply:

- The fleet scenarios without hydrogen-based propulsion and with supply of bio-based drop-in SAF as only alternative fuel
- The fleet scenarios with hydrogen-based propulsion and with supply of all alternative fuels (i.e., bio-based and synthetic drop-in SAF and hydrogen)
- The fleet scenarios without hydrogen-based propulsion and with supply of both bio-based and synthetic drop-in SAF as alternative fuels

In the first case, demand and availability are analyzed in more detail, up to the national level throughout Europe. In the second and third cases, the analysis jointly looks at the EU and UK.

4.1 Supply of bio-based drop-in sustainable aviation fuels only, up to national level

Various residue-based biomass sources have been identified for the 4 selected technologies for sustainable biofuels routes, resulting in 69 combinations of feedstock and conversion technology. Availability of these feedstocks was investigated for the European countries, assuming full self-supply of SAF by each of the countries. The total biomass available for energy applications per country is estimated as 60% of the theoretical biomass supply. In addition, several levels of competing use (0%, 50%, 90% and 95%) are considered to incorporate realistic expectations on the future biomass market potential for SAF production.

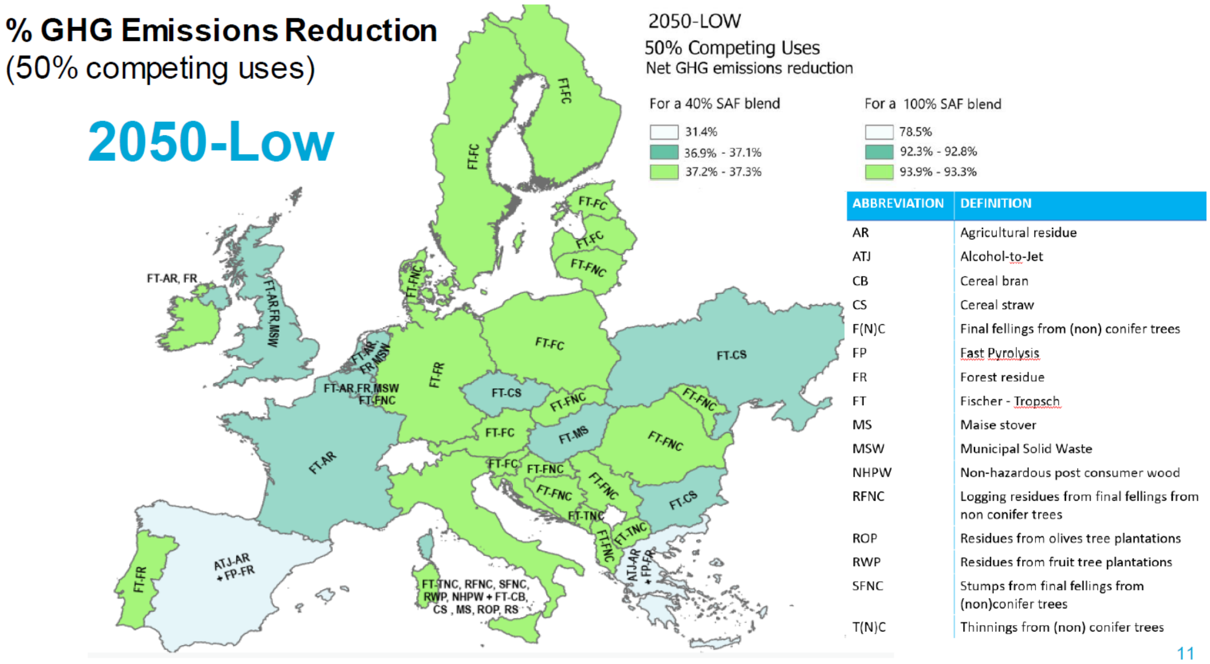
The total fuel demand per European country has been calculated based on the fleet level evaluation, restricted to flights departing from Europe. The national SAF demands are based on the fuel demand per country and a maximum share of sustainable drop-in fuel per scenario (10%, 40% or 80%).

Potential SAF supply and GHG emissions savings were evaluated for two time-scenarios (2030 and 2050), and a Low and High demand scenario for 2050 (i.e. 2050-Low and 2050-High), and several levels of competing use (i.e., 0%, 50%, 90% and 95%).

Results show that the European countries can produce sufficient SAF to meet the total European SAF demand in each scenario, assuming low competing use (up to 50% competing use). In all cases, the use of Fischer-Tropsch (FT) offers the best route to maximize life-cycle CO_2 emissions reduction.

In the 2030 scenario, a 9.28% - 9.31% reduction in net GHG emissions compared to conventional jet fuel is feasible for a 10% SAF blend. This results in a maximum total GHG emissions reduction potential collectively for Europe of 19 Mt (50% competing use). The maximum net GHG emissions reduction potential in the 2050-Low scenario is approximately 37% which means that the maximum European GHG emissions reduction is 67 Mt (50% competing use), for a 40% SAF blend when compared to conventional jet fuel. In the 2050-High scenario the maximum net GHG emission reduction potential ranges between 62.8% and 74.5% for an 80% SAF blend when compared to conventional jet fuel, which means that the total European GHG emissions reduction potential is in the range 122 Mt to 170 Mt (50% competing use).

The data is also analyzed on a national level. For example, Figure 2 shows results on greenhouse gas emissions reduction potential for the 2050-Low scenario (with 40% SAF blend) and a biomass competing use level of 50% (i.e. 50% of biomass available is used for other energy applications than SAF production):



ABBREVIATION	DEFINITION
AR	Agricultural residue
ATJ	Alcohol-to-Jet
CB	Cereal bran
CS	Cereal straw
F(N)C	Final fellings from (non) conifer trees
FP	Fast Pyrolysis
FR	Forest residue
FT	Fischer - Tropsch
MS	Maise stover
MSW	Municipal Solid Waste
NHPW	Non-hazardous post consumer wood
RFNC	Logging residues from final fellings from non conifer trees
ROP	Residues from olives tree plantations
RWP	Residues from fruit tree plantations
SFNC	Stumps from final fellings from (non)conifer trees
T(N)C	Thinnings from (non) conifer trees

Figure 2 - %GHG emissions reduction due to biofuels (40% SAF blend) in European countries, considering 50% competing use, including associated production technologies and feedstock)

Further details of the study can be found in [16].

4.2 Supply of alternative fuels for the fleet with hydrogen-powered propulsion

This section considers demand for alternative fuels by flights departing from EU and UK. Supply is predominantly sourced from the EU and UK as well. The demand for hydrogen as fuel follows from the respective subset of flights of the global fleet-level assessment conducted in Section 3.3. The demand for drop-in SAFs until 2050 is modelled based on the fleet level evaluation with 100% drop-in SAF for the drop-in-SAF-based aircraft and blends of 50% drop-in SAF for other (older) kerosene-powered aircraft.

The analysis starts with supplying the hydrogen-powered aircraft in the fleet with hydrogen. Next, the drop-in SAF powered aircraft are supplied with the available bio-based drop-in SAF. Finally, the remaining hydrogen is used for the production of synthetic fuel for the remaining drop-in SAF powered flights. An overview of the demand and supply for drop-in SAF powered aircraft is presented, including the minimum supply following from the proposed RefuelEU Aviation mandate...

4.2.1 Supply of hydrogen as fuel

Hydrogen supply was derived from various publications – ranging from bottom-up estimates to strategic objectives – which have made estimates about hydrogen availability in the period spanning 2030 to 2050. These consider both European (EU + UK) production, as well as select non-European production (in for example Ukraine and Northern Africa), of which part would be available for imports to Europe. Based on these studies, estimates of the hydrogen availability have been derived, see [12] for more details. The resulting combination of supply and demand, as well as the CO_2 emissions reduction achieved due to the use of hydrogen-powered aircraft (analyzed in Section 3.1), is shown in Figure 3.

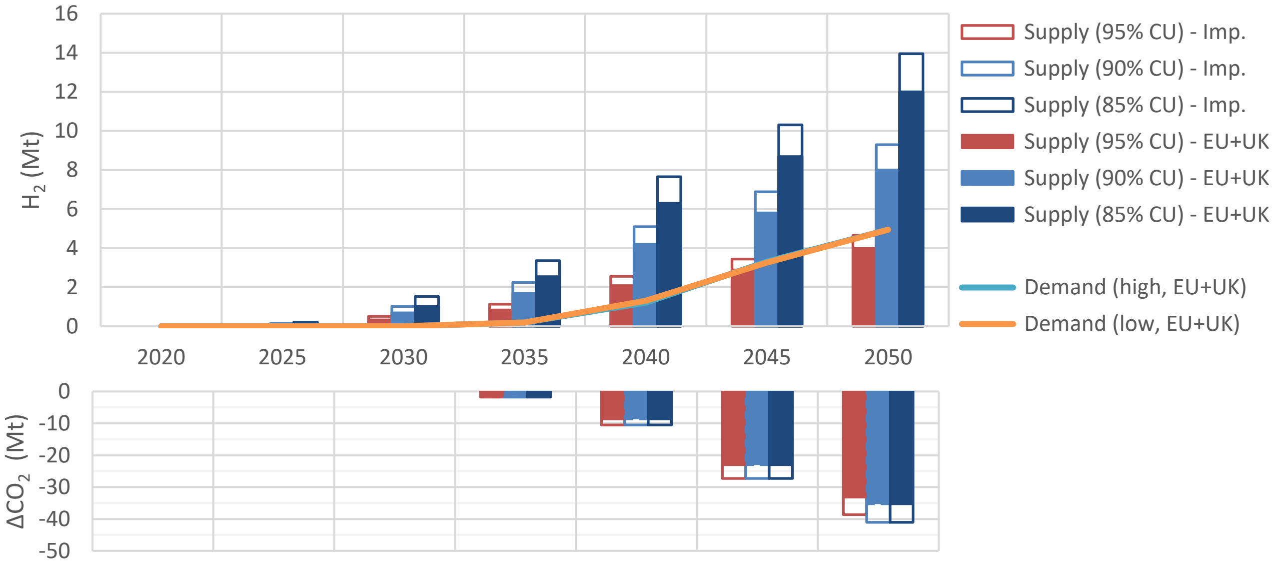


Figure 3 - Hydrogen supply and demand (top; almost identical between low and high traffic scenarios) and gross CO_2 emissions reduction (bottom) in different traffic scenarios (high, low) and cases of hydrogen competing use (CU) with supply from EU + UK only or with additional import from selected non-European production (Imp.)

Supply projections show that the demand for H_2 can be largely met – even without considering imports. Only in case of 95% competing use, European (EU + UK) production is insufficient to meet demand in 2045 and 2050. As seen from the bottom part of the figure, deploying hydrogen-powered aircraft in the fleet may reduce CO_2 emissions by about 40 Mt in 2050.

4.2.2 Supply of bio-based drop-in SAF

Based on the European bio-based drop-in SAF availability study in Section 4.1, the total supply of bio-based drop-in SAF has been analyzed for the EU and UK, whereby it is assumed that intra-EU trade (of feedstock or bio-based SAF produced from it) resolves country-specific over- and undersupply. As in Section 4.1, feedstocks and production routes were selected as to maximize life-cycle CO_2 emissions reduction, resulting in predominant use of Fischer-Tropsch (FT).

Figure 4 - Drop-in SAF demand based on technological and regulatory fleet-based blending limits (solid lines) or ReFuelEU mandate (dotted lines) and drop-in SAF supply (split in bio-based SAF supply and synthetic SAF supply) for flights departing from EU and UK (top). Net CO2 emissions reduction based on the drop-in SAF supply (bottom). Results are shown for (low, high) traffic scenarios, for different cases of biomass and hydrogen competing use (CU), and with feedstock supply from the EU and UK and limited imports.

Figure 4 shows that overall, until 2030, the feedstock availability for drop-in SAF is found to be sufficient to meet the ReFuelEU Aviation SAF mandate – even in the 95% competing use scenario. Provided enough production facilities are realized to process the available feedstock, which could be stimulated by effectuating the ReFuelEU Aviation mandate, the supply of drop-in SAFs is on the right way. However, compared to total drop-in SAF demand, the supply is found to be significantly smaller.

After 2030, the projected supply of drop-in-SAF falls below the ReFuelEU Aviation mandate, increasingly so towards 2050. This is exacerbated in a scenario with 95% competing use scenario for green hydrogen and the use of hydrogen-powered aircraft, in which case no green hydrogen remains available as feedstock for the production of synthetic drop-in SAF.

In more detail, at fleet-level, the 22 Mt supply available in 2050 in case of 90% CU translates into a 32% or 42% blend in the high and low traffic scenarios. In order to meet the mandated 63%, an additional supply of 19 (low) to 30 (high) Mt is required by 2050 based on the low and high traffic scenarios.

The shortage of green hydrogen to both supply hydrogen-powered aircraft and produce sufficient amounts of synthetic SAF indicates a possible competition between these two alternative fuels. Hence, considering that the sub-mandate for synthetic SAF in ReFuelEU Aviation is likely to prioritize hydrogen for synthetic SAF production, the hydrogen demand for hydrogen-powered aircraft might not be met by green hydrogen.

4.3 Supply of drop-in SAFs for the fleet without hydrogen-powered propulsion

As in Section 4.2, only demand from flights departing from EU and UK are considered, with alternative fuels supplied predominantly from EU and UK feedstock. The demand for drop-in SAF follows from the global fleet-level assessment conducted in Section 3.3.

Up to 2035, the total CO_2 emission reductions do not differ between scenarios with and without hydrogen-powered aircraft, since the hydrogen-powered aircraft enter into service in 2035. The scenario without hydrogen-powered aircraft is analyzed until 2050 in detail in [12]. As shown in Figure 5 by 2050 and with 90% competing use, CO_2 emission reductions are 10% lower in a scenario with hydrogen-powered aircraft. For scenarios with 95% CU, this difference is magnified to 16%.

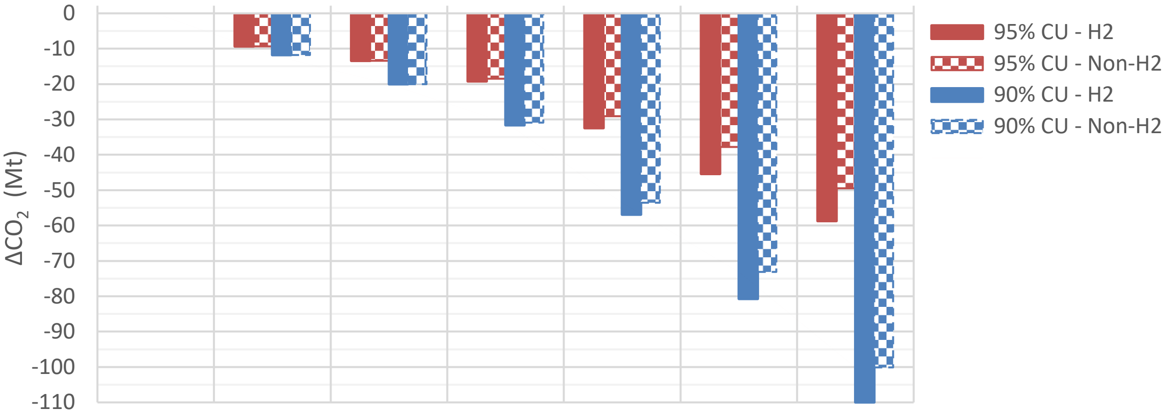


Figure 5 - Total CO_2 emissions reduction realised in scenarios with and without hydrogen-powered aircraft and different levels of competing use (CU)

5. Discussion and conclusion

5.1 Discussion on sensitivity of outcomes

The prediction of the future until 2050 in this paper is depending on many parameters, each of them affecting the outputs through the complex analysis shown in the paper. To analyze the sensitivity, the outcomes of this paper have been compared with other studies, which find different CO_2 reductions. Both in situations with and without hydrogen-powered aircraft in the fleet, the relative CO_2 reductions that can be achieved (around 40%) are substantially lower than objectives set for 2050, such as the 90% reduction target from transport emissions set in the Smart & Sustainable Mobility Strategy [26] or various net-zero goals – even though some of these were supported by similar analyses as presented here [5]. A number of factors help explain these differences and indicate sensitive parameters.

Efficiency improvements realized by improvements in aircraft and engine technology in the paper are modelled based on the first assessment in Clean Sky 2, but do not yet take into account possible further improvements (following from the second assessment in Clean Sky 2, and from Clean Aviation, for example). This indicates the sensitivity of the outcomes for the technological improvements that are assumed.

Emissions savings due to operational efficiency improvements, estimated between 5 and 10% by [5], were not considered in the paper, but also contribute to decarbonization. Similarly, out-of-sector decarbonization measures can reduce net CO_2 emissions. This indicates the sensitivity of CO_2 emissions for non-modelled parameters related to operational measures and out-of-sector decarbonization measures.

Last, and especially visible in the high traffic scenario, the baseline growth rate of the number of flights in the paper is notably higher (1.7%) than reported in [5] (1.4% in the reference scenario; 0.8% in its sustainability scenario). Moreover, the growing share of larger aircraft in the fleet mix, as seen in Section 2, suggests the growth in passenger movements to be bigger still when compared to [5] (2.0% and 1.4%). This indicates the sensitivity of the outcomes for the traffic scenario, which is likely to be impacted by COVID-19 as well.

Related to the previous remark, the traffic scenarios used have not been updated with possible demand reductions caused by increased (fuel) costs that are passed on to consumers, through increases in ticket prices, even though these can be expected [27]. This indicates the sensitivity of the outcomes due to increased fuel costs.

5.2 Discussion on other factors than feedstock availability

The paper shows the differences between the demand, the proposed ReFuelEU Aviation mandate and the supply for the alternative fuels, whereby the supply has been based on the availability of bio-based feedstocks and green hydrogen. Other factors to be considered for the availability of sustainable drop-in SAF and green hydrogen are the availability of production facilities with sufficient production capacity for the alternative fuels and the availability of sufficient green energy and green electricity.

Economic viability of alternative fuels is another factor to be considered. As shown in [12], the minimum selling price of alternative fuels per MJ is predicted to be higher than for kerosene. The price difference between alternative fuels and kerosene is predicted to rapidly decrease towards 2050, with green hydrogen as fuel expected to be only slightly more expensive (~10%) than kerosene per MJ. The price difference until 2050 may limit the uptake of these alternative fuels beyond the regulatory blending mandate proposed in ReFuelEU Aviation. Additional (carbon) costs related to fossil kerosene, which were not modelled, can be expected to reduce the cost difference.

5.3 Conclusions

Propulsion technology, together with aircraft technology, and alternative fuels are key contributors to reduction of the climate impact of aviation in 2030 and in 2050. Aircraft and propulsion technologies contribute to reduce the demand of drop-in SAF that is needed, where hydrogen-powered propulsion provides the opportunity to obtain even larger reductions of greenhouse gas emissions.

Overall, the feedstock availability for drop-in SAF was found to be sufficient to meet the ReFuelEU Aviation SAF mandate until 2030, even in the 95% competing use scenario. Provided enough production facilities are realized to process the available feedstock, which could be stimulated by effectuating the ReFuelEU Aviation mandate, the supply of drop-in SAFs is on the right way. However, compared to total drop-in SAF demand, the supply was found to be significantly smaller. Also, the projected cost of drop-in SAFs for airlines is significantly higher than the projected cost of fossil kerosene, not taking into account carbon pricing. Given the competitive and international nature of the aviation industry, this means that drop-in SAF uptake is unlikely to exceed regulatory requirements (such as the ReFuelEU Aviation mandate), unless cost differences are reduced.

From 2035, prioritizing aviation’s supply of hydrogen to hydrogen-powered aircraft, the supply of hydrogen matches the demand for these aircraft completely, or almost completely in case of 95% competing use. However, the projected supply of drop-in-SAF is below the ReFuelEU Aviation SAF mandate and the gap is increasing towards 2050. Moreover, if the available hydrogen for aviation would first be used to satisfy the regulatory requirements set by the ReFuelEU mandate, a significant part of the flights with hydrogen-powered aircraft would have to use non-green hydrogen.

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