Dedicated to innovation in aerospace

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Novel propulsion and alternative fuels for aviation towards 2050

Promising options and steps to take (TRANSCEND Deliverable D3.2)

CUSTOMER: Clean Sky 2 Joint Undertaking

Royal NLR - Netherlands Aerospace Centre

EXECUTIVE SUMMARY
UNCLASSIFIED

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REPORT NUMBER
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REPORT CLASSIFICATION
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DESCRIPTOR(S)
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emissions

Problem area

In 2019, the European Commission announced the European objective to be climate-neutral by 2050. The European Climate Law stipulates a reduction of net greenhouse gas emissions of 55% across Europe by 2030. Moreover, the European Commission published its hydrogen strategy for a climate-neutral Europe. In addition, the aviation sector's commitments towards net-zero CO_2 have grown, as exemplified in Europe by its flagship sustainability initiative Destination 2050. New legislative proposals, such as ReFuelEU Aviation, aim to stimulate the use of sustainable aviation fuels (SAFs). The Clean Sky 2 (CS2) Technology Evaluator has assessed the reduction of emissions that can be obtained due to the Clean Sky 2 developments on aircraft and propulsion technologies for fossil-kerosene-driven aircraft. The overarching research question for this report is: what can alternative fuels and novel propulsion, complementary to the Clean Sky 2 developments, add to these reductions of emissions towards climate neutrality in 2050?

Description of work

The TRANSCEND project, within the Clean Sky 2 (CS2) Technology Evaluator, has investigated both novel propulsion technologies and alternative fuels for aviation as potential key technological contributors to climate neutral aviation towards 2050. Concepts for propulsion and potential alternative fuels and their production routes have been identified. Promising propulsion concepts, bio-based and synthetic sustainable aviation fuels (SAFs), and green hydrogen as aviation fuel were selected and evaluated on technological, economical (fuels only), and environmental aspects. The identification, selection and evaluation was carried out through literature study and analysis, supported by expert workshops. Evaluations were carried out at aircraft and at fleet level, globally and for the EU and UK together.

Results and conclusions

SAF-powered gas turbine based propulsion technologies from CS2 and three hydrogen-powered propulsion concepts were selected. These technologies were evaluated with four promising production routes for bio- and waste-based SAFs and two promising production routes for synthetic SAF and green hydrogen. Gross CO_2 emissions reduce up to 20% in 2050 due to the introduction of hydrogen-powered aircraft. Until 2030, the projected supply of SAF from EU and UK feedstocks, with 95% use of the biomass for energy applications outside aviation and 95% use of green hydrogen outside aviation, satisfies the minimum SAF supply requirements from the ReFuelEU Aviation mandate. After 2035, prioritising the 5% green hydrogen for aviation to use as fuel in hydrogen-powered aircraft, the projected supply of green hydrogen matches the projected demand for these aircraft. However, the projected supply of SAF then falls below the ReFuelEU Aviation mandate. Towards 2050, the gap is increasing. Net CO_2eq emissions could reduce up to 43% in 2050 in a scenario with SAF and hydrogen-powered aircraft compared to a similar scenario with aircraft powered by fossil kerosene. The projected cost of SAF and green hydrogen for airlines is higher than the projected cost of fossil kerosene. Based on these conclusions, strategic recommendations are given to public and private parties in aviation, fuel, and energy sectors to achieve the projected alignment of the supply of SAF with the ReFuelEU Aviation mandate in 2030 and to contribute to climate neutrality in aviation from 2035 towards 2050.

Applicability

The strategic recommendations in this report can be taken up by the public and private parties.

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Summary

Anthropogenic climate change and environmental impact are increasingly addressed by governments, international bodies, and industry. The TRANSCEND project, within the Clean Sky 2 (CS2) Technology Evaluator, has investigated both novel propulsion technologies and alternative fuels for aviation up to 2050 as potential key technological contributors to climate neutral aviation. This report presents the final results of TRANSCEND.

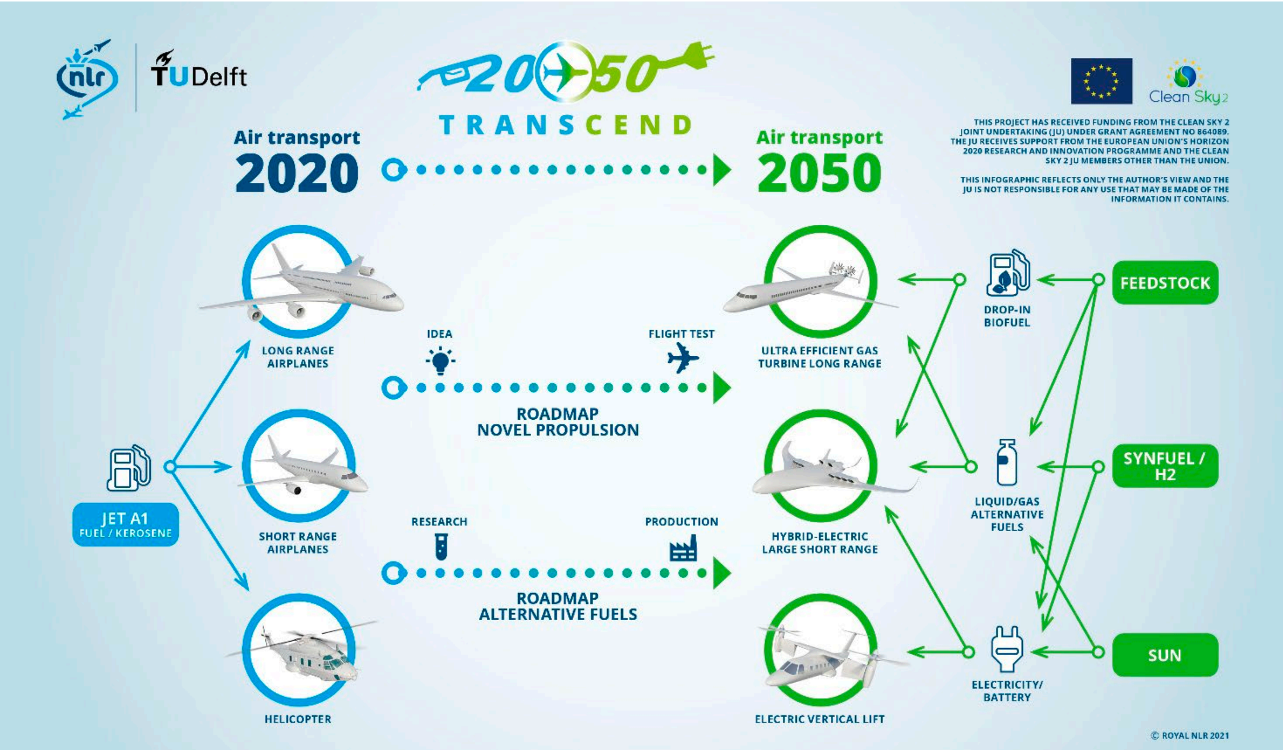


Figure 1: Infographic of the TRANSCEND project on the evaluation of the potential contribution of novel propulsion and alternative fuels to climate neutral aviation in 2050 and on roadmaps for novel propulsion and alternative fuels to achieve this potential contribution. The aircraft and fuels shown in 2050 indicate propulsion and fuels considered, not necessarily the propulsion and fuels that have been evaluated

Selection of promising novel propulsion concepts and alternative fuels

The following promising novel propulsion concepts with promising alternative fuels have been identified for global application in aircraft and have been further evaluated in TRANSCEND:

- Sustainable aviation-fuel-powered gas turbine based CS2 propulsion technologies for aircraft in all seat classes above 20 passengers, with entry-into-service (EIS) in 2035, referred to as the promising SAF-based aircraft.
- Three promising hydrogen-powered propulsion concepts: fuel cell based propulsion for seat classes 20-100 (EIS 2035), combustion-based propulsion for seat class 211-300 (EIS 2040), and hybrid fuel cell/combustion based propulsion for seat classes 101-210 (EIS 2035), for shorter aircraft ranges than usual. The hydrogen is assumed to be green hydrogen.

Sustainable aviation fuel (SAF) is fuel that is qualified to replace fossil kerosene in aircraft. Current SAFs may be used in blends with at least 50% fossil kerosene. SAF is available in two types: bio- or waste-based, i.e., with carbon from sustainable biomass, and synthetic, i.e., with carbon recycled or captured from the air. The production of synthetic

SAF also requires green hydrogen, thus leading to a dependency between synthetic SAF and green hydrogen as fuels. Four promising production routes for bio- or waste-based SAFs have been identified, each requiring different organic waste sources and production processes. Both for synthetic SAF and hydrogen, one promising production route has been identified.

Aircraft and fleet-level evaluation of novel propulsion concepts and hydrogen as alternative fuel

The identification and aircraft level evaluation of promising concepts (propulsion, alternative fuels, production routes) was carried out based with respect to technological, economical, and environmental aspects, based on literature and supported by expert workshops.

The impact of the selected propulsion concepts on the gross gaseous emissions and energy consumption of the global fleet has been evaluated in high and low global pre-COVID traffic scenarios that have been used for the first assessment of the CS2 Technology Evaluator, shown in Figure 2.

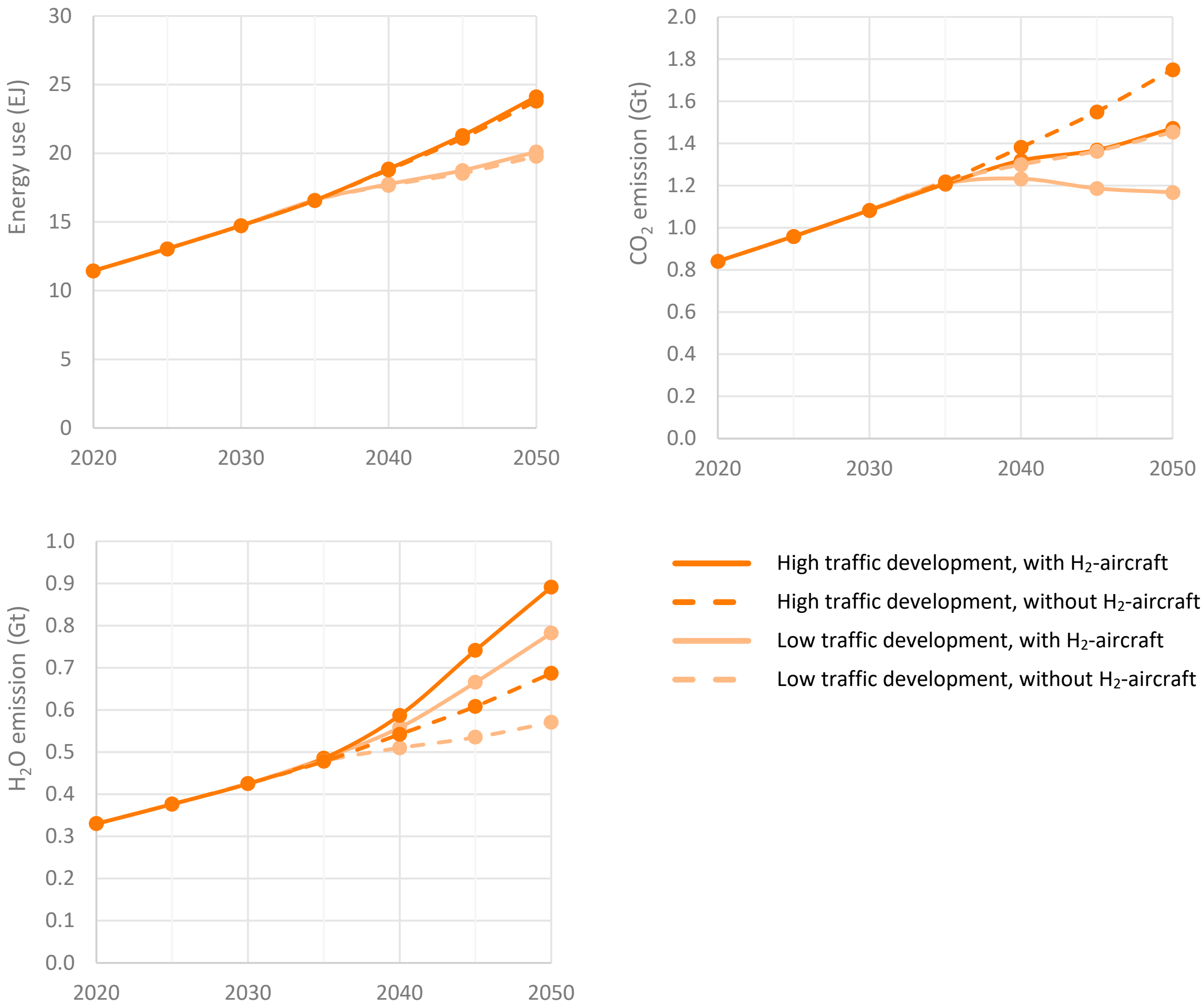


Figure 2: Global aircraft energy use and gross emissions at fleet level in ***high*** *or* ***low*** *traffic scenarios, both with (solid lines) and without (dashed lines) hydrogen-powered aircraft in the fleet*

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 SAF-based aircraft. In this scenario advanced aircraft technologies are applied as well, consistent with the CS2 concept aircraft that have been assessed by the CS2 Technology Evaluator in its first assessment. During the evaluation period 2035-2050, promising SAF-based aircraft are gradually entering the fleet consistent with this first assessment. In the scenario with hydrogen-powered propulsion, the promising SAF-based aircraft in the preceding scenario that are in the seat classes 20-300 and carry out short-range flights are replaced by hydrogen-powered aircraft with the three promising hydrogen-powered propulsion concepts mentioned before.

As shown in Figure 2, 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).

Supply, demand, emissions impact and economic viability of alternative fuels and novel propulsion

For flights departing airports in the EU and UK, the supply and demand, emissions impact and economic viability of alternative fuels were studied as resulting from the fleet-level evaluations with and without hydrogen-powered propulsion. The total demand for SAF until 2050 was modelled based on the fleet level evaluation with 100% SAF for CS2 aircraft concepts and blends of 50% SAF for other (older) kerosene-powered aircraft. Supplies of alternative fuels were considered taking into account scenarios for competing uses (other than for aviation) of these alternative fuels or their feedstocks.

From 2035, prioritising the supply of hydrogen for aviation to hydrogen as fuel for hydrogen-powered aircraft, the supply of hydrogen matches the demand for these aircraft almost completely, even in case of 95% competing use (i.e., 5% of the green hydrogen is available for aviation).

Figure 3 shows that overall, until 2030 the feedstock availability for SAF was found to be sufficient to meet the ReFuelEU Aviation mandate in the 95% competing use scenario (i.e., 5% of the feedstock is available for flights). Provided enough production facilities are realised to process the available feedstock, which could be stimulated by effectuating the ReFuelEU Aviation mandate, the supply of SAF is on the right way. However, compared to total SAF demand, the supply was found to be significantly smaller. Also, the projected cost of SAF for airlines is significantly higher than the projected cost of fossil kerosene (factor 3.5 to 5 by 2030 to 2 to 2.5 by 2050). Given the competitive and international nature of the aviation industry, this means that SAF uptake is unlikely to exceed regulatory requirements (such as the ReFuelEU Aviation mandate), unless cost differences are reduced. Additional (carbon) costs related to fossil kerosene, which were not modelled, can be expected to reduce the cost difference.

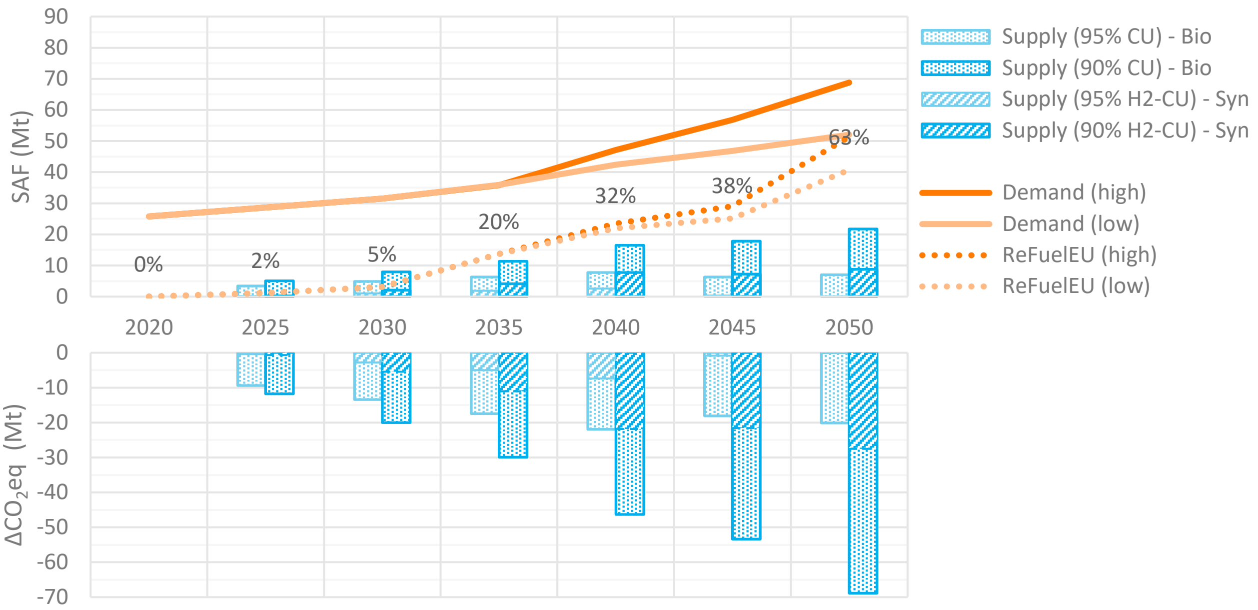


Figure 3: SAF demand based on technological and regulatory fleet-based blending limits (solid lines) or ReFuelEU Aviation mandate (dotted lines) and SAF supply (split in bio- or waste-based SAF supply and synthetic SAF supply) for flights departing from EU and UK (top). Net CO_2eq emissions reduction based on the SAF supply (bottom). Results are shown for traffic scenarios with hydrogen-powered aircraft fully flying on green hydrogen with different traffic levels, for different cases of biomass and hydrogen competing use (CU), and with supply from the EU and UK and limited imports. SAF demand is based on maximum allowed use of SAF. SAF supply is based on projected feedstock (sustainable biomass and green hydrogen) availability

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 SAF. Moreover, if, as an alternative, the available hydrogen for aviation would first be used to satisfy the regulatory requirements set by the ReFuelEU Aviation mandate, a significant part of the flights with hydrogen-powered aircraft would have to use non-green hydrogen, reducing the contributions of these aircraft to climate neutrality.

In the scenario without hydrogen-powered propulsion, total CO_2eq reductions were found to be at least 10% smaller, compared to the scenario with hydrogen-powered propulsion. Total fuel costs and well-to-wake energy demand (for the production of hydrogen and synthetic SAF) were found to be at least 10% and 30% higher in 2050, compared to the scenario with hydrogen-powered propulsion.

Roadmaps for novel propulsion concepts and alternative fuels

Roadmaps for the novel propulsion concepts for 2023-2050 were derived in relation to the public-private Clean Aviation and Clean Hydrogen programmes in Horizon Europe. Roadmaps for bio- or waste-based SAF, synthetic SAF, and green hydrogen were developed addressing supply and demand, including supply of feedstock and availability of production facilities, production technology development, economic aspects, and aircraft and airport infrastructure development. The roadmap for green hydrogen combines its use as fuel with its use as feedstock for synthetic SAF.

Strategic recommendations to public and private parties

Finally, nine strategic recommendations are given to public and private parties to obtain the predicted alignment of demand for aviation, ReFuelEU Aviation mandate, and supply of SAFs and green hydrogen in 2030 and to contribute to climate neutrality in aviation from 2035 towards 2050:

- SR 1: Develop the regulations needed for the use of aircraft powered by liquid hydrogen before 2028
- SR 2: Follow-up the TRANSCEND study with a study on the full climate impact of new fuels
- SR 3: Develop sustainable aviation fuels not requiring blending with fossil kerosene
- SR 4: Continue at European, national, regional and private levels the development of required technologies for energy-efficient SAF-powered and hydrogen-powered aircraft for regional and short/medium range
- SR 5: Ensure the European supply of SAF and green hydrogen
- SR 6: Ensure sufficient availability of renewable electricity and biomass/waste for the production of fuels to meet the ReFuelEU Aviation mandate
- SR 7: Follow-up the TRANSCEND study with an assessment on the impact of cost increases due to the increased use of alternative fuels on aviation demand and emissions, and possibly introduced policies to reduce negative effects
- SR 8: Follow-up the TRANSCEND study with a sensitivity study and integrated scenario studies to identify the most effective and ensure the most stable policies
- SR 9: Periodically update studies such as TRANSCEND to include the latest developments

These strategic recommendations are introduced through considerations, are detailed in sub-requirements, and are supported by comments. Considerations and comments include detailed values as obtained from this study.

Contents

1 Introduction

Anthropogenic climate change and environmental impact are increasingly addressed by governments, international bodies, and industry. In the 2015 Paris Agreement (UNFCCC, 2015), the participating countries set the goal of limiting the global temperature increase well below 2°C above pre-industrial levels and pursuing efforts to limiting this to 1.5°C, which means that net CO_2 emissions should be reduced to zero by 2070 or 2050, respectively[1] (IPCC, 2018, C.1). In 2019, the European Commission through its Green Deal 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 (EC, 2019; EC, 2020a). This further stipulates a reduction of CO_2 emissions of 55% across Europe by 2030, compared to levels in 1990. In 2020, the European Commission published its hydrogen strategy for a climate-neutral Europe (EC, 2020b).

For aviation specifically, Europe set environmental goals as part of Flightpath 2050, launched in 2011 (EC, 2011). Through successive technology research programmes (such as Clean Sky and Clean Sky 2), Europe is accelerating the progress towards the Flightpath 2050 with high level objectives for reduction of CO_2, NO_X, and noise emissions to be achieved through development of new aircraft and propulsion technologies (Clean Aviation, 2022b; EC, 2007; EC, 2014). Recently, aviation industry's commitments towards net-zero CO_2 have grown, as exemplified in Europe by Destination 2050 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) and the Clean Aviation Strategic Research and Innovation Agenda (Clean Aviation, 2021), and addressed globally by work of the Air Transport Action Group and the International Air Transport Association (ATAG, 2021; IATA, 2021). Besides emissions reductions through new aircraft and propulsion technologies, these reports highlight the promise of alternative fuels for aviation. New legislative proposals, such as the ReFuelEU Aviation SAF blending mandate (EC, 2021), also aim to stimulate the use of such alternative fuels.

1.1 Objectives

The TRANSCEND project has investigated both novel propulsion technologies and alternative fuels for aviation up to 2050 as potential key technological contributors to climate neutral aviation. This report presents the final results of TRANSCEND. It presents the main options for alternatives to conventional fossil jet fuels which are (promising to be) suitable for aircraft propulsion, as visualised in Figure 4.

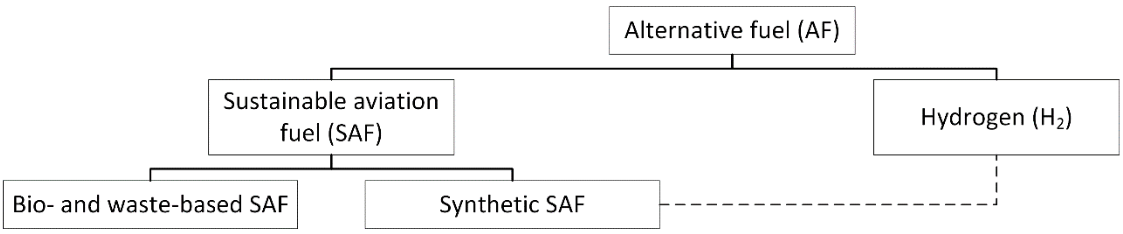


Figure 4: Types of alternative fuel considered in TRANSCEND

Firstly, there are various forms of **sustainable aviation fuel (SAF)**. 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 International[2] (ASTM International, 2021). Current SAFs need to be

[1] "In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range)". (IPCC, 2018, C.1)

[2] ASTM International was formerly known as the American Society for Testing and Materials.

blended with at least 50% fossil kerosene (CAAFI, 2021). Although gross (tailpipe) CO_2 emissions are similar to fossil kerosene, net CO_2eq emissions of sustainable aviation fuels are substantially lower. Reductions of up to 100% are possible, but typical figures vary around 80% (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021; EP, 2018). This is due to the fact that the carbon contained in the fuel is sourced from sustainable biomass – in case of bio- or waste-based SAF – or recycled or captured from the air – in case of synthetic SAF (EP, 2018). Included in the net CO_2eq emissions reductions realised by SAF are changes in other greenhouse gas emissions during feedstock cultivation, conditioning, processing and extraction, transportation, the feedstock-to-fuel conversion process, and fuel transportation and distribution (ICAO, 2019). Future aircraft powered completely by SAF can contribute to reduced emissions of greenhouse gases, both by reducing fuel consumption (gross and net emissions) and by eliminating the need for blending with fossil kerosene (net emissions).

Secondly, **hydrogen (H_2)** is an alternative fuel that cannot be used in current aircraft engines[3] 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 (2021). In this study, all hydrogen is assumed to be produced in a sustainable way. Such hydrogen is also referred to as green hydrogen. 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. This is illustrated by the dashed line in Figure 4.

The novel propulsion technologies and alternative fuels considered in this report were studied and assessed in terms of technological feasibility and environmental performance (energy usage and gross/net emissions of CO_2(eq), NO_X and water vapour) and, for alternative fuels only, availability and economic viability.

1.2 Reading guide

Following Section 1.3, about TRANSCEND, the remainder of this report is structured as follows. Chapter 2 briefly describes the worldwide traffic development scenarios used as input for the work conducted in TRANSCEND. Chapter 3 deals with novel propulsion technologies, in particular hydrogen-powered propulsion, and quantifies the changes in gross emissions from hydrogen-powered aircraft and translates the aircraft-level impacts into on global fleet-level effects. Chapter 4, on alternative fuels, investigates supply and demand of green hydrogen, bio- or waste-based SAF, and synthetic SAF in Europe and UK, thereby also highlighting any gaps that might exist towards environmental goals, including net emissions. Both Chapters 3 and 4 conclude with a roadmap. Chapter 5 presents conclusions, leading up to strategic recommendations, which are presented in Chapter 6. Various appendices provide additional results and relevant background material.

1.3 About TRANSCEND

TRANSCEND is a project within the Clean Sky 2 Technology Evaluator (TE, Clean Aviation, 2022a), which evaluates the reduction of emissions that can be obtained due to Clean Sky 2 developments on aircraft and propulsion technologies for fossil-kerosene-driven aircraft. Complementary to the TE, TRANSCEND mainly focuses on alternative fuels and propulsion technologies not yet investigated in Clean Sky 2. The objectives of TRANSCEND are visualised in Figure 5. More information about TRANSCEND is available at the project website, https://project.nlr.nl/transcend/

[3] There are other alternative fuels that cannot be used in current engines, see for example Goldmann et al. (2018). In line with Clean Aviation Partnership (2020), EC (2020b), McKinsey & Company (2020), and Hydrogen Europe and Hydrogen Europe Research (2020) the choice for hydrogen has been made in this study.

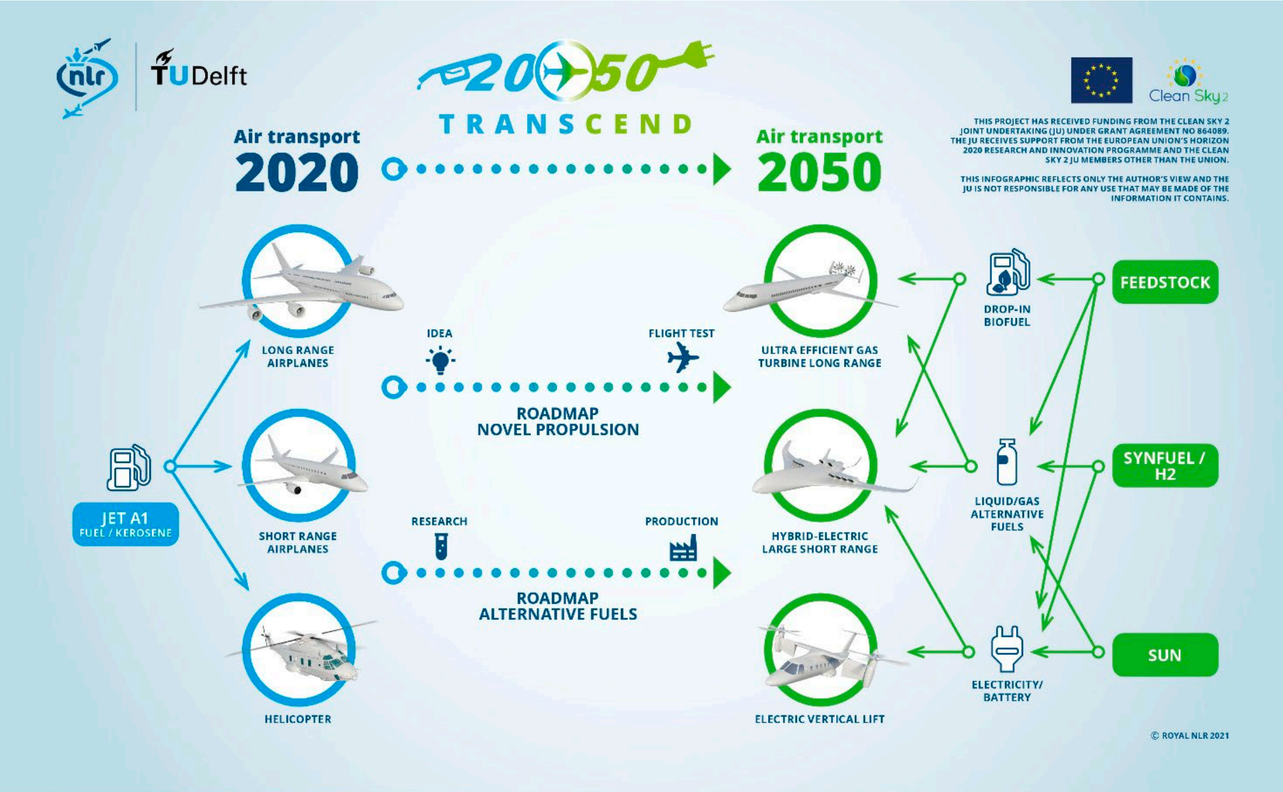


Figure 5: Infographic of the TRANSCEND project on the evaluation of the potential contribution of novel propulsion and alternative fuels to climate neutral aviation in 2050 and on roadmaps for novel propulsion and alternative fuels to achieve this potential contribution. The aircraft and fuels shown in 2050 indicate propulsion and fuels considered, not necessarily the propulsion and fuels that have been evaluated

2 Traffic development scenarios

To assess the impact of novel propulsion technologies and alternative fuels on global, fleet-level scale, two traffic development scenarios, referred to as the DLR Clean Sky 2 (CS2) scenario (Gelhausen, Grimme, Junior, Lois, & Berster, 2022), have been used as a starting point. As these traffic scenarios were developed external to TRANSCEND, this chapter does not go into detail on the background or composition of these scenarios. Rather, it briefly introduces them and highlights aspects that are of relevance for understanding the outcomes presented in this report.

The scenarios mainly differ in terms of growth: 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. As Figure 6 shows, the scenarios start to grow apart from 2035 onwards. Neither scenario includes the impact of COVID-19. Results for 2020 are pre-COVID estimates for that year, rather than actual figures realised.

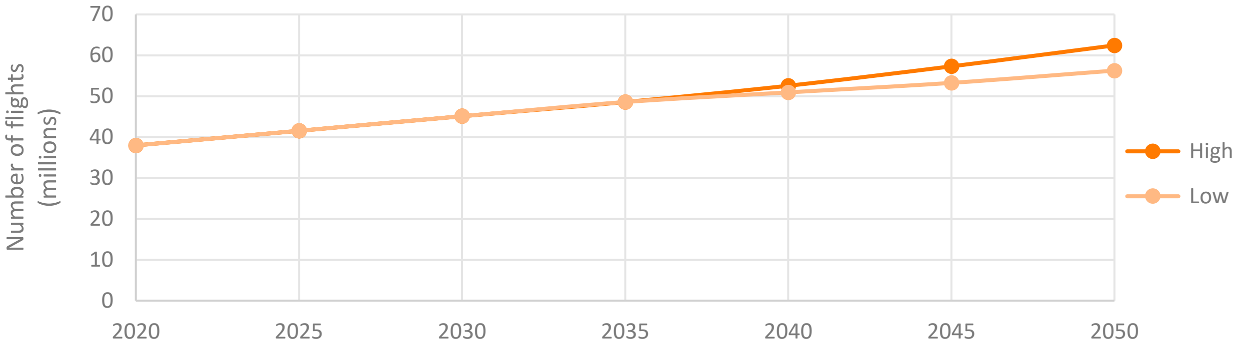


Figure 6: Traffic development (number of flights) in the two traffic development scenarios considered (based on Gelhausen, Grimme, Junior, Lois, & Berster, 2022)

Besides a different number of flights, the average aircraft size differs between the scenarios. This is shown in Figure 7. In the Low scenario (left), 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).

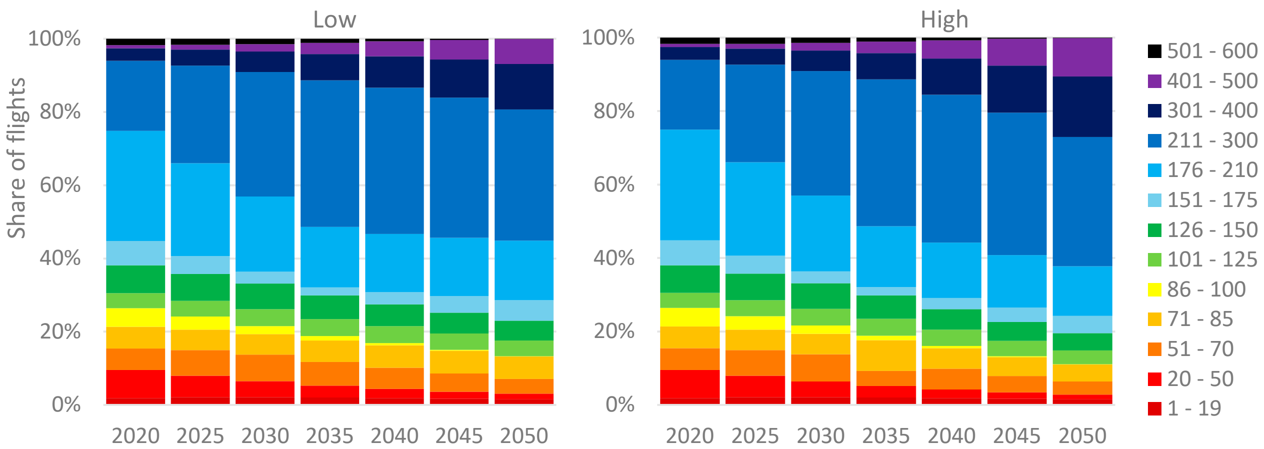


Figure 7: Fleet composition according to aircraft size class in the two traffic development scenarios considered (based on Gelhausen, Grimme, Junior, Lois, & Berster, 2022)

As aircraft size growth is a consequence of airport capacity constraints, the increasing share of larger aircraft does not result in substantial changes over stage length over time, or between scenarios. In all cases, average stage lengths vary around 1825 kilometres.

The traffic scenario includes the introduction of new aircraft, using Clean Sky 2 technology. These enter the market from 2030 onwards. Different aircraft models have different entry into service (EIS) years, with larger aircraft typically entering the market later than smaller models. Figure 8 shows the fleet composition according to aircraft entry into service year, thereby illustrating the rate of fleet renewal. From 2045 onwards, the share of aircraft with EIS 2040 is larger than the share of aircraft with EIS 2030 or 2035. This is directly linked to the fact that from 2040, larger aircraft enter into service, which are used for a larger share of the flights (indicated in Figure 7). The percentage values shown in the dark blue columns indicates the share of flights operated by older aircraft.

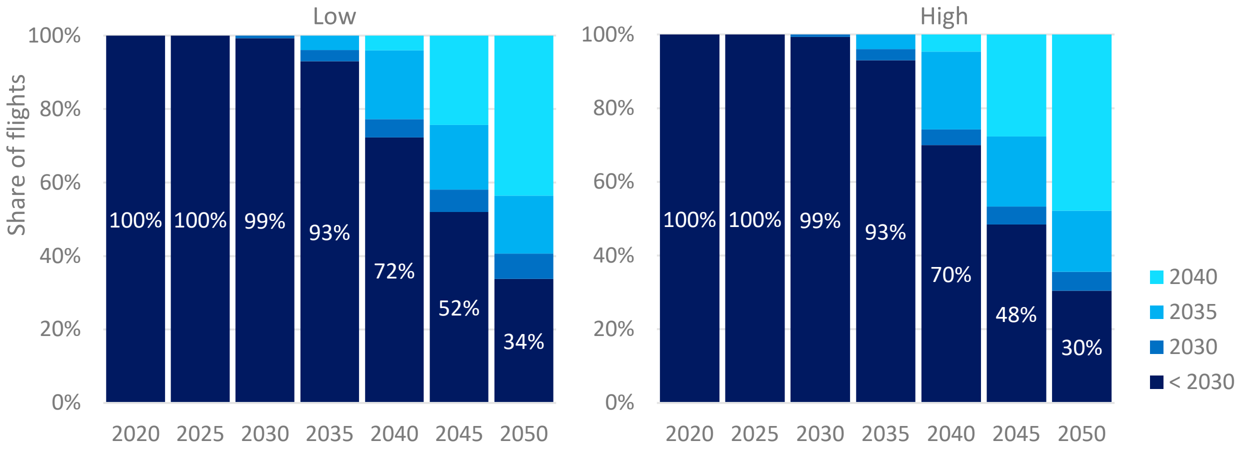


Figure 8: Fleet composition according to aircraft entry into service (EIS) year in the two traffic development scenarios considered (based on Gelhausen, Grimme, Junior, Lois, & Berster, 2022). Aircraft with EIS in 2030 or later are Clean Sky 2 aircraft

Appendix C.1 presents the figures shown in this chapter specific to flights departing from airports in the EU and the EU and UK.

3 Novel propulsion and hydrogen-powered aircraft

This chapter shows how the various environmental quantities of interest (energy usage and gross[4] emissions of CO_2, NO_X and H_2O) are projected to develop between 2020 and 2050 based on the traffic development scenarios with novel propulsion integrated into aircraft powered by alternative fuels. Promising novel propulsion concepts with their alternative fuels are presented and their potential integration into aircraft is indicated. Aircraft with novel propulsion concepts and alternative fuel are selected for further evaluation. The evaluation is carried out first on aircraft level and finally on fleet level.

3.1 Novel propulsion and focus on hydrogen-powered aircraft

In TRANSCEND's previous literature study (van Muijden, et al., 2021), seven promising propulsion concepts with numerous underlying novel propulsion technologies were identified for potential aircraft application with entry into service well before 2050. These 7 propulsion concepts are defined by two characteristics. The first characteristic is the energy source that is stored in the aircraft and used for propulsion, which can be SAF, hydrogen, or chemical energy as stored in a battery. The second characteristic are 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. These devices are either gas turbine based engines that convert the chemical energy from 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.

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 (van Muijden, et al., 2021). B = battery, S = 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

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
SAF combustion	S	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	

For these 7 promising propulsion concepts, the gross emissions of the greenhouse gasses CO_2 and NO_X during operation are either zero or nonzero. In case both gross CO_2 and NO_X emissions are nonzero the underlying novel propulsion technologies enable significant reductions in these gross emissions compared to present propulsion.

[4] Gross emissions are the emissions as they leave the aircraft. Alternative to gross emissions are net emissions. Net emissions take into account emissions reductions realized elsewhere in the life cycle, such as is the case with sustainable aviation fuel (SAF). Gross emissions do not take this into account. That means that the gross CO_2 emission quantities presented here might be further reduced in 'net' case due to the use of alternative fuels.

These 7 propulsion concepts need to be integrated into aircraft. The literature study shows that zero-gross-emission concepts have higher weight and/or volume of the whole propulsive system (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.

The CS2 Technology Evaluator (Clean Aviation, 2022a) assesses fossil-kerosene-powered aircraft with CS2 propulsion technologies, which are gas turbine based engine technologies. Complementing the CS2 Technology Evaluator, the following propulsion concepts were chosen for further evaluation:

- Gas turbine based CS2 propulsion technologies with 100% SAF.
- Hydrogen-powered propulsion concepts, which have the potential for zero gross emissions.

Based on their applicability for regional and larger aircraft, (hybrid) hydrogen-powered fuel cell and/or combustion concepts have been selected as the three hydrogen-powered propulsion concepts for further study.

3.2 Hydrogen-powered aircraft level modelling and analysis

Aircraft with the selected three hydrogen-based propulsion concepts were modelled and analysed to represent three seat classes, with limited design range compared to aircraft presently in operation, and entry into service (EIS) years:

1. Seat class 20-50: turboprop aircraft with electric fuel cell based propulsion[5], design range 1000 km, EIS 2035
2. Seat class 151-175: turbofan single-aisle aircraft with hybrid propulsion, design range 2000 nm, EIS 2035
3. Seat class 211-300: turbofan twin-aisle aircraft with combustion based propulsion, design range 2000 nm, EIS 2040

The aircraft were modelled based on ATR-42-600 (seat class 20-50), Airbus A320neo (seat class 151-176), and Boeing 787-8 (seat-class 211-300) aircraft that are currently in operation. First, Clean Sky 2 technology improvements were included in the model. Then, hydrogen-propulsion technology was integrated to the level needed to have the main impact on gross emissions and energy consumption. In all propulsion concepts hydrogen was stored in liquid state (LH_2). This is presently the storage option with the lowest weight compared to alternative storage solutions for the same amount of fuel that is needed for regional and larger aircraft. Aircraft technology improvements for fossil kerosene aircraft in 2035 and 2040 with respect to the reference models were derived from CS2 information.

For each of these seat classes, the following sections describe key results, such as gross NO_X emission, gross water emission, and energy consumption for a flight, as varying dependent on flight range and number of passengers. For all hydrogen-powered propulsion concepts, the gross CO_2 emissions, soot emissions, and other gaseous and particle emissions are zero[6].

Preliminary evaluations of these aircraft level evaluations were provided before and discussed during a workshop with more than 25 experts from aircraft and engine industry, potential key solution providers from other sectors, research organisations, and academia (NLR, n.d.). The experts' feedback has been used to update the modelling assumptions and to detail the modelling approach further[7]. (Lammen, Peerlings, van der Sman, & Kos, 2022) provides further details on the modelling and analysis of the H_2-powered aircraft, in addition to what is described in the next sections.

[5] Initially a hybrid hydrogen propulsion concept was modelled with a parameter for the use of both fuel cell and combustion concepts, similar to the A320neo (see Section 3.2.2). It appeared that the purely fuel cell based propulsion had a better performance in terms of NO_X emissions and energy consumption.
[6] Even though this is out of scope for this document, it is useful to take into account when considering the climate impact due to the significantly increased H_2O emissions of hydrogen-powered aircraft compared to their SAF alternatives.
[7] During the expert workshop the hybrid hydrogen concepts for ATR-600 and A320neo aircraft were discussed. Later, the hydrogen combustion approach for the Airbus A320neo has been applied to the hydrogen version of the Boeing 787-8.

3.2.1 Seat class 20-50: turboprop

For the H_2-powered turboprop in the 20-50 seat class, distributed propulsion units (4 or 6) were assumed, consisting of a propeller, electric motor and inverter, and a fuel cell. Electric motor and Inverter specific power was modelled as 10 kW/kg each; total electric system efficiency was modelled at 94%. A propeller efficiency of 85% was assumed, taking into account distributed propulsion. Fuel cell specific power was modelled at 2 kW/kg, including cooling system. Fuel cell (plant) efficiency was modelled as a function of flight phase and ambient conditions, taking into account the fuel cell compressor power needed. Fuel cell stack efficiency was assumed at 60%, excluding compressor losses. LH_2 tanks were assumed to be cylindric and located behind the cabin, for which the fuselage has been extended. This extension is causing an increase in weight and drag. LH_2 tank gravimetric index was modelled at 0.3. To compensate the shift in aircraft centre of gravity due to the fuel tanks, the wings were shifted backwards.

The aircraft configuration has 3400 kW total sized fuel cell power, distributed over 4 or 6 propulsion units, with a design range of 1000 km and a design payload of 5.1 tonnes (persons and their luggage), a cruise speed of 556 km/h (TAS), altitude cruise at 20,000 ft, and a maximum take-off weight of 19.2 tonnes.

Compared to the ATR 42 aircraft with technology improvements for fossil kerosene aircraft in 2035, depending on flight range and number of passengers, the flight energy needed by the H_2-powered turboprop in the 20-50 seat class decreases between 31% and 33%, the gross H_2O emission increases between 72% and 77%, and the gross NO_x emission decreases by 100%.

3.2.2 Seat class 151-176: single-aisle turbofan

The H_2-powered aircraft in the 151-176 seat class has a parallel hybrid propulsion architecture consisting of a combustion turbofan with parallel fuel cell power train. The turbofan core mass flow was downscaled to 92%. Due to the uncertainty about the NO_X emissions of hydrogen combustion, this was assumed to remain unchanged, based on the expert's advice. Constant fuel cell power was applied during the flight. Fuel cells and electric system were modelled as for the seat class 20-50 (Section 3.2.1), taking into account the difference in the cruise altitude between the seat classes 20-50 and 151-176. For the LH_2 tanks a gravimetric index of 0.35 was applied.

Figure 9: Artist impression of H_2-powered aircraft in the 151-176 seat class

The aircraft configuration has 2300 kW total sized fuel cell power (e.g., implemented by 2 fuel cells of 1150 kW), a design range of 2000 nm with a design payload 16 tonnes (persons and their luggage), a cruise altitude of 35,000 ft at Mach 0.78, and maximum take-off weight 74.6 tonnes. An artist impression of the H_2-powered aircraft in the 151-176 seat class is shown in Figure 9.

In relation to the Airbus A320neo reference aircraft with technology improvements for fossil kerosene aircraft in 2035, depending on the flight range and number of passengers, the flight energy needed by the H_2-powered single aisle turbofan in the 151-176 seat class increases between 8% and 13%, the gross H_2O emission increases between 180% and 191%, and the gross NO_X emission varies between a 4% decrease and a 12% increase.

3.2.3 Seat-class 211-300: twin-aisle turbofan

The H_2-powered aircraft in the 211-300 seat class applied two combustion turbofans. As for the seat class 101-210, the NO_X emissions of hydrogen combustion was assumed to be the same as for the Boeing 787-8 reference aircraft. For the LH_2 tanks a gravimetric index of 0.37 was applied. The aircraft configuration has a design range of 2000 nm, with a design payload of 28.6 tonnes (persons and their luggage), cruise altitude of 37,000 ft at Mach 0.85, and a maximum take-off weight 165 tonnes.

In relation to the Boeing 787-8 reference aircraft with technology improvements for fossil kerosene aircraft in 2040, depending on the flight range and number of passengers, the flight energy needed by the H2-powered twin aisle turbofan in the 211-300 seat class increases about 7%, the gross H_2O emission increases between 175% and 177%, and the gross NO_X emission increases between 10% and 18%.

3.2.4 Interpolation to cover seat classes 50-210

Hydrogen-powered aviation holds greater potential than the three seat classes in considered in Sections 3.2.1 to 3.2.3. As such, the results from these sections were used to estimate the change hydrogen propulsion would have on energy and gross emissions in all seat classes between 50 and 210 passengers, with limited ranges.

For various turboprop aircraft seating up to 100 passengers, the hydrogen performance was modelled based on the results obtained from the 20 to 50 seat class (turboprop aircraft). For aircraft with capacity for 101 to 210 passengers, the results obtained for the 151-176 seat class (single-aisle turbofan) were used as a basis. The seat classes in the DLR CS2 scenario between 101 and 210 passengers mostly contain turbofan-equipped aircraft with 4, 5 or 6 abreast seating, but also an innovative turboprop seating in seat class 126-150, introduced into service in 2040. Due to the larger size of this turboprop, modelling was based on the single-aisle turbofan, as technology modelled for the hydrogen-powered turboprop was not found to be suitable for this larger aircraft at the relevant point in time.

The combination of interpolation results and the aircraft level modelling for hydrogen-powered aircraft in the 20-50 and 210-300 seat classes supports scenario analysis of hydrogen-powered aircraft in all seat classes between 20 and 300 seats. Figure 10 shows the share of flights operated by hydrogen-powered compared to non-hydrogen-powered aircraft for each of the years considered.

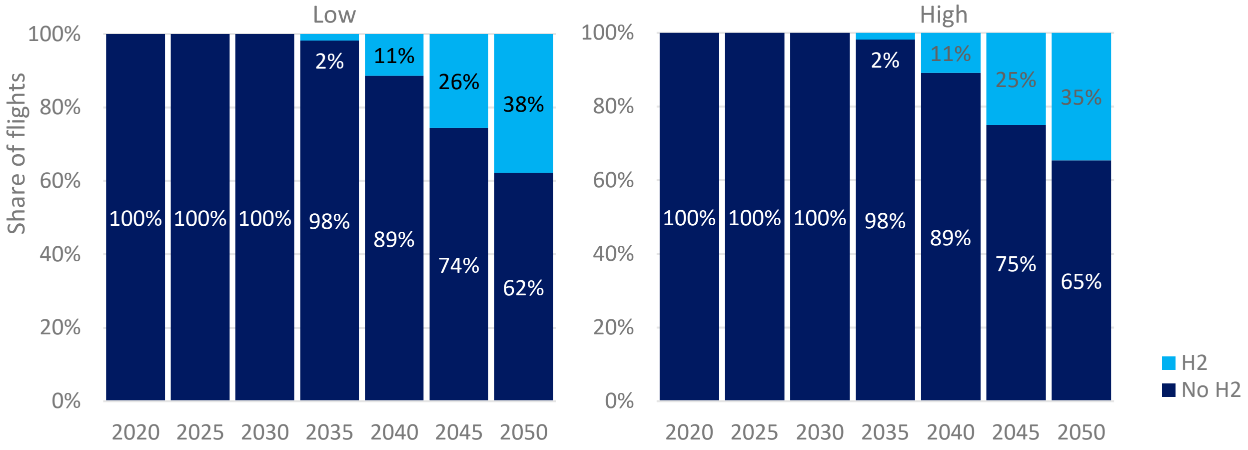


Figure 10: Share of flights operated by hydrogen-powered (H_2) and flights operated by non-hydrogen-powered aircraft (No H_2) in the two traffic development scenarios considered

3.3 Impact on global and EU aviation energy and gross emissions

Following the aircraft-level assessment, the impacts on EU and global fleets were analysed. This analysis was done using NLR's CO_2-tool, a full-flight gross emissions model based on EUROCONTROL BADA (v3.14) developed for the analysis of flights operated by both existing and future aircraft types. The model was also used to determine overall energy use and fuel consumption, serving as an input for the analyses presented in Chapter 4. Gross emissions and energy were computed on a flight-by-flight basis, taking into account flight distance between origin and destination and aircraft performance characteristics.

Figure 11 shows the development of energy use and emissions for global aviation in the four cases considered. These are combinations of traffic development scenario (low or high) and the possible use of hydrogen-powered aircraft. Results show that in all cases, global aviation energy use and emissions increase compared to 2020 levels. The impact of hydrogen-powered aircraft in the low traffic scenario is slightly bigger than in the high scenario, because of a higher share of flights in the hydrogen-applicable seat classes (up to 300 seats), as seen in Figures 7 and 10.

Aircraft **energy use** is mainly governed by the traffic scenario. Higher traffic development results in higher total energy consumption – up from 11 EJ in 2020 to 24 EJ in 2050 (low traffic scenario in 2050: 20 EJ). Total aircraft-level energy use is also slightly higher in case hydrogen-powered aircraft are introduced in the fleet, reflecting findings from the aircraft-level analysis. This effect is slightly more visible in the low traffic scenario, because that scenario contains a larger share of hydrogen-powered flights[8].

Gross **CO_2 emissions** are also driven by traffic development, but even more so by the use of hydrogen-powered aircraft – which emit zero CO_2. In the low traffic scenario, the introduction of hydrogen-powered aircraft helps to stabilise and even reduce overall CO_2 emissions from 2035 onwards to below 1.2 Gt in 2050. In the high traffic scenario, gross CO_2 emissions continue to rise to 1.5 Gt in 2050, but less so than if no hydrogen-powered aircraft were used (1.8 Gt). Clear step changes are observed in 2035 and 2040 in both traffic scenarios, when hydrogen-powered aircraft types are introduced. Reductions in net CO_2eq emissions by SAF are not included in this analysis, but will be treated in Section 4.3.

[8] This, in turn, is a result of the less pronounced aircraft size growth, further discussed in Chapter 2.

NO_X emissions again follow traffic development and are slightly increased by the possible use of hydrogen-powered aircraft. This is a direct consequence of the increase in energy consumption in the scenario with hydrogen-powered aircraft. **H_2O (water vapour) emissions** increase more substantially (26% in high traffic scenario; 32% in low traffic scenario) when hydrogen-powered aircraft are introduced. Further non-CO_2 climate effects, e.g. from contrail formation and contrail cirrus (Lee, et al., 2020; EASA, 2020), were not studied.

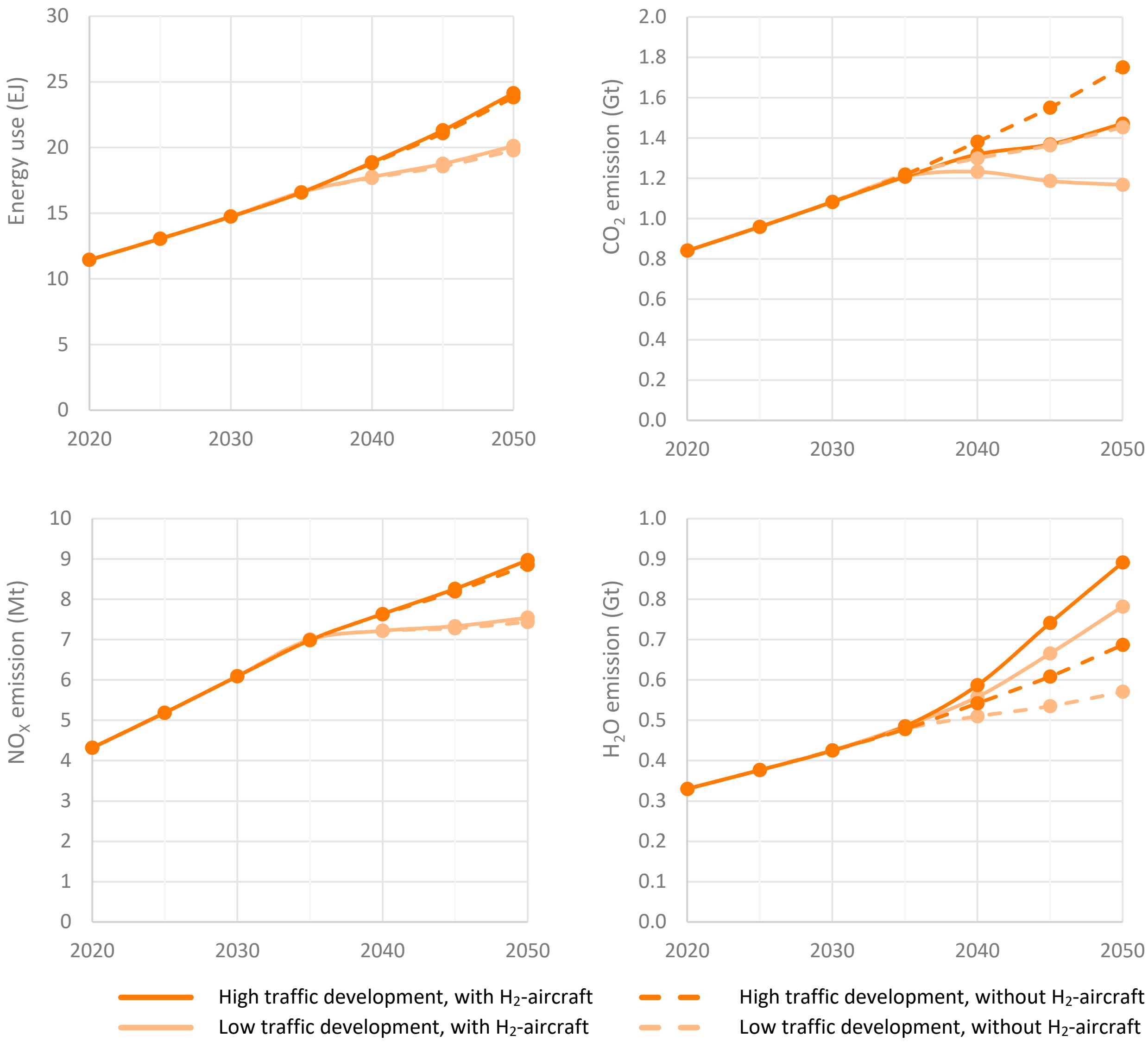


*Figure 11: Global aircraft energy use and emissions under **high** or low traffic development, and with (solid lines) or without (dashed lines) hydrogen-powered aircraft*

In Appendix C.2, Figure 36 shows results specific to flights departing from airports in the EU. Overall EU trends are similar to the global results shown in Figure 11.

3.4 Novel propulsion roadmap

To achieve the predicted impact on gross gaseous emissions, the promising novel propulsion technologies themselves and aircraft with these propulsion technologies need to be developed and these aircraft need to enter into service. Recently, various initiatives for these aircraft and propulsion technology developments have been taken.

At European level, strategic research and innovation agendas for Clean Aviation (Clean Aviation, 2021) and the Clean Hydrogen for Europe institutionalised partnership (Hydrogen Europe and Hydrogen Europe Research, 2020), with a roadmap on aviation, appeared already in their first drafts in 2020. Clean Aviation is built upon three pillars: disruptive technologies for a hybrid-electric regional aircraft (HER), disruptive technologies for ultra-efficient short/medium range aircraft (SMR) and disruptive technologies to enable hydrogen-powered aircraft. At national level, research programmes were initiated. For example, the 2nd call of the German Lufo VI programme for aeronautics, announced in 2020 a program line on Hydrogen technologies and (hybrid-) electric flight (zero emission aircraft) (Bundesministerium für Wirtschaft und Energie, 2020) and UK started early in 2021 the FlyZero project (ATI, 2022). FlyZero has identified six key technology bricks which require development at pace to unlock liquid hydrogen flight together with the enabling technologies, a sustainability assessment, operational and infrastructure requirements and economic analysis. FlyZero recently published technology roadmaps for 13 technology bricks (Hadnum, Pacey, & Milne, 2022) of which 9 are directly related to hydrogen-powered propulsion.

Also, the private sector took initiatives for hydrogen-powered aircraft. Airbus introduced ZEROe aircraft in 2020 (Airbus, 2020) and announced recently a partnership with CFM International to pioneer hydrogen combustion with the objective to ground and flight test a direct combustion engine (Airbus, 2022a). Research organisations also published about the pathway to 2050, like TUD and NLR jointly with Towards a Sustainable Air Transport System (TUD and NLR, 2021) and DLR with its Aeronautics Strategy for the Green Deal (DLR, 2021).

Figure 12 presents a European roadmap for SAF-powered propulsion. The roadmap foresees two routes: direct exploitation of CS2 propulsion technologies in new aircraft from 2030 and further, and complementary developments within Clean Aviation with entry into service in 2035. In the direct exploitation route, further research and innovation on CS2 technologies, including certification, is needed to enable 100% SAF blends, to be in line with the modelling approach taken in Section 3.1. In the Clean Aviation call, the adoption of 100% non-blended SAF and full adaptability to 100% (non-blended) SAF are addressed for regional aircraft and short-range/short-medium-range aircraft respectively (Clean Aviation Joint Undertaking, 2022). In both routes, a 5-years aircraft development programme is assumed to be needed before entry-into-service. The market uptake of CS2 technologies has been taken as modelled by the CS2 Technology Evaluator. More detailed roadmaps for the SMR and HER pillars in Clean Aviation are included in the Clean Aviation work programme (Clean Aviation Joint Undertaking, 2022), including scheduled TRL levels, major deliverables, and major milestones.

Figure 13 presents an European roadmap for H2-powered propulsion. The roadmap until 2025/2026 is based on the first calls of Clean Hydrogen (Clean Hydrogen Joint Undertaking, 2022) and Clean Aviation (Clean Aviation Joint Undertaking, 2022). The call topics cover the key components of hydrogen-powered aircraft as modelled in Section 3.2. All topics have been scheduled to lead to projects in the 2023-2025/2026 range, reflecting the 36-48 months duration requested in the Clean Aviation calls[9]. More detailed roadmaps until 2030 for technology developments for H2 propulsion are found in the roadmaps for H2 and HER pillars in the Clean Aviation Work Programme (Clean Aviation Joint Undertaking, 2022), including scheduled TRL levels, major deliverables, and major milestones. These roadmaps, together with the aviation roadmaps in the Clean Hydrogen SRIA (Hydrogen Europe and Hydrogen Europe Research, 2020), have been used to indicate the Phase 2 part of the roadmap in Figure 13. Alike for SAF-based propulsion, a 5-years aircraft development programme is assumed before entry-into-service of single aisle hydrogen-powered aircraft. Small twin aisle aircraft development programme and market uptake has been included with an earliest entry-into-service into 2040, compatible with the transfer of Clean Aviation technology.

[9] The Clean Hydrogen call topics are less restrictive about the proposed project duration.

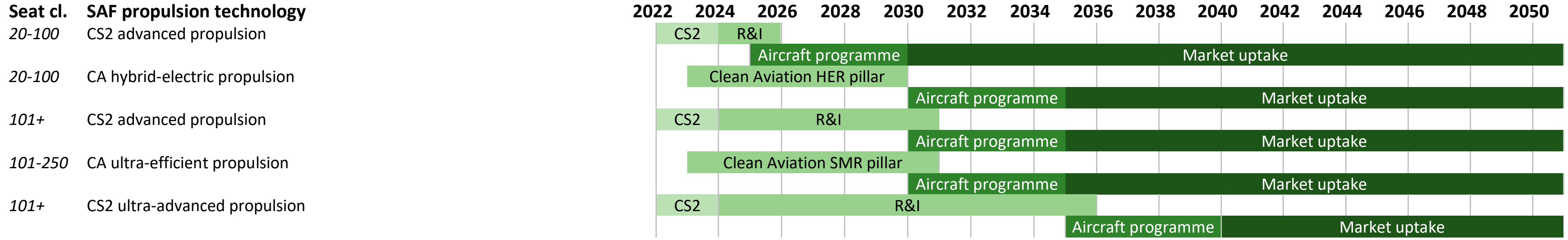


Figure 12: European roadmap for SAF propulsion technology. CS2 is Clean Sky 2, CA is Clean Aviation, R&I is research and innovation

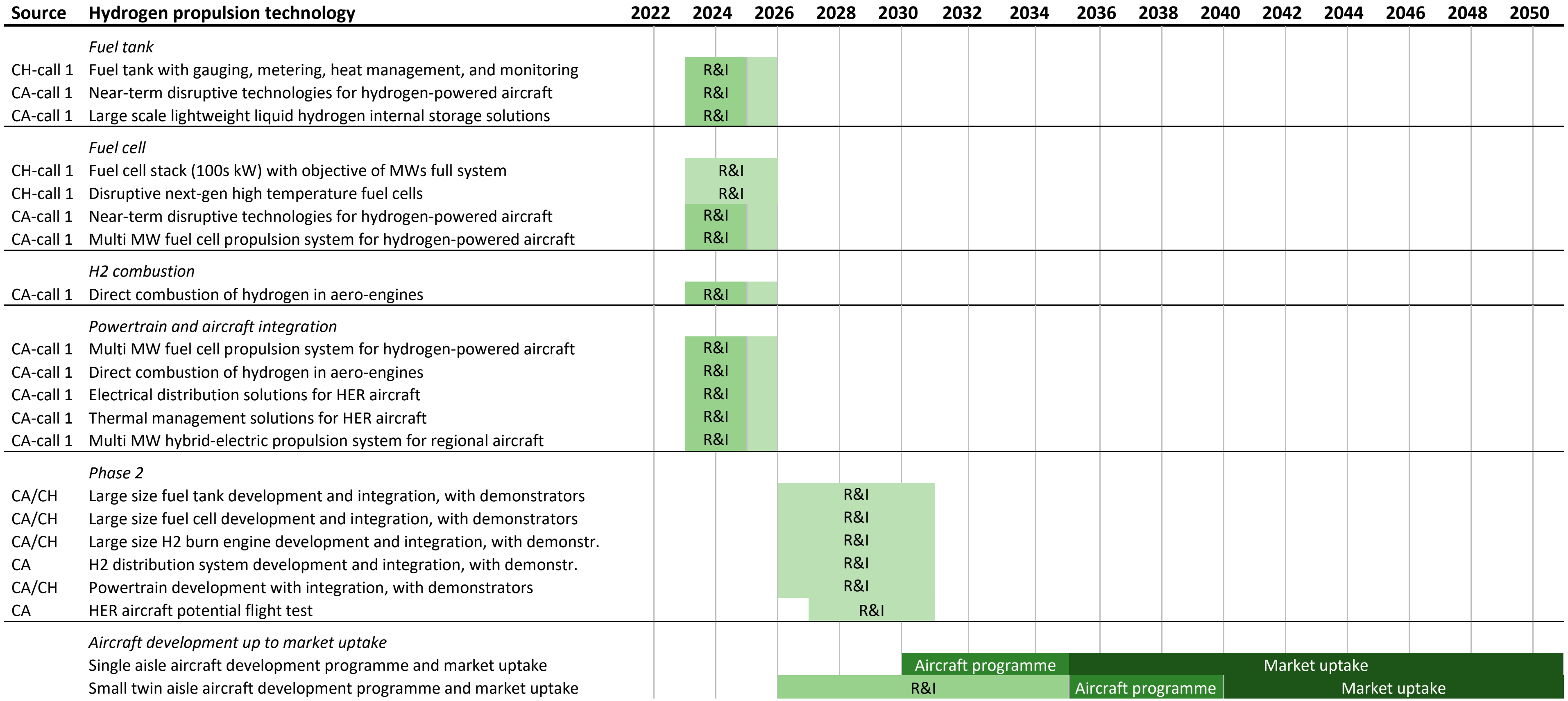


Figure 13: European roadmap for hydrogen-powered propulsion (based on Clean Aviation, 2021; Clean Aviation Joint Undertaking, 2022; Hydrogen Europe and Hydrogen Europe Research, 2020). CA is Clean Aviation, CH is Clean Hydrogen, R&I is research and innovation. The lightest green indicates scheduling uncertainty

4 Alternative fuels

Alongside improvements in aircraft and engine technology, such as the novel propulsion methods treated in Chapter 3, alternative fuels can also help to reduce the negative environmental impact of aviation. The potential of alternative fuels are seen in numerous roadmaps and decarbonisation commitments (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021; IATA, 2021; ATAG, 2021), but also in policy proposals. Part of Fit for 55, ReFuelEU Aviation[10] is a Commission proposal to set a blending mandate (EC, 2021). Similar initiatives or stimuli are considered elsewhere[11].

This chapter is dedicated to these three main categories of alternative fuels (AF) identified in Chapter 1: bio- or waste-based SAF, synthetic SAF and hydrogen. SAF is used to reduce net CO_2eq emissions, whereas the use of hydrogen in hydrogen-powered aircraft yields a decrease in gross CO_2 emissions. For each, supply and demand, emissions impact and economic viability are discussed. The economic viability is expressed in the minimum selling price (hereafter called 'costs') to airlines for different types of AF. This does not include subsidies and potential cost savings associated to having to surrender a lower amount of allowances in the EU Emissions Trading System (EU ETS). Appendix E supports the cost estimates presented and includes an energy-equivalent cost comparison of different AF.

The demand for SAF is governed by the total kerosene demand, scaled down by technological and regulatory limits with respect to blending. CS2 aircraft were modelled to be compatible with 100% SAF from a technological as well as regulatory point of view[12]. For other aircraft, a blending limit of 50% was taken into account, consistent with blending limits for current ASTM-certified SAFs. Figure 14 shows the fleet-based blending limit for SAF, increasing from 50% in 2020 to 80 to 87% as CS2 aircraft enter the fleet.

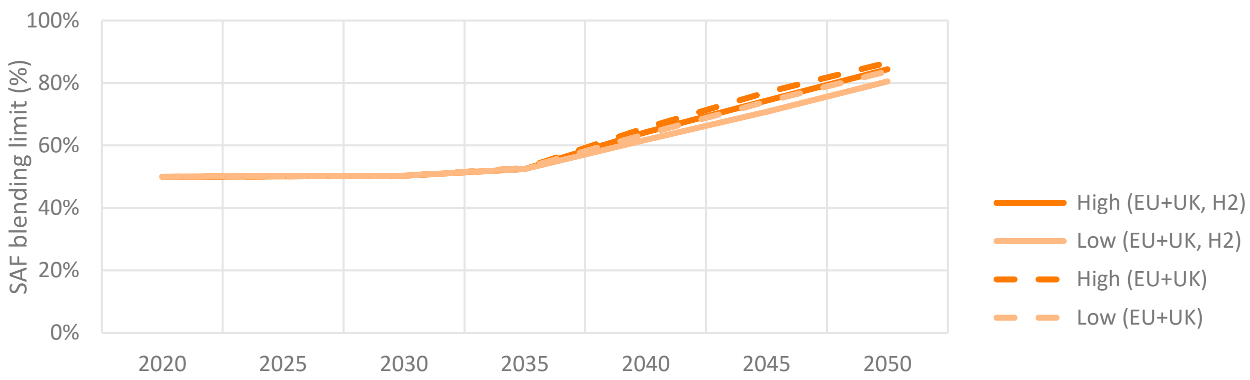


Figure 14: Fleet-based blending limit for SAF

As synthetic SAF is produced from H_2, the analysis on the supply side starts with H_2, for which hydrogen-powered aircraft present a clear demand. Next, bio- or waste-based SAF is treated. By its use, the remaining demand for SAF is reduced. Combined with any remaining H_2 available, the amount of synthetic SAF can be evaluated. Supply and demand are assessed from an EU and UK[13] perspective, meaning that the supply of SAF in the EU and UK[14] is

[10] Through ReFuelEU Aviation, the European Commission proposed a blending mandate of 2% in 2025, increasing in 5 year intervals to reach 63% in 2050. Part of this total blending mandate, is a sub-mandate for synthetic SAF, increasing from 0.7% in 2025 to 28% in 2050 (EC, 2021). The Council agreed on a general position that, in terms of blending levels, differs slightly from the Commission proposal (Council of the European Union, 22). This report is based on the original Commission proposal, published in July 2021 (EC, 2021).
[11] In 2021, the UK Department for Transport held a consultation on a SAF mandate (Department for Transport, 2021). Also in 2021, the Biden administration announced steps to increase the use of SAF in the United States (The White House, 2021).
[12] Although this certification is currently not in place, numerous flight tests or demonstrations with 100% SAF have been operated (Neste, 2021a; Palmer, 2021; Airbus, 2022c; ATR, 2022). As such, no barriers are expected.
[13] Many projections for hydrogen supply were made when the UK was still part of the EU and hence include an EU + UK figure. This scope was maintained.
[14] The EU supply for AF mainly consists of AF produced in the EU, from EU feedstock. In some cases, a limited quantity of imported AF is taken into account.

compared to the demand for SAF by flights departing from EU and UK airports. Furthermore, three different competing use scenarios for biomass and hydrogen – 85% (not for bio- or waste-based SAF), 90% and 95% – have been considered. This means that of the total supply, 15%, 10% or 5% would be available for aviation[15]. Figures for the resulting fuel demand (per scenario and per type) are included in Appendix C.3. As the traffic scenarios do not include the impact of COVID-19, neither do the scenarios for fuel demand. Moreover, presented demand for 2020 is a pre-COVID estimate for that year, rather than actual figures.

4.1 Identification of promising alternative fuels and their production routes

Sustainable aviation fuels are developed on the basis of feedstocks which can be categorized into biomass feedstocks (e.g. used cooking oil, agricultural residues, forestry residues and municipal solid waste) and renewable electricity, produced from renewable sources such as wind, solar and hydro. For each feedstock, different conversion processes can be used to reach a fuel that meets current jet fuel specifications. In Deliverable D1.1 of the TRANSCEND project (van Muijden, et al., 2021), six most promising SAF production routes are selected through literature review and with expert validation in a workshop. These production routes can be seen in Table 2.

Table 2: SAF production route choices (Kos & Posada Duque, 2021)

Abbreviation	Group of SAFs production routes	Product	TRANSCEND team preselection	Experts' agreeing on preselection	TRANSCEND team 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	✔
IH²	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

These six routes are explained in more detail together with their feedstocks and associated production technologies below. The six pathways are divided under the three main categories of SAF identified in Chapter 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 and relatively low production cost. Unfortunately, it also has technological disadvantages like low current density, limited ability to operate at low loads, and the inability to operate at high pressure (Chisholm, 2016).

[15] Ben Salah (2022) considered 50, 90 and 95% competing use scenarios for biofuel feedstock in 2030 and 2050. Van der Sman et al. (2021) considers 92% and 87% competing use for hydrogen in 2030 and 2050 (pp. 41-42) and 96% competing use for biofuel feedstock in 2050, classifying the latter as "realistic and feasible" (p. 102). The greenhouse gas emissions from flights departing from EU and UK airports in 2017 were about 4% of total EU GHG emissions (EEA, 2019; EASA, EEA, & EUROCONTROL, 2019). Energy use for these flights was approximately 2300 PJ (based on EASA, EEA, & EUROCONTROL, 2019, p. 22), compared to an EU final energy consumption of about 39400 PJ (eurostat, 2022b; eurostat, 2022a) – a share of some 6%.

Bio- or waste-based SAF

The **Hydro-processed Esters and Fatty Acids** (HEFA), **Fischer-Tropsch** (FT), **Fast Pyrolysis** (FP) and **Alcohol-to-Jet** (ATJ) pathways are four types of bio- or waste-based SAFs. This study only considers second generation feedstock, and is focused on residual biomass – which has several advantages over energy crops (Ben Salah, 2022, p. 11). HEFA is the most mature SAF pathway and is currently commercially available. It uses fatty feedstocks such as waste oils and fats, which undergo a deoxygenation reaction where hydrogen is added to break down the compounds into hydrocarbons (Pavlenko, Searle, & Christensen, 2019). Secondly, FT is a process in which synthetic gas is converted into ultra-clean fuels and value-added chemicals. Biomass gasification is combined with FT synthesis and catalytic cracking to produce synthetic paraffinic kerosene (SPK). Feedstocks that are used are lignocellulosic biomass and municipal solid wastes (Mawhood & al., 2016; Pavlenko, Searle, & Christensen, 2019; Michailos & Bridgwater, 2019). The pathway FP is based on organic materials which are heated up to 450 – 600 °C in the absence of air in order to produce organic vapours, pyrolysis gases and charcoal. Afterwards, they are condensed to bio-oil (Venderbosch, 2010). Lastly for ATJ, SAF is produced 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 (Pavlenko, Searle, & Christensen, 2019).

Synthetic SAF

The pathway to produce synthetic 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 created by using hydrogen and CO_2. This 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 for synthetic fuels.

4.2 Hydrogen

In order to operate hydrogen-powered aircraft and realise associated gross CO_2 emissions reductions, liquid hydrogen is required. The production of green hydrogen in Europe, although still marginal and expensive (IRENA, 2019), has increasingly gained the attention of policymakers, industries and society at large – for example evidenced by the publication of the European Commission's hydrogen strategy for a climate-neutral Europe (EC, 2020b).

Hydrogen demand for use in hydrogen-powered aircraft directly follows from the fleet-level assessment conducted in Section 3.3. 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 hydrogen availability are derived in Appendix D[16]. The resulting combination of supply and demand, as well as the CO_2 emissions reduction achieved due to the use of hydrogen-powered aircraft (analysed in Section 3.3), is shown in Figure 15.

Supply projections show that the demand for H_2 can be largely met – even without considering imports. Only in case of 95% competing use[17], European (EU + UK) production is insufficient to meet demand in 2045 and 2050. In 2050, imports are unable to fully resolve that gap, leaving a shortage of about 0.2Mt. As seen from the bottom figure, deploying hydrogen-powered aircraft in the fleet may reduce CO_2 emissions by about 40 Mt in 2050.

[16] Hydrogen availability for intermediate years, 2035 and 2045, has been interpolated.

[17] As the aviation sector is likely one of the very few sectors requiring liquified hydrogen, competing use figures refer to competing use for the totality of hydrogen available – both in gaseous and liquified form.

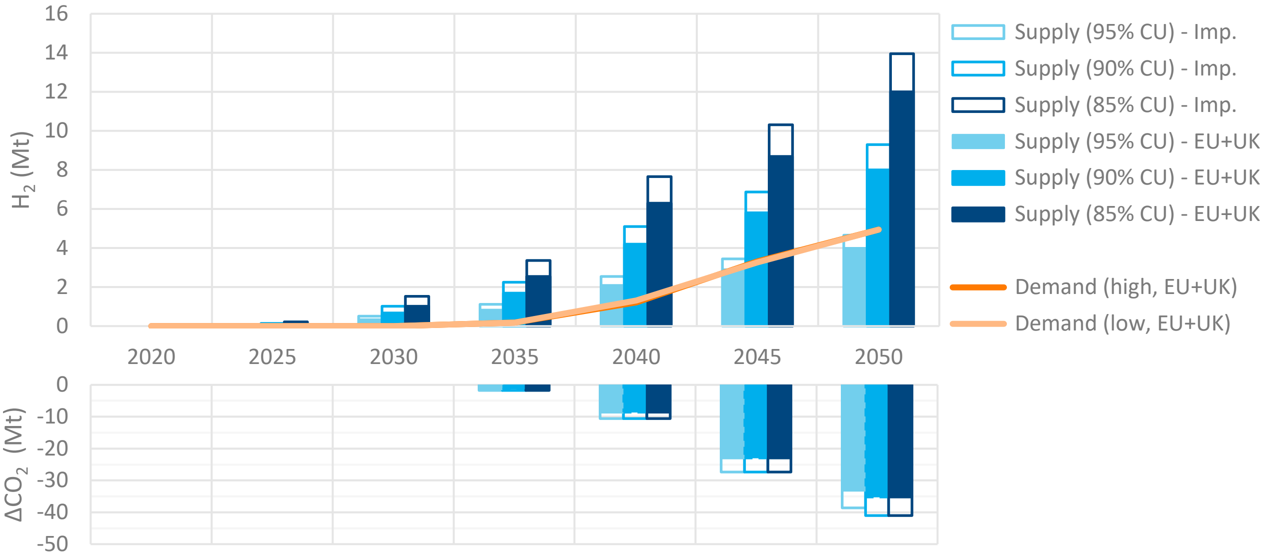


Figure 15: Hydrogen supply and demand (top; almost identical between low and high traffic scenarios) and gross CO_2 emissions reduction (bottom) in different traffic scenarios and cases of hydrogen competing use (CU) with supply from EU + UK only or with additional import from selected non-European production (Imp.)

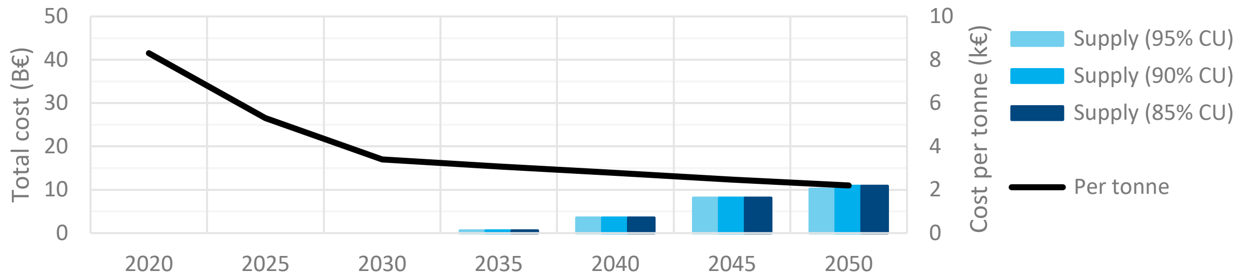


Figure 16: Total annual cost of liquid hydrogen supplied from EU, UK and imported production in different cases of competing use (CU) in billions of Euros (left axis) and cost per tonne in thousands of Euros (right axis)

Figure 16 shows the cost for renewable LH_2. It can be seen that current costs of green hydrogen are around 8000 €/tonne. In 2030, there is a tipping point after which the decrease in costs stagnates to 2200 €/tonne in 2050. This leads to a total yearly cost of 10B€ (95% CU) to 11B€ (85% CU) in 2050. Further detailed explanation of the costs of AF can be found in Appendix E. This appendix also shows that on an energy-equivalent basis, green LH_2 in 2050 is anticipated to be only slightly more expensive than fossil kerosene (without carbon price and/or tax).

4.3 Sustainable aviation fuel (SAF)

SAF can be produced from bio- or waste-based feedstocks or in synthetic form, in which hydrogen and CO_2 are processed to create synthetic kerosene. Even though SAF does not (or only barely) influences gross CO_2 emissions, it can substantially reduce net CO_2eq emissions.

4.3.1 Bio- or waste-based SAF

As part of TRANSCEND, Ben Salah (2022) investigated feedstock availability for bio- or waste-based SAF production in Europe on a per-country basis for 2030 and 2050 – the latter in two scenarios. The study identified the combinations of technology and feedstock for each country that result in the largest CO_2eq emissions reduction, while covering (national) demand. Figure 17 illustrates this work by presenting results for 2030 in a scenario with 10% SAF blend in a scenario with 90% competing use.

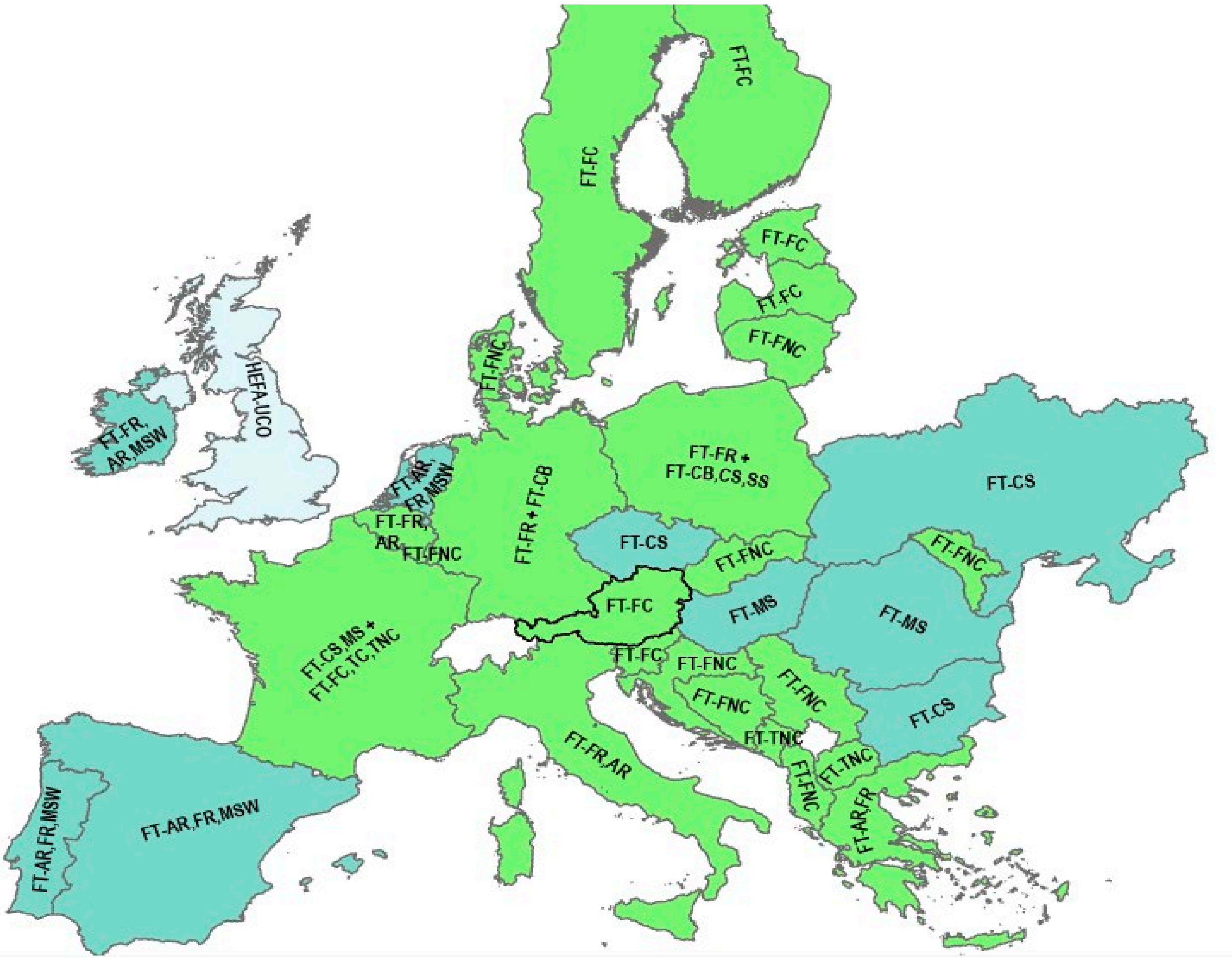


Figure 17: Selected combinations of technology and feedstock per country, optimised for highest net CO_2eq emissions reduction (Ben Salah, 2022, p. 28). Technologies vary between Fischer-Tropsch (FT) and Hydro-processed Esters and Fatty Acids (HEFA). The former uses feedstocks varying between agricultural residue (AR), cereal bran or straw (CB / CS), logging residues from final fellings or thinnings from conifer or non-conifer trees (FC / FNC / TC / TNC), forestry residue (FR), maize stover (MS), municipal solid waste (MSW) and sunflower straw (SS); the latter uses used cooking oil (UCO). Colours indicate the minor difference in relative net CO_2eq emissions reduction potential per country. For a 10% blend and 90% competing use, this ranges from 7% (light grey; UK only) to 9% (greens)

The remainder of this report compares supply and demand at an aggregate EU level – in line with the level of detail of the assessment of hydrogen (Section 4.2) and synthetic SAF (Section 4.3.2). Starting from the country-specific availability identified by Ben Salah (2022), it is assumed that intra-EU trade (of feedstock or bio- or waste-based SAF produced from it) resolves country-specific over- and undersupply. Feedstocks and production routes were selected as to maximize life-cycle CO_2eq emissions reduction, resulting in predominant use of Fischer-Tropsch (FT) – also observed in Figure 17. FT is an advanced pathway that uses a mix of feedstocks and will lead larger net CO_2eq reductions compared to other pathways. Based on the identified availability, Figure 18 shows supply and net CO_2eq emissions reductions for 90% and 95% competing use, after taking into account that only 60% of theoretical biomass supply would be available for energy applications[18]. For 2050, the high supply scenario is shown, and for other years, availability is inter- (2035, 2040, 2045) or extrapolated (2025). Production labelled as EU+UK is from feedstock from the EU and UK; imports are from a select number of other European (but non-EU) countries listed in Appendix B.1.1 – but typically contribute less than 10%.

[18] The remainder is left on the fields to maintain or promote soil quality.

The top of the figure clearly shows total SAF demand is much higher than bio- or waste-based SAF supply. The gap towards maximum SAF use grows from 26 Mt in 2030 to 29 Mt in 2035, even in the 90% CU scenario. This supply-demand gap is about 80% of total SAF demand – meaning that only a 10% blend[19] could be sustained across all flights. With hydrogen-powered aircraft in the fleet, the gap in 2050 varies between 39 (low traffic scenario; yielding a 20% blend) and 56 Mt (high traffic scenario; 16% blend). Without hydrogen-powered aircraft, the gap to maximum SAF – governed by blending limits, as shown in Figure 14 – in 2050 varies from 52 (low; 17%) to 69 Mt (high; 14%) – compared to a total bio- or waste-based SAF availability of 11 Mt. As the bottom of the figure shows, net CO_2eq emissions reduce by about 10 to up to 41 Mt in 2050 (90% CU). This yields an average lifecycle emissions reduction factor of 83% in 2030, increasing to 96% by 2050.

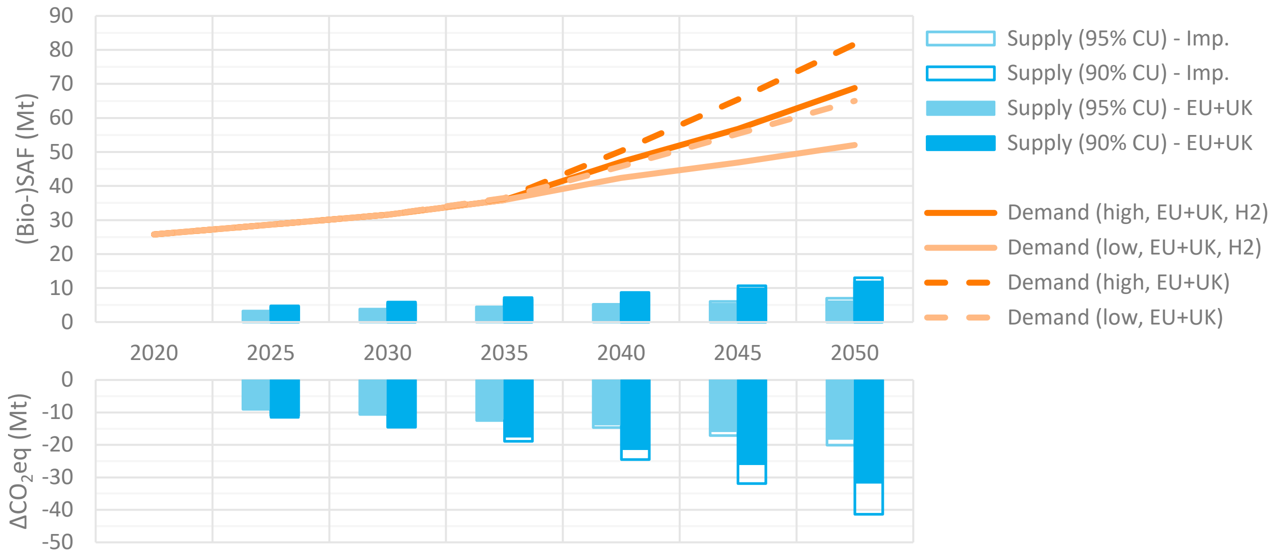


Figure 18: Bio- or waste-based SAF supply from Fischer-Tropsch production and total SAF demand (top) and associated net CO_2eq emissions reduction (bottom) in different traffic scenarios and cases of competing use of biomass (CU) with supply from EU + UK only or with additional import from selected non-European production (Imp.)

The current cost of bio- or waste-based SAF (Fischer-Tropsch pathway) is about 2550 €/tonne[20], which is less than one third of the cost of hydrogen in 2020 (8300 €/tonne), as can be seen in Figure 19. It is expected that the cost of bio- or waste-based SAF will decrease to approximately 1350 €/tonne in 2050, approximately two times as much as the expected cost for fossil kerosene by that year. This leads to a total annual cost of 9.4B€ in case of 95% CU and 17.4B€ for 90% CU in 2050. Appendix E provides further information on the costs of bio- or waste-based SAF.

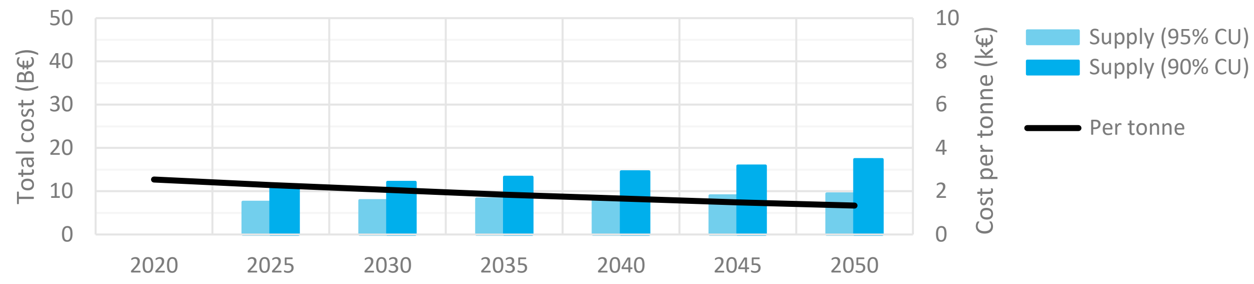


Figure 19: Total annual cost of bio- or waste-based SAF produced using Fischer-Tropsch supplied from EU, UK and imported production in different cases of competing use (CU) in billions of Euros (left axis) and cost per tonne in thousands of Euros (right axis)

[19] Computed from (1 – 80%) × 51% [average blending limit in the period 2030 to 2035]
[20] Costs of other bio-based SAF production pathways vary: some are less and some are more expensive than F-T. As the net CO_2eq emissions reduction potential has been based on bio-based produced using F-T, this study consistently uses the costs of that and only that pathway.

4.3.2 Synthetic SAF

As bio- or waste-based SAF, synthetic SAF can reduce the net greenhouse gas emissions of kerosene-powered aircraft. Hydrogen is a feedstock for the production of synthetic SAF. Synthetic fuels are also known as e-fuels or Power-to-Liquid fuels.

Figure 20 shows total SAF demand and the availability of synthetic SAF in the scenario including hydrogen-powered aircraft, derived from the amount of hydrogen remaining – if any – after taking into account demand by hydrogen-powered aircraft (Section 4.2)[21]. Also indicated is the associated net CO_2eq emissions reduction, based on emission reduction factors increasing from 80% in 2025 to 100% in 2050 (based on van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). As for previous sections, three competing use cases for H_2 were considered, using EU and UK demand and SAF availability from either the EU and UK, or the EU, UK and select non-EU countries.

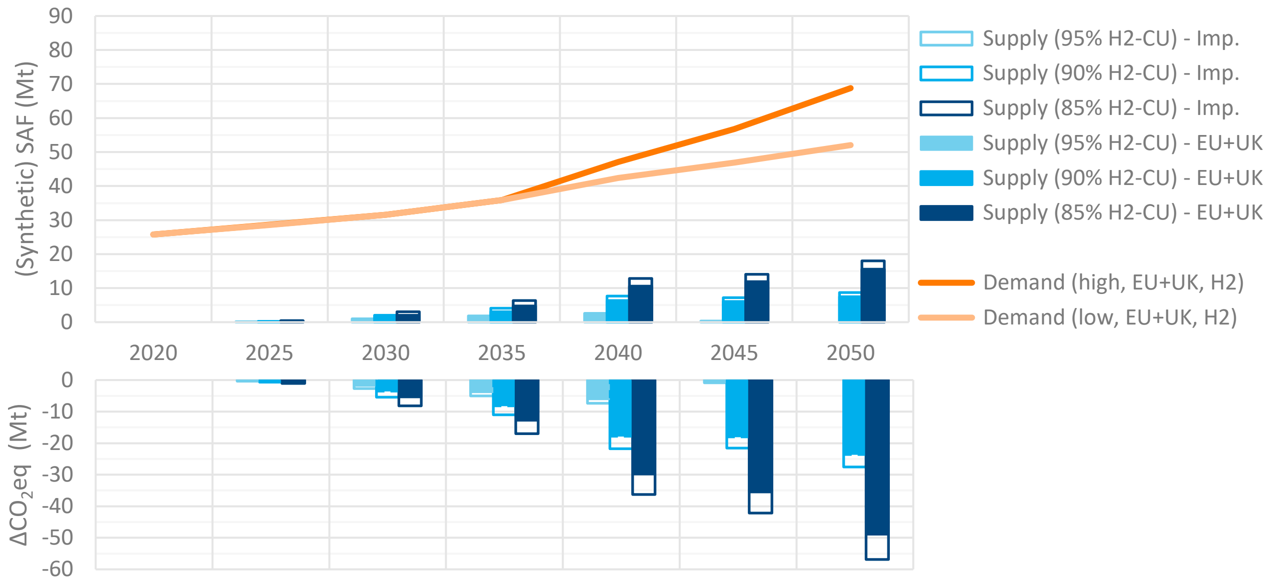


Figure 20: Synthetic SAF supply and total SAF demand (top) and associated net CO_2eq emissions reduction (bottom) in different traffic scenarios (with hydrogen-powered aircraft) and cases of hydrogen competing use (CU) with supply from EU + UK only or with additional import from selected non-European production (Imp.)

Following limited hydrogen availability in 2025, synthetic SAF availability is also low in that year. In case of 95% competing use, hardly any synthetic SAF can be produced in 2045 – and none in 2050. With less competing use, availability grows to 9 (90% CU) to 18 Mt (85% CU) in 2050. At 90% CU, the gap to maximum SAF (based on Figure 14) is 30 Mt in 2030 (94% of total SAF demand). By 2050, the gap varies between 43 (low traffic scenario; 14% blend) and 60 Mt (high traffic scenario; 11% blend). With 90% CU, net CO_2eq emissions reduce by about 28 Mt. Appendix C.4 shows the situation without hydrogen-powered aircraft.

Synthetic SAF has a cost of 1600 €/tonne in 2050, compared to estimates of 690 €/tonne for fossil kerosene (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The annual total cost decreases from 27B€ in 2040 to 25.5B€ in 2045, as shown in Figure 21. This is related to an increasing supply of 10% and a decreasing cost of 15% from 2040 to 2045. This significant lower increase is the consequence of a significant growth in hydrogen demand as can be seen in Hydrogen 4.2. From 2045 to 2050, the demand increases by 30% against a cost decrease of 14%. Appendix E provides further information about the costs.

[21] H_2 demand by hydrogen-powered aircraft was averaged between high and low traffic scenarios in order to arrive at a single figure for remaining H_2. Hydrogen demand to support the production of bio-based SAF was not taken into account. One tonne of H_2 was modelled to yield two tonnes of synthetic SAF, based on a mass balance analysis (Adolf, et al., 2018; Yugo & Soler, 2019; Diakakis, 2019; van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Up to and including 2030, results for the scenario with hydrogen-powered aircraft are identical to those for a scenario without hydrogen-powered aircraft.

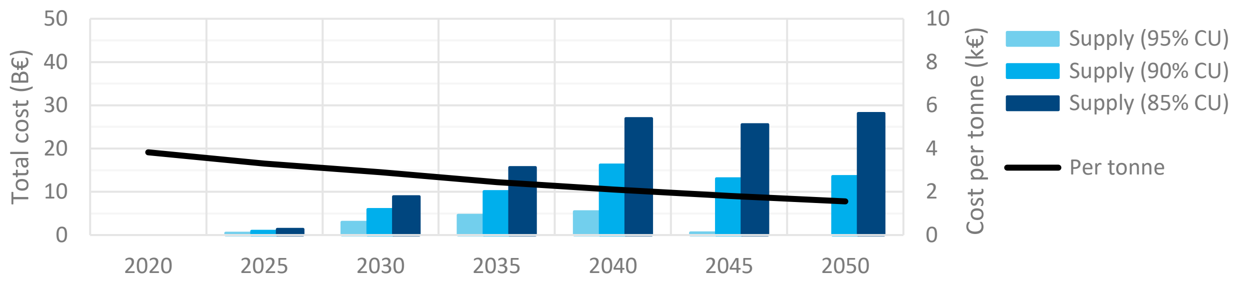


Figure 21: Total annual cost of synthetic SAF supplied from EU, UK and imported production in traffic scenario with hydrogen-powered aircraft and different cases of competing use (CU) in billions of Euros (left axis) and cost per tonne in thousands of Euros (right axis)

4.3.3 Overview

Figure 22 shows the total SAF demand and availability for bio- or waste-based produced using Fischer-Tropsch and synthetic SAF combined, as well as the associated net CO_2eq emissions reduction for traffic scenarios with hydrogen-powered aircraft. Demand for SAF is shown once as it is determined from the fleet-based blending limit (Figure 14) and once as determined from the ReFuelEU Aviation blending mandate. The situation without hydrogen-powered aircraft is shown in Appendix C.4.

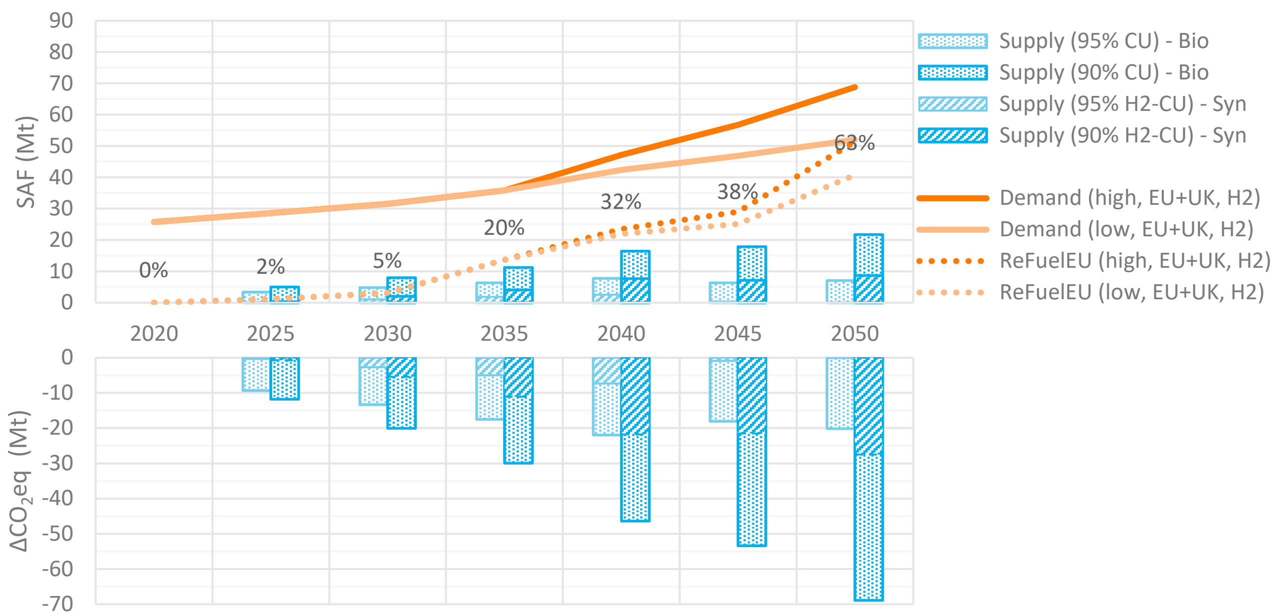


Figure 22: Total SAF supply (bio- or waste-based Fischer-Tropsch and synthetic) and SAF demand (based on fleet-based blending limits or ReFuelEU Aviation mandate[22] as numerically indicated; top) and net CO_2eq emissions reduction (bottom) in different traffic scenarios (with hydrogen-powered aircraft) and cases of biomass and hydrogen competing use (CU) with EU, UK and imported supply

The figure shows that even when bio- or waste-based and synthetic SAF supplies are combined, the total SAF demand cannot be met. Supply is sufficient to meet the blending mandate proposed as part of ReFuelEU Aviation up to 2030 but afterwards, when the blending mandate increases more quickly, increases in supply cannot keep up. 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. Appendix G documents the necessary SAF supply to meet the ReFuelEU Aviation mandate in the low traffic scenario of TRANSCEND, in a situation with hydrogen-powered aircraft.

[22] This analysis assumes that flights departing the UK are subject to a similar blending mandate, as ReFuelEU Aviation does not apply there, in line with SEO & NLR (2022).

The shortage of green hydrogen to both supply hydrogen-powered aircraft with their fuel and produce sufficient amounts of synthetic SAF indicates a possible competition between these two alternative fuels. The sub-mandate for synthetic SAF in ReFuelEU Aviation prioritises hydrogen for synthetic SAF production[23]. In that case, the demand for hydrogen by hydrogen-powered aircraft cannot be met by green hydrogen.

Figure 23 shows that the total SAF cost increases up to 2040 for both 90 and 95% CU. In case of 95% CU, the cost will decrease from 14.1 to 9.4B€ in 2050 due to a lower volume growth, combined with higher cost reductions – also seen in Section 4.3.2. In case of 90% CU, the total SAF cost decrease from 2040 to 2045 and will increase afterwards.

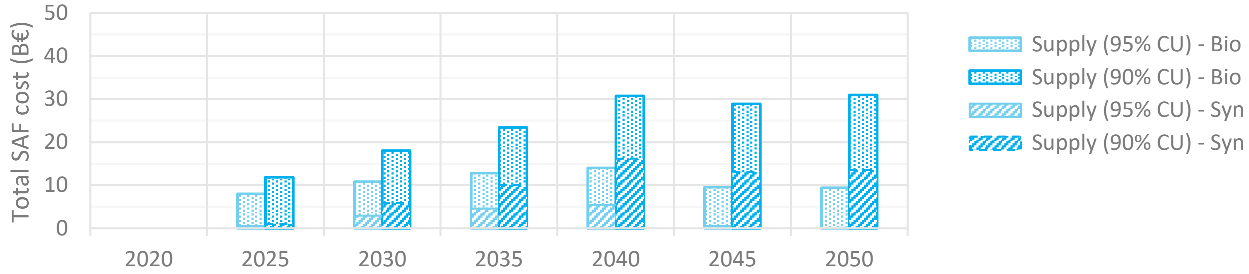


Figure 23: Total annual cost of SAF supplied from EU, UK and imported production in traffic scenario with hydrogen-powered aircraft and different cases of competing use (CU) in billions of Euros

4.4 Combined impact of alternative fuels

Figure 24 shows the total CO_2eq emission reductions realised by the combination of both hydrogen-powered aircraft (gross emissions reduction) and maximum use of available SAF for 90 and 95% competing use (net emissions reduction). This combines the results from Section 4.2 on hydrogen and Section 4.3.3 on SAF. As the demand for hydrogen fuel does not vary with traffic scenario and because SAF supply is never enough to satisfy demand, the overall absolute CO_2eq emissions reduction is independent of traffic scenario. Compared to a situation without alternative fuels, but with fuel efficiency improvements delivered by the introduction of Clean Sky 2 aircraft as shown in Appendix C.2 (Figure 37), alternative fuels can, in a situation with 90% competing use, reduce 2050 net CO_2eq emissions by 37% in the high traffic scenario and by 43% in the low traffic scenario.

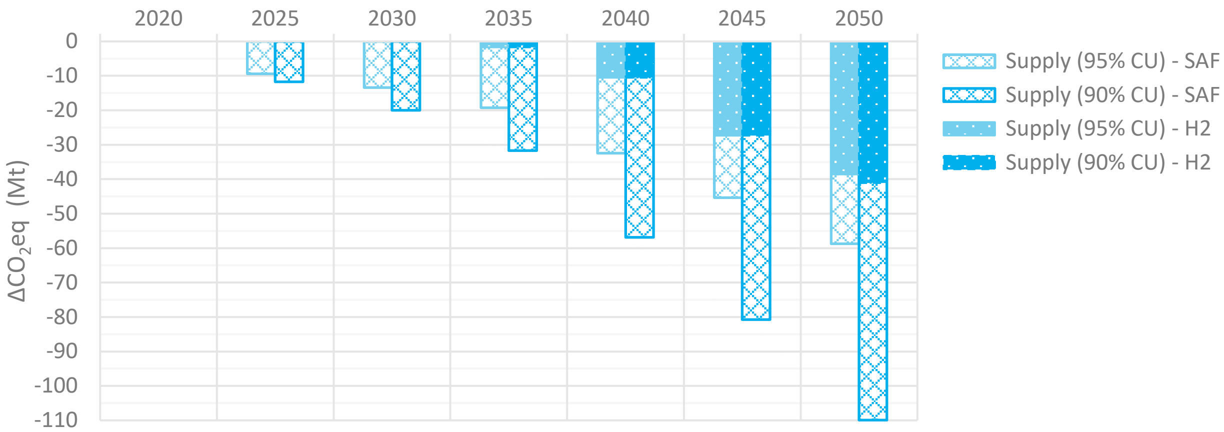


Figure 24: Total emissions reduction delivered by SAF (bio- or waste-based Fischer-Tropsch and synthetic; net CO_2eq emissions reduction) and hydrogen (gross emissions reduction) in traffic scenarios with hydrogen-powered aircraft

[23] From 2030, the proposed ReFuelEU Aviation regulation includes a sub-mandate for synthetic fuels, which requires (green) hydrogen for production. In case there is limited availability of (green) hydrogen, the mandate will direct all that (green) hydrogen to be used as feedstock for synthetic SAF production, such that no (green) hydrogen remains for use in hydrogen-powered aircraft.

The total annual AF cost will gradually increase in case of 95% CU as can be seen in Figure 25. Rapid increase of costs will take place between 2025 and 2040, after which growth will stagnate. This is even more visible in the total SAF costs with a supply of 90% CU. The total SAF cost will increase from 18B€ in 2030 to 42B€ in 2050. This means a price premium of 13B€ in 2030, increasing to 25B€ in 2050[24]. Details on costs can be found in Appendix E.

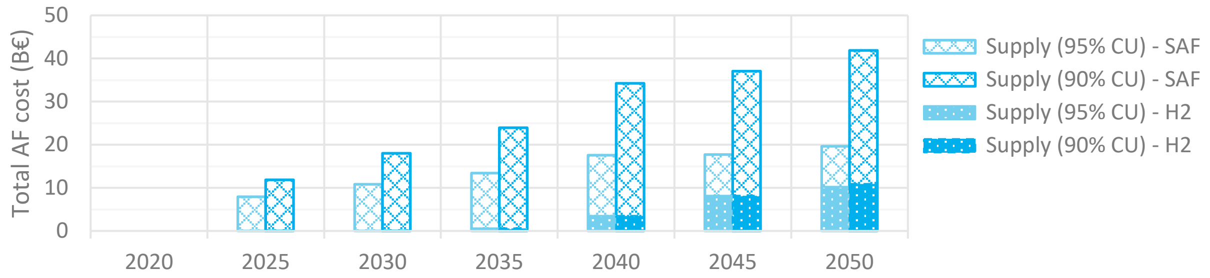


Figure 25: Total annual cost of alternative fuels supplied from EU, UK and imported production in traffic scenario with hydrogen-powered aircraft and different cases of competing use (CU) in billions of Euros

Up to 2035, the total CO_2 emission reductions (gross CO_2 reduction from hydrogen; net CO_2eq reduction from SAF) and total costs do not differ between scenarios with and without hydrogen-powered aircraft, the latter analysed in Appendix C.4. As shown in Figures 26 and 27, by 2050 and with 90% competing use, CO_2 emission reductions are 10% lower and fuel costs are 10% higher in the scenario without hydrogen-powered aircraft. As shown in Appendix F, well-to-tank (WtT) energy demand for production of liquid hydrogen and synthetic SAF is about 30% higher in a scenario without hydrogen-powered aircraft. Given limited differences between tank-to-wake energy demand for H_2 and non-H_2 scenarios (Appendix C.2), well-to-wake (WtW) energy demand is also about 30% higher. For scenarios with 95% CU, these differences are magnified to 16% (lower CO_2 reduction), 22% (higher cost) and 90% (higher energy demand). The well-to-tank energy requirements to produce the (minimum) quantities of green hydrogen and synthetic SAF to meet the ReFuelEU Aviation mandate is shown in Appendix G.2.

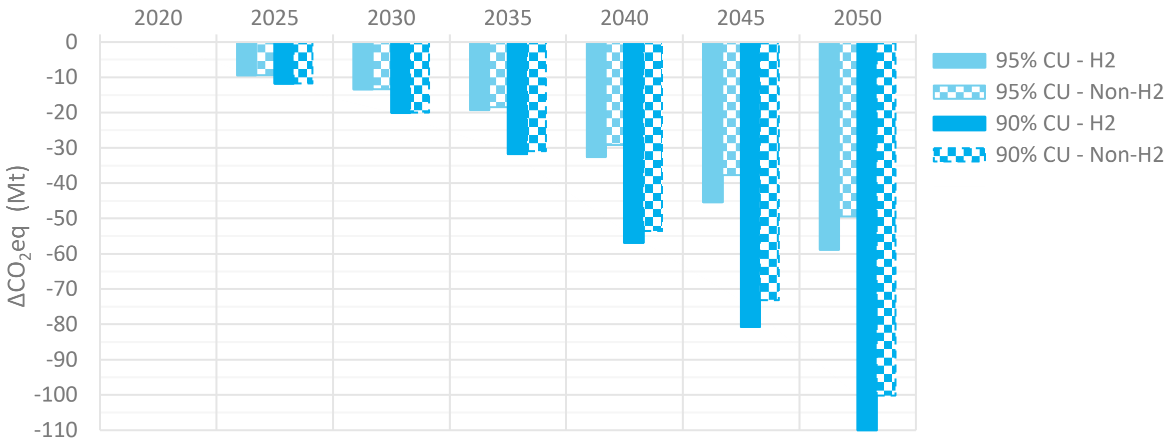


Figure 26: Total CO_2(eq) emissions reduction realised in scenarios with and without hydrogen-powered aircraft and different cases of competing use (CU)

[24] The cost premium is computed as the difference between the total AF cost and the cost of fossil kerosene prevented through the use of AF. Costs for fossil kerosene were modelled to increase from 600 €/tonne to 690 €/tonne (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Carbon costs or taxes (more) applicable to fossil kerosene (than to SAF) were not modelled but can be expected to reduce the cost premium.

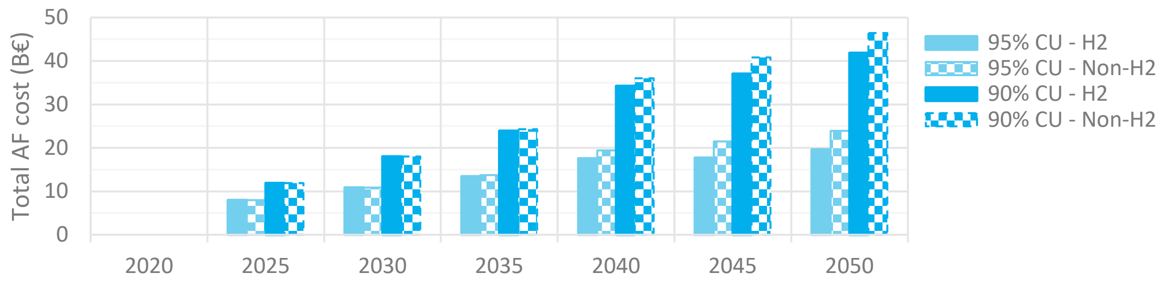


Figure 27: Total annual cost of alternative fuels supplied from EU, UK and imported production in scenarios with and without hydrogen-powered aircraft and different cases of competing use (CU) in billions of Euros

Both in situations with and without hydrogen-powered aircraft in the fleet, the relative CO_2eq reductions that can be achieved (around 40%) are substantially lower than percentages in objectives set for 2050, such as the 90% reduction target from transport emissions set in the Smart & Sustainable Mobility Strategy (EC, 2020c) or various net-zero goals – even though some of these were supported by similar analyses as presented here (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Several factors help explain these differences:

- The TRANSCEND scenario without hydrogen-powered aircraft and without the use of alternative fuels, used as 'reference scenario' for the previous comparison, already includes fuel efficiency improvements from Clean Sky 2 aircraft of approximately 15 to 20% compared to current aircraft, identified in the first assessment. The combined effect of those aircraft and the alternative fuels compared to a 'no action' reference will be larger than 40%.
- Efficiency improvements realised by improvements in aircraft and engine technology in TRANSCEND are modelled based on the Clean Sky 2 first assessment (Clean Sky 2, 2020), but do not yet take into account possible further improvements (following from the second assessment of Clean Sky 2 or Clean Aviation, for example).
- Emissions savings due to operational efficiency improvements, including SESAR, estimated between 5 and 10% by Van der Sman et al. (2021), were not considered in TRANSCEND, but also contribute to decarbonisation. Similarly, out-of-sector decarbonisation measures can reduce net CO_2eq emissions.
- Especially in the high traffic scenario, the baseline growth rate of the number of flights is notably higher (1.7%) than reported in e.g. Destination 2050 (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 Chapter 2, suggests the growth in passenger movements to be bigger still when compared to Destination 2050 (2.0% and 1.4%).
- Related to the previous remark, the TRANSCEND traffic scenarios 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 (see e.g. SEO & NLR, 2022). A more recent outlook by EUROCONTROL (2022)also expects lower growth (44% growth by 2050 compared to 2019, equivalent to a compound annual growth rate of 1.2%).

4.5 Alternative fuels roadmap

The combined use of alternative fuels – hydrogen and bio- or waste-based and synthetic SAF – can reduce net CO_2(eq) emissions in 2050 by approximately 40% in a scenario with 90% competing use. These savings are additional to reductions achieved by improvements in aircraft and engine technology and (not modelled in this study) operational efficiency. In order to realise these savings, alternative fuels need to be available in sufficient amounts and (airport) infrastructure should be in place to allow the operation of hydrogen-powered aircraft.

This section presents roadmaps for bio- or waste-based SAF, synthetic SAF and green hydrogen. The roadmap for bio- or waste-based SAF is focused on SAF produced using the Fischer-Tropsch pathway, a pathway selected in order to maximize life-cycle CO_2eq emissions reductions. As such, the roadmap presented here is not intended as an overall and all-encompassing roadmap for bio- or waste-based SAF. All three roadmaps describe supply (assuming 90% competing use) and demand, production technology development, economic aspects, and aircraft and airport infrastructure development.

The roadmaps span scenarios with and without hydrogen-powered aircraft and assume 90% competing use for feedstocks for bio- or waste-based SAF and green hydrogen. In case total (across-economy) availability of alternative fuels is lower, modelled CO_2(eq) emissions reductions can only be realised in case competing use is reduced below 90%. The latter might hamper the decarbonisation of other parts of the economy.

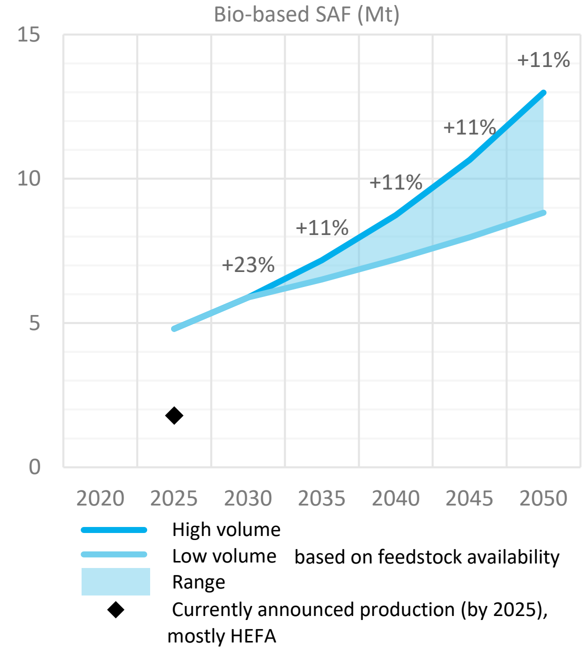
Bio- or waste-based sustainable aviation fuel

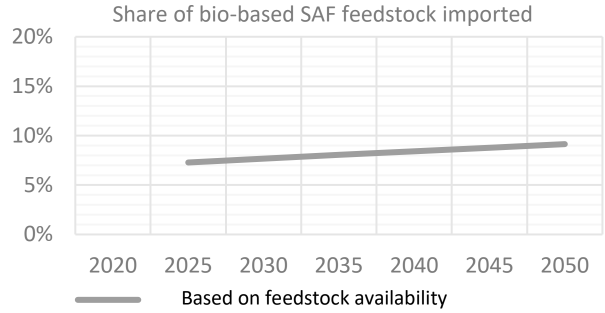
Produced using Fischer-Tropsch from waste streams (forestry and agricultural residue and MSW), limited in supply

Supply and demand

The (total) availability of feedstocks for bio- or waste-based SAF can, with 90% competing use, support an aviation-specific supply of almost 6 Mt by 2030, increasing to 13 Mt by 2050. This supply relies on imports from a limited but increasing extent. Indicatively, total SAF demand (for both bio- or waste-based and synthetic SAF) increases from approximately 25 Mt by 2030 to 40 to 70 Mt by 2050.

Recently announced production facilities (identified in Appendix G) are estimated to be able to supply a little over 1.8 Mt by 2025, mostly via the HEFA pathway. This is a risk since the announced production facilities for bio- or waste-based SAF indicate that there is not sufficient production capacity for the to-be-supplied bio- or waste-based SAF. This means that producers must be able to scale up annual production by almost 4.2 Mt of SAF within 6 years in order to meet the 2030 SAF goal. However, other producers like Altalto (Altalto, 2022) made announcements of a SAF plant, but did not mention the expected amount of SAF production and are therefore not included in the expected capacity. A complete overview of the facility announcements can be found in Appendix G.





Production technology development

Modelled SAF supply and emissions impact is based on the Fischer-Tropsch pathway. Currently, this pathway has a technology readiness level 6 to 8 (van Muijden, et al., 2021). It is not produced commercially yet , but already certified for blends up to 50% (CAAFI, 2021). TRL 9 should be achieved by 2030 at the latest.

Economic aspects

Technological improvement, learning and economics of scale are anticipated to reduce cost of bio- or waste-based SAF produced through the FT pathway from approximately 2550€/tonne (0.06€/MJ) now to about 1350€/tonne (0.03€/MJ) in 2050.

Aircraft and airport infrastructure development

For bio- or waste-based SAF, no major necessary aircraft or airport infrastructure requirements are foreseen. If the total SAF blend increases beyond 50%, existing aircraft might need to be adapted, or separate refuelling systems might be necessary.

Synthetic sustainable aviation fuel

Production from green hydrogen and recycled or captured carbon

Supply and demand

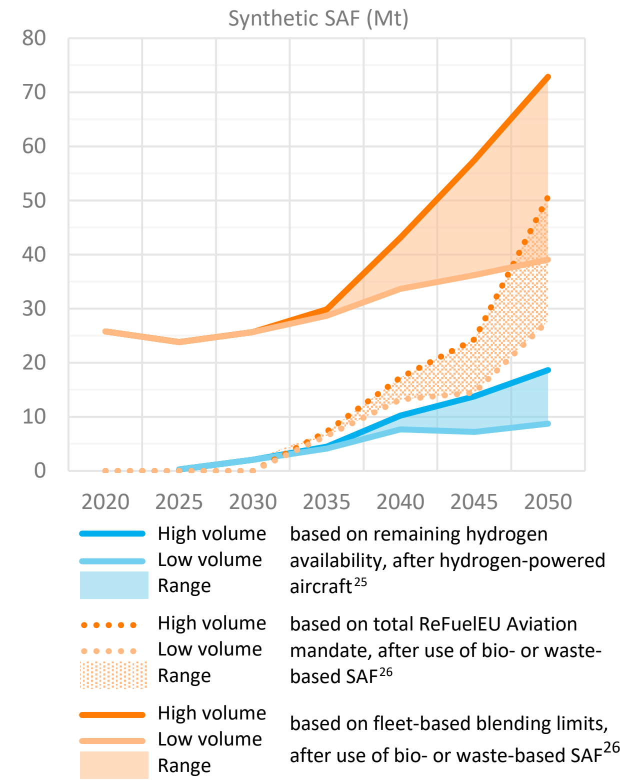
Even when combined with bio- or waste-based SAF supply, the synthetic SAF availability as analysed in this work (90% competing use) is insufficient to meet the proposed overall ReFuelEU Aviation blending mandate for SAF from 2035 onwards. Assuming synthetic SAF (for which feedstock availability and subsequent production can be scaled more easily) is used to overcome this gap, an additional synthetic SAF supply of approximately 19 to 32 Mt would be required by 2050.

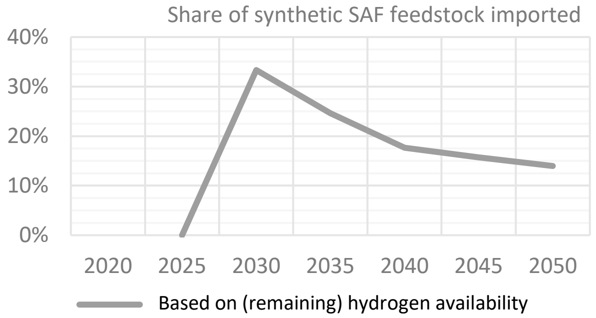
If synthetic SAF production were to be scaled up further to meet the maximum SAF blending (based on technological capability and supporting certification), this would require an additional supply of 12 to 22 Mt by 2050 – relative to the increases already required for ReFuelEU Aviation. Compared to the volume estimates based on remaining hydrogen availability, this means 30 to 54 Mt of additional supply.

Additional synthetic SAF production also requires additional green hydrogen production.

In order to produce these amounts of synthetic SAF, production facilities have to be developed. As of yet, no industrial scale plants have been announced.

By 2025, the full synthetic SAF supply is sourced from EU and UK feedstocks (i.e., green hydrogen). Imports make up over 30% by 2030, but this share gradually decreases towards 2050.





Production technology development

Current, synthetic SAF is at TRL 6 to 7 (van Muijden, et al., 2021). It should reach TRL 9 by at latest 2030, also given the ReFuelEU Aviation sub-mandate for synthetic SAF. Sufficient production of synthetic SAF requires satisfactory availability of green hydrogen (and electrolyser capacity). Furthermore carbon recycling and/or direct air capture technologies should be drastically scaled up.

Economic aspects

Cost of synthetic SAF is anticipated to decrease from approximately 3800 €/tonne (0.09€/MJ) now to about 1600 €/tonne (0.04€/MJ) in 2050 due to technological improvement, learning and economics of scale.

Aircraft and airport infrastructure development

For synthetic SAF, no major necessary aircraft or airport infrastructure requirements are foreseen. When the total SAF blend increases beyond 50%, existing aircraft might need to be adapted, or separate refuelling systems might be necessary.

[25] High volume is based on synthetic SAF supply without hydrogen-powered aircraft; low volume is based on synthetic SAF supply from hydrogen remaining after use by hydrogen-powered aircraft.

[26] High volume is based on SAF demand in high traffic scenario, no use of hydrogen-powered aircraft, minus minimum supply from bio-based SAF. Contrarily, low volume is based on SAF demand in low traffic scenario, use of hydrogen-powered aircraft, minus maximum supply from bio-based SAF.

Hydrogen

Green hydrogen produced from renewable resources, for use as fuel or feedstock for synthetic SAF

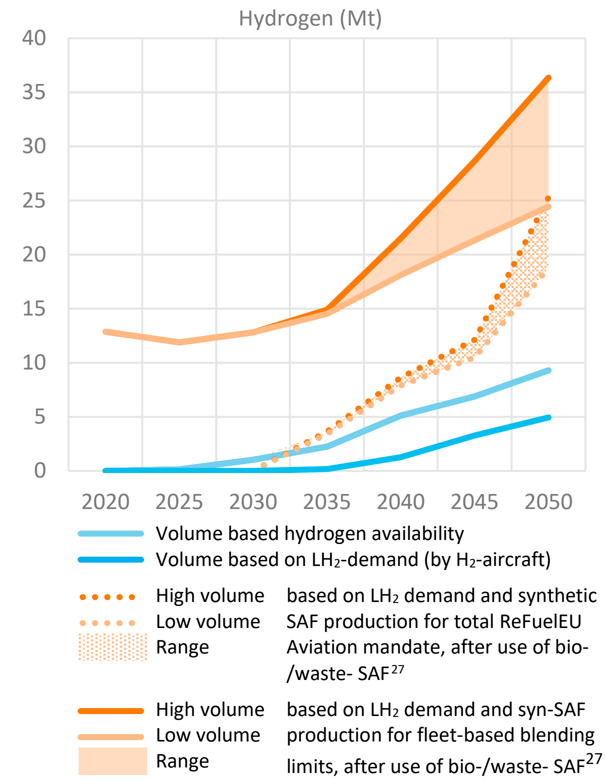
Supply and demand

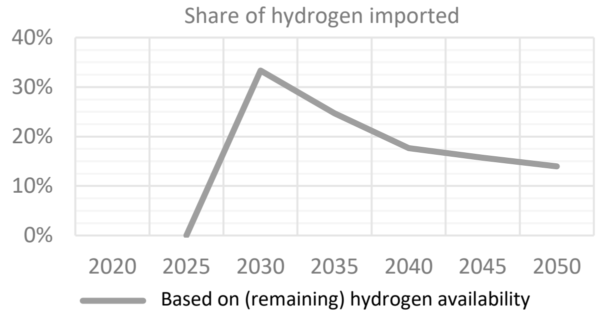
In order to have sufficient hydrogen for aviation in a situation with 90% competing use, the total annual production needs to scale up from the very limited quantities produced today to 1.5 Mt in 2025, 22 Mt in 2035 and 93 Mt in 2050. In 2025, no hydrogen imports are expected. By 2030, imports make up over 30% of total hydrogen supply. This share reduces gradually towards 2050.

Although all European projects in the IEA Hydrogen Project Database add up to a production capacity of 23Mt (aligning with aforementioned 2035 estimate), only 0.2 Mt is at or beyond a final investment decision (IEA, 2021). This indicates a risk of significantly lower supply. Put differently: in order to meet the anticipated supply, all concepts or feasibility studies currently identified by IEA need to be realised.

To produce the additional synthetic SAF to meet the ReFuelEU Aviation mandate, 10 to 16 Mt of additional hydrogen is required by 2050. Based on the previously indicated total production figure of 93 Mt, this means competing use has to be limited to 80% or even 73%. Alternatively, maintaining 90% CU, total annual hydrogen production should increase to 190 to 250 Mt.

To realise maximum SAF blends, hydrogen supply would need to increase further – by 6 to 11 Mt in 2050, compared to the increases required for ReFuelEU Aviation. Compared to the estimated amount of hydrogen available for aviation (9.3 Mt in 2050), this would require 15 to 27 Mt. This could only be met with a maximum of 74 to 60% competing use.





Production technology development

Green hydrogen production and liquefaction are at TRL 9. Producing by 2050 the 93 Mt of hydrogen anticipated in literature requires between 400 and 500 GW of electrolyser capacity. As the share of imports is estimated to decrease over time, the majority should be realised in Europe. In case competing use does not drop below 90%, increased production and electrolyser capacity is required to help meet SAF demands.

Economic aspects

Technological improvement, learning and economics of scale are needed to reduce the cost of green liquid hydrogen (LH_2) for use as fuel from approximately 8000 €/tonne (0.07€/MJ) now to about 2200 €/tonne (0.02€/MJ) in 2050. On an energy-equivalent basis, this makes green LH_2 in 2050 only 15% more expensive than fossil kerosene (without carbon price and/or tax).

Aircraft and airport infrastructure development

The use of hydrogen in hydrogen-powered aircraft makes a substantial contribution to the CO_2 emissions reduction. In order to realise this, airport infrastructure should be available at the relevant airports. This includes refuelling facilities, but also the infrastructure to transport to the airport, as well as infrastructure possibly required for on-site liquefaction and the temporary (buffer) storage of (liquid) hydrogen (Postma-Kurlanc, Leadbetter, & Pickard, 2022; McKinsey & Company, 2020; ACI & ATI, 2021).

[27] High volume is based on hydrogen demand for production of synthetic SAF to fulfil SAF demand in high traffic scenario (minus minimum supply from bio-based SAF) and no use of hydrogen-powered aircraft. Contrarily, low volume is based on hydrogen demand for production of synthetic SAF to fulfil SAF demand in low traffic scenario (minus minimum supply from bio-based SAF) with use of hydrogen-powered aircraft.

5 Conclusions

The following novel propulsion concepts and alternative fuels have been identified as promising for the following aircraft categories:

- SAF-powered gas turbine based Clean Sky 2 (CS2) propulsion technologies for all seat classes from 20 passengers.
- Three green hydrogen-powered propulsion concepts: fuel cell based propulsion for seat classes 20-100, combustion-based propulsion for seat class 211-300, and a hybrid fuel cell/combustion based propulsion for seat classes 101-210.

Three representative hydrogen-powered aircraft in the seat classes 20-50, 151-176, and 211-300, each with one of the three hydrogen-powered propulsion concepts, have been evaluated on their gross gaseous emissions and energy consumption.

Four promising production routes for bio- or waste-based SAFs were identified, each requiring different organic waste sources and production processes: Hydro-processed Esters and Fatty Acids (HEFA), Fischer-Tropsch, Fast Pyrolysis and Alcohol-to-Jet. Both for synthetic SAF and hydrogen one promising production route was identified: Power-to-Liquid Fischer-Tropsch and alkaline electrolysis, respectively.

5.1 Impact of novel propulsion concepts and alternative fuels on global aviation energy and gross emissions

The impact of the selected propulsion concepts on the gross gaseous emissions and energy consumption of the global fleet has been evaluated in high and low global traffic scenarios with (kerosene-powered) CS2 aircraft concepts that have been used for the first assessment of the CS2 Technology Evaluator. Two scenarios for the introduction of the promising propulsion concepts have been evaluated. One scenario assumes that the CS2 aircraft concepts are powered by SAF, up to 100%. In an additional scenario, hydrogen-powered propulsion is introduced in aircraft that replace the CS2 aircraft concepts in the seat classes 20-300 passengers in flights with short ranges (<1000 km for seat classes 20-100; <2000 nm for seat classes 101-300). This hydrogen-powered propulsion is introduced in the fleet in 2035 for single aisle aircraft (seat-classes 20-210) and in 2040 for small twin aisle aircraft (seat class 211-300). The scenario with hydrogen-powered propulsion, in which 35% (high traffic scenario) to 38% (low traffic scenario) of all flights are operated by hydrogen-powered aircraft in 2050, leads to a fleet level reduction of 20% (low traffic scenario) and 16% (high traffic scenario) in global gross CO_2 emissions in 2050 compared to the scenario without hydrogen-powered propulsion and the use of SAF, whereas global energy consumption slightly increases and H_2O emission increases significantly, as indicated in Figure 28. Further non-CO_2 climate effects were not studied.

Roadmaps for the novel propulsion concepts from 2023-2050 were derived in relation to Clean Aviation and Clean Hydrogen. Taking into account the propulsion technologies to be developed in Clean Aviation, further reduction of energy consumption, CO_2 emissions, and NO_X emissions can be expected in regional and short-medium range aircraft, with entry-into-service from 2035. In addition, novel long-range aircraft may enter into service after 2040, taking advantage of Clean Aviation and complementary developments. The CO_2 reductions for these long-range aircraft will have limited contribution to fleet level CO_2 reduction in 2050 due to limited fleet penetration, but enable a significant further CO_2 reduction after 2050.

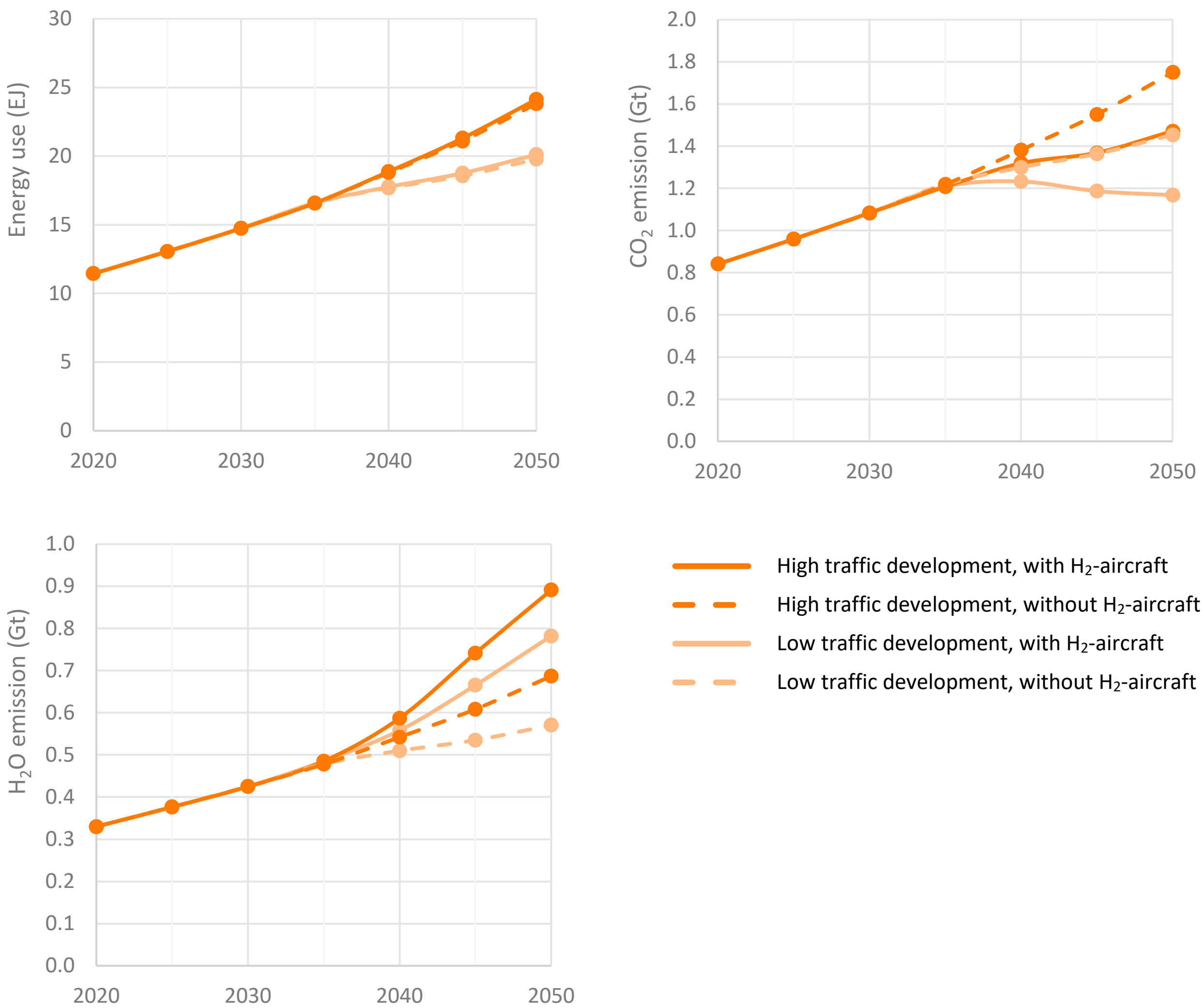


*Figure 28: Global aircraft energy use and gross emissions at fleet level in **high** or low traffic scenarios, both with (solid lines) and without (dashed lines) hydrogen-powered aircraft in the fleet*

5.2 Emissions impact and viability of alternative fuels and novel propulsion in the EU and UK

In addition to the global fleet-level assessment, the supply and demand, emission impact and economic viability of alternative fuels resulting from the fleet-level evaluation, were studied for flights departing airports in the EU and UK. In 2020, the consumption of fossil kerosene in the EU and UK modelled was about one-fifth of the global consumption. The demand for SAF until 2050 was modelled based on the fleet level evaluation with 100% SAF for CS2 aircraft and blends of 50% SAF for other (older) aircraft. Based on the findings, alternative fuels roadmaps were developed for all three fuel types considered (hydrogen, bio- or waste-based SAF and synthetic SAF), addressing alternative fuels availability in relation to demand, production technology development, economic aspects, and aircraft and airport infrastructure

Green hydrogen for hydrogen-powered aircraft

Supplies of alternative fuels were considered taking into account scenarios for competing uses (i.e., uses other than aviation) of these alternative fuels or feedstocks. It can be concluded that in each of the competing use scenarios studied (85%, 90% and 95%) the demand of green hydrogen for the hydrogen-powered aircraft in the fleet can be met with the supply from EU and UK production until 2040. For 2045 and 2050, a limited quantity of imports is needed. The total annual cost of green hydrogen supplied to airlines for direct use by hydrogen-powered aircraft was estimated to be 10B€ (95% CU; in which demand cannot be fully met) up to 11B€ (90% CU) in 2050. Although the anticipated green hydrogen supply, as determined primarily from top-down estimates, was found mostly sufficient to meet demand, production capacity from existing and announced facilities is much lower – indicating a risk of significantly lower supply. Airport infrastructure changes for hydrogen, such as refuelling and possibly on-site liquefaction facilities, are also required.

Bio- or waste-based and synthetic sustainable aviation fuel

For SAF, the supply of bio- or waste-based and synthetic SAF (separately but also combined) was found to be insufficient to meet the demand. The available supply allows the ReFuelEU Aviation blending mandate to be achieved, but only until 2030. In 2050, an extra SAF supply of 19 (low) to 30 (high) Mt would be needed to achieve the ReFuelEU Aviation mandate for that year (63%), see Figure 29.

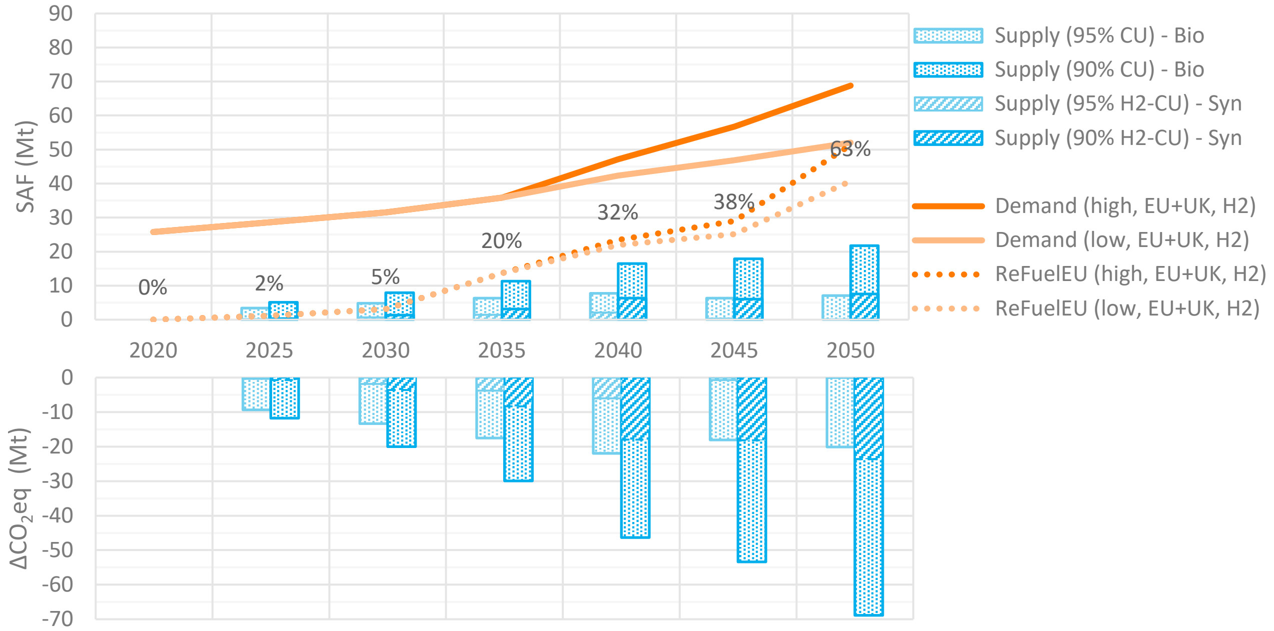


Figure 29: SAF demand based on technological and regulatory fleet-based blending limits (solid lines) or ReFuelEU Aviation mandate (dotted lines) and SAF supply (split in bio- or waste-based SAF supply produced using Fischer-Tropsch and synthetic SAF supply) for flights departing from EU and UK (top). Net CO_2eq emissions reduction based on the SAF supply (bottom). Results are shown for traffic scenarios with hydrogen-powered aircraft fully flying on green hydrogen with different traffic levels, for different cases of biomass and hydrogen competing use (CU), and with supply from the EU and UK and limited imports. SAF supply is based on projected feedstock (sustainable biomass and green hydrogen) availability

Since the supply of bio- or waste-based feedstock would then likely already be exhausted, the extra SAF demand must be met by synthetic SAF, developed from hydrogen and renewable electricity. This doubles the total demand for hydrogen by the aviation sector, which might be achieved by reducing competing use or growing the total hydrogen supply. In order to fulfil the total SAF demand as determined from fleet-based blending limits, the hydrogen supply for aviation should increase by another 50%. Announced production facilities for bio- or waste-based SAF anticipate lower supply than was projected based on available feedstock, indicating the risk that production capacity might be insufficient to process the available feedstocks, reducing the production of bio- or waste-based SAF. Production facilities for synthetic SAF have not been announced at industrial scale.

Net emissions and cost impacts

Looking at the combined impact of alternative fuels, the net CO_2(eq) emissions could be reduced by up to 43% in 2050 – realised by the use of hydrogen-powered aircraft and CS2-technology aircraft combined with maximum use of available SAF – compared to a scenario with CS2-technology aircraft powered by fossil kerosene. Associated annual fuel costs for airlines for liquid hydrogen and both types of SAF (but excluding the remaining need for fossil kerosene) could rise from 18B€ in 2030 to 42B€ in 2050. Compared to a situation where no alternative fuels would be used, these figures represent a fuel cost increase for airlines of 13B€ by 2030, increasing to 24B€ in 2050 – not taking into account possible carbon pricing.

Scenario without hydrogen-powered aircraft

As hydrogen-powered aircraft were modelled to be introduced from 2035, conclusions presented for the period up to 2035 hold equally for scenarios with and without hydrogen-powered aircraft. After 2035, results deviate. In a scenario without hydrogen-powered aircraft, total CO_2(eq) reductions were found to be at least 10% smaller, compared to the scenario with hydrogen-powered aircraft. Total fuel costs and well-to-wake energy demand (for the production of hydrogen and synthetic SAF) were found to be at least 10% and 30% higher in 2050, compared to the scenario with hydrogen-powered aircraft.

5.3 Key take-aways up to 2030 and beyond

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

From 2035, prioritising aviation's supply of hydrogen to hydrogen-powered aircraft, the supply of hydrogen matches the demand for these aircraft almost completely, even in case of 95% competing use. However, the projected supply of SAF is below the ReFuelEU Aviation 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 Aviation mandate, a significant part of the flights with hydrogen-powered aircraft would have to use non-green hydrogen.

The projected cost of SAF and liquid hydrogen (as fuel) for airlines is significantly higher than the projected cost of fossil kerosene. This limits the likelihood of voluntary uptake of these alternative fuels beyond the regulatory blending mandate proposed. Additional (carbon) costs related to fossil kerosene, which were not modelled, can be expected to reduce the cost difference.

6 Strategic recommendations

This chapter presents nine strategic recommendations. For each of the strategic recommendation (SR), shown in sections 6.1 up to and including 6.9, considerations are provided first. These lead up to the actual recommendation (printed in green), often split up in various sub-recommendations, and addressed to particular stakeholders. Where deemed relevant, comments on the recommendation(s) are given at the end of each section.

6.1 Enable the use of aircraft powered by liquid hydrogen as fuel

The use of hydrogen as aviation fuel enables operations with zero-carbon emissions during flight. Hydrogen can also be produced with zero-carbon emissions by electrolysis of water, using renewable electricity, leading to the so-called green hydrogen. Hydrogen is commonly used today in various sectors, like petrochemistry, fertilizer production, and space travel. Most of today's hydrogen is produced from fossil sources and as such is not green. In 2020, the European Commission published *A Hydrogen Strategy for a Climate-neutral Europe*.

TRANSCEND compared a global air traffic scenario with green hydrogen-powered aircraft entering into service from 2035 to the same air traffic scenario with SAF-powered aircraft only. With aircraft up to 300 seats and for short ranges[28] powered by green hydrogen, the global gross CO_2 emissions from air traffic in 2050 would be reduced by 20% compared to the traffic scenario with SAF-powered aircraft only. The energy consumption of air traffic in the scenario with hydrogen-powered aircraft is slightly higher than in the scenario with SAF-powered aircraft. For flights departing Europe and UK, the total net CO_2eq reductions were found to be at least 10% larger compared to the scenario with SAF-powered aircraft[29]. Total fuel costs and well-to-wake energy demand (for the production of hydrogen and synthetic SAF) were found to be at least 10% and 30% lower in 2050 compared to the scenario with SAF-powered aircraft. Summarising, hydrogen-powered aircraft hold promise to further reduce aviation's climate impact compared to SAF-powered aircraft only, with a better score on economic viability and energy demand.

Current aircraft and engines, however, cannot be operated nor certified for the use of hydrogen as fuel. Hydrogen storage on-board aircraft introduces penalties in volume due to the low energy density compared to present kerosene-powered aircraft. For example, liquid hydrogen, stored at 20K in low-pressure, insulated tanks would have a volumetric density of 71 kg/m^3, whereas gaseous hydrogen, compressed at 700 bar in heavy tanks, would have a lower density of 42 kg/m^3 at 0°C. For liquid hydrogen, also targeted in the Clean Aviation work programme, the aircraft weight and volume penalties are considerably lower than for heavily-compressed gaseous hydrogen.

SR 1 Develop the regulations needed for the use of aircraft powered by liquid hydrogen before 2028

a Develop certification for liquid hydrogen use as aviation fuel, before 2028
This recommendation is addressed to ASTM, aircraft and engine manufacturers, and liquid hydrogen suppliers/developers

b Develop certification regulation, including acceptable means of compliance and guidance material, for hydrogen-powered aircraft, including those for refuelling of aircraft, before 2028
This recommendation is addressed to civil aviation authorities, aircraft and engine manufacturers, and airports.

[28] Up to 1000 km for aircraft with less than 100 seats and up to 2000 nm (3704 km) for aircraft with 101-300 seats. Single aisle hydrogen-powered aircraft (up to 210 seats) are assumed to enter into service from 2035; while twin aisle hydrogen-powered aircraft (211-300 seats) are assumed to enter into service from 2040. Further details are provided in Chapter 3, and Section 3.2 specifically.
[29] Not taking into account non-CO_2-emissions during flight.

The year 2028 has been chosen to allow for some development up to TRL6 before a 5-years hydrogen-powered aircraft programme is started aiming for entry-into-service in 2035. Depending on the differences between the state of research on hydrogen-powered aircraft and the certification regulation more time may be needed than these 7 years before entry-into-service.

The development of certifications and regulations for hydrogen-powered aircraft will have to fit with the aircraft and propulsion technologies to be developed (see SR 3).

6.2 Address climate impact of emissions for the full life-cycle

The use of SAF and green hydrogen affects the climate impact of aviation both in terms of net CO_2 and non-CO_2 emissions. For example, SAF reduces soot emissions due to the lower sulphur and aromatics content of the fuel, which in turn affects contrail formation and characteristics. Estimating the climate impact of new hydrogen propulsion technologies and large-scale use of new fuels such as SAF and hydrogen in aviation needs further research along the whole life cycle. The TRANSCEND study focused on CO_2, NO_X and water vapour emissions. The climate impact of the net emissions released during fuel production, distribution and use needs to be addressed in future work. Understanding the full climate impact of aircraft emissions over the life cycle is necessary to achieve a climate neutral aviation system.

SR 2 Follow-up the TRANSCEND study with a study on the full climate impact of new fuels for the full life-cycle
This recommendation is addressed to: universities, research centres, aircraft and engine manufacturers, and policy makers.

The climate impact results from this recommendation shall be taken into account in the developments of both SAFs (SR 3) and propulsion (SR 4).

6.3 Develop sustainable aviation fuels not requiring blending with fossil kerosene

The present use of sustainable aviation fuels (SAFs) is limited by regulation to ASTM-certified SAFs, which must be blended with at least 50% fossil kerosene. The proposed ReFuelEU Aviation mandate requires that 63% of the fuel supplied in 2050 is SAF. Hence, a significant part of the fleet in 2050 needs to be powered with 100% SAFs or in a blend with a far lower percentage of fossil kerosene than the 50% for presently ASTM-certified SAFs.

In addition, aircraft and engine manufacturers are investigating the use of 100% SAFs in task forces of ASTM[30], targeting to introduce 100%-SAF-powered aircraft by the end of the decade. One task force investigates 100% SAF not requiring any changes on aircraft and engines and a second task force investigates 100% SAF that improves climate benefits (contrails, particulate matter) and has better availability currently, but which may require some changes for legacy aircraft and/or engines compared to current aircraft and engines.

Moreover, the public and private sector have taken strong initiatives (e.g., the European Clean Aviation programme) to develop ultra-efficient novel aircraft and propulsion technology for regional and short/medium-range aircraft with the

[30] During TRANSCEND Dissemination Workshop "Aviation fuel meets propulsion towards 2050", held on June 8th, 2022, attendees informed the workshop that aircraft and engine manufacturers are leading specific investigations in the frame of ASTM on SAFs that could be used on kerosene-powered aircraft.. Several flight tests have already been reported (see, e.g., Airbus, 2022c) with no identified showstopper.

aim to introduce them on the market in 2035. This is an opportunity to introduce 100% SAF on a new generation of aircraft that will make up a large share of the 2050 fleet.

SR 3 Develop sustainable aviation fuels not requiring blending with fossil kerosene

a Ensure – by continuing working in ASTM Task Forces, monitoring the work, and taking (corrective) actions – the development and certification of 100% SAFs
This recommendation is addressed to: ASTM, policymakers, SAF suppliers/developers, and aircraft and engine manufacturers.

b Provide timely, at latest before 2030, the regulations and requirements for propulsion and aircraft technology development for ultra-efficient aircraft that are powered by certified 100% SAFs and that enter into service in 2035
This recommendation is addressed to: ASTM, authorities, SAF suppliers/developers, and aircraft and engine manufacturers.

There are multiple routes for developing SAFs not requiring blending with fossil kerosene. For current ASTM-certified pathways, which require blending with at least 50% fossil kerosene, the development could focus on certification of the SAF without the blending requirement. Alternatively, existing ASTM-certified pathways may be modified or new pathways may be developed for neat use of SAFs. In addition, the 100% SAFs may reduce as well non-GHG emissions during flight (see SR 2). Finally, some modification of present aircraft and engines may be required for 100% SAF compatibility. In this case, new technical requirements for aircraft and engines will need to be developed, which need to be firmly known by 2030 to be taken on-board commercial development programmes for ultra-efficient aircraft entering into service in 2035. Depending on the level of changes needed with respect to present aircraft and engines requirements, provision before 2030 may be required.

This recommendation is focused on, and aligned in time with, aircraft types entering into service from 2035. However, older aircraft may still be flying for decades, even far beyond 2050. If the 100% SAFs are not compatible with older aircraft, retrofit packages for in-service aircraft and/or for certified adaptations on aircraft in production may enable the use of 100% SAFs also on older aircraft. This would increase the technology-driven potential of net CO_2eq emissions reductions at fleet level beyond the projections by TRANSCEND.

SR 3 shall be carried out in line with SR 5 to ensure that the 100% SAF can also be supplied.

6.4 Develop technologies for energy-efficient SAF-powered and hydrogen-powered aircraft for regional and short/medium range

Even with the upcoming aircraft energy-efficiency increase realized through technology developments, as assessed by the Clean Sky 2 Technology Evaluator, these reductions in fuel burn do not nearly make up for the fuel cost increase due to the switch from kerosene to SAF. Moreover, the energy resources needed are scarce (see SR 5 and SR 6), and hence any further opportunity to improve energy efficiency should be pursued.

The development of new aircraft therefore needs to focus on energy efficiency as well as the compatibility with new fuels. As it takes several years to develop these aircraft, ongoing research and development needs to continue and to accelerate. Private, regional, national and European initiatives are being taken. For example, Airbus (ZEROe) and the public-private Clean Aviation programme are addressing the development of aircraft and propulsion technologies by 2030, including ones related to hydrogen-powered propulsion. Entry-into-service of these technologies on ultra-efficient regional and short/medium range aircraft up to 250 seats, is targeted no later than 2035.

SR 4 Continue at European, national, regional and private levels the development of required technologies for energy-efficient SAF-powered and hydrogen-powered aircraft for regional and short/medium range

a Continue the development of novel propulsion technologies for both SAF-powered propulsion and hydrogen-powered propulsion
This recommendation is addressed to: aircraft and engine manufacturers, their industrial supply chain, research centres and academia, and policy makers.

b Continue the development of propulsion integration and general aircraft technologies
This recommendation is addressed to: aircraft and engine manufacturers, their industrial supply chain, research centres and academia, and policy makers.

c Continue to ensure the developments of technologies under A and B towards the next generation, ultra-efficient regional and short/medium range aircraft up to 250 seats with entry into service no later than 2035
This recommendation is addressed to: aircraft and engine manufacturers, their industrial supply chain, research centres and academia, policy makers.

As indicated in relation to SR 2, small twin-aisle aircraft can also be powered by hydrogen for short ranges. Technologies may be transferred from the initiatives for single-aisle aircraft, complemented with dedicated developments for small twin-aisle configurations. At European level, this research and development could start in the Horizon Europe research programme. Technology development targets per aircraft category have been defined in the Clean Aviation Strategic Research and Innovation Agenda and in the first Work Programme. This programme is a public-private initiative from its members and the EU. The Clean Aviation Joint Undertaking monitors the progress of the research programme and is taking corrective actions.

This recommendation shall take into account the regulations and requirements following from SR 1, SR 2 and SR 3.

6.5 Ensure the European supply of SAF and green hydrogen

In parallel to the development of SAF and production routes (SR 1), the supply of SAF to European airports needs to align with the ReFuelEU Aviation mandate from 2025, including the minimum percentages for synthetic SAF from 2030. Similarly, with reference to SR 2, the European supply of green hydrogen as fuel needs to be ensured from 2035.

The ReFuelEU Aviation mandate does not mention a minimum supply of green hydrogen for hydrogen-powered aircraft. For the recommendations here stated, it is assumed that all hydrogen required for the hydrogen-powered aircraft has to be green.

SR 5 Ensure the European supply of SAF and green hydrogen

a Explicitly mention green hydrogen as fuel for hydrogen-powered aircraft from 2035 in the ReFuel EU Aviation mandate
This recommendation is addressed to: EU policymakers.

b Take public and private action to ensure availability of hydrogen infrastructure (with sufficient capacity) at airports, starting with the development of detailed plans, which should include possible demonstration facilities, targets and regulations.
This recommendation is addressed to: fuel suppliers, EU policymakers, airports, aircraft and engine manufacturers, and authorities.

c Ensure, by taking action and closely monitoring, sufficient supply of SAF and hydrogen for flights departing from Europe.
This recommendation is addressed to: fuel suppliers, airports, and EU policymakers.

For SR 5c, TRANSCEND has estimated the amount of SAF and hydrogen supplies needed for flights departing from Europe and UK. The minimum amounts of bio- or waste-based SAF, synthetic SAF and green hydrogen as fuel have been based on the low scenario of the DLR Clean Sky 2 (CS2) scenario (Gelhausen, Grimme, Junior, Lois, & Berster, 2022) and the ReFuelEU Aviation commission proposal of July 14th, 2021. Supply of SAF is managed in absolute numbers rather than percentages, which requires an estimate of the total amount of fuel that has to be supplied. Next, the minimum required amounts of synthetic SAF and all SAFs can be determined. As green hydrogen is also a feedstock for synthetic SAF, the necessary supply of green hydrogen includes hydrogen for direct use as fuel and for feedstock for synthetic SAFs. The resulting minimum amounts of fuels for EU and UK are shown in Table 3 (from Appendix G.1). As the impact of COVID-19 was not taken into account and the traffic growth rates of the DLR CS2 scenario are higher than those used in other sources (e.g. van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), future fuel demands might differ from the values shown in the table.

Table 3: (Minimum) amounts of bio- or waste-based SAF, synthetic SAF and green hydrogen for EU+UK to meet the ReFuelEU Aviation mandate (as proposed in 2021). The minimum amounts are derived from the total amount of kerosene needed to power the non-hydrogen-powered aircraft, based on the DLR Clean Sky 2 low traffic scenario.

	2025	2030	2035	2040	2045	2050
Total amount of kerosene [Mt]	**57.0**	**62.7**	**68.4**	**68.6**	**66.2**	**64.6**
ReFuelEU Aviation mandate for SAF	2%	5%	20%	32%	38%	63%
Total amount of bio-/waste-based and synthetic SAF [Mt]	1.1	3.1	13.7	22.0	25.2	40.7
ReFuelEU Aviation sub-mandate for synthetic SAF	0%	0.7%	5%	8%	11%	28%
Minimum amount of synthetic SAF [Mt]	0	0.4	3.4	5.5	7.3	18.1
Green hydrogen for use as feedstock for minimum amount of synthetic SAF [Mt]	0	0.2	1.7	2.7	3.6	9.1
Green hydrogen for use as fuel [Mt]	n/a	n/a	0.2	1.3	3.3	4.9
Sum of green hydrogen for use as fuel, and as feedstock for minimum amount of synthetic SAF [Mt]	0	0.2	1.9	4.0	6.9	14.0

The minimum amount of bio- or waste-based SAF could be difficult to meet based on TRANSCEND's analysis of feedstock availability (detailed further in the comment regarding SR 6b). Therefore, the minimum amount of synthetic SAF – and accordingly, of green hydrogen required for its production – might be higher than the amounts shown in Table 3. In addition, hydrogen is also needed for the production process of bio- or waste-based SAF (during the hydrogenation, cracking, and isomerization steps; depending on the production method). This is not included in the analysis performed within TRANSCEND.

Specifically regarding SR 5a, it is noted that the ReFuelEU Aviation mandate includes revision moments, the first in 2028. This revision moment seems to be the right moment to evaluate the inclusion of green hydrogen for hydrogen powered aircraft.

Specifically regarding SR 5c, the supply of SAF and hydrogen should take into account European energy security. It is therefore recommended to encompass European availability (of feedstocks, energy carriers, and/or end products) and availability from non-European countries from which those feedstocks, energy carriers and/or end products can be imported. The monitoring and corrective actions should cover:

- **Bio- and waste-based SAF**, addressing feedstock (waste and potentially new promising sustainable biomass sources) availability, production capacity, associated process technology development (including the most promising options identified in TRANSCEND), industrial scale-up, availability of renewable energy, and distribution infrastructure.
- **Synthetic SAF**, addressing CO_2 availability (recycled from point sources or captured using direct air capture technology), green hydrogen availability (addressing availability of renewable electricity, electrolyser capacity, and distribution infrastructure), and production capacity for the synthetic SAF with associated availability for renewable energy, and distribution infrastructure.
- **Green hydrogen,** addressing availability of renewable electricity, electrolyser capacity, and distribution infrastructure.

6.6 Ensure renewable electricity and biomass for the production of fuels

To produce the fuels mentioned in SR 5, sufficient sustainable feedstocks need to be available. The required primary energy input depends on the efficiency of the production process and the product slate. Two sources of sustainable feedstocks are of interest: renewable electricity and biomass. The availability of each of these feedstocks should be sufficient to satisfy the amount of fuel required to meet the ReFuelEU Aviation mandate.

SR 6 Ensure sufficient availability of renewable electricity and biomass/waste for the production of fuels to meet the ReFuelEU Aviation mandate

a Regularly identify and provide the renewable electricity required for the production of synthetic SAF and hydrogen.
This recommendation is addressed to: energy suppliers and EU policymakers.

b Regularly identify and provide the sustainable biomass/waste needed for the production of the bio-/waste-based SAFs.
This recommendation is addressed to: biomass/waste suppliers and EU policymakers.

c Take the European aviation demand for renewable energy into account in the European, national or regional energy planning.
This recommendation is addressed to: European, national and regional policymakers, and energy suppliers.

Regarding SR 6b, and as indicated in connection to SR 5, TRANSCEND analysed the availability of bio- and waste-based SAF produced from waste streams. The analysis concluded that these are less scalable – or not at all – as that would mean generating additional waste and that the supply of bio-/waste-based SAF might be lower, such that additional synthetic SAF supply is required. This, in turn, requires an increased availability of renewable electricity, as mentioned in SR 6a.

The required renewable energy to produce green hydrogen and the minimum amount of synthetic SAF, as presented in Table 3, is given in Table 4. Appendix G.2 provides further details.

In order to meet the (minimum) ReFuelEU Aviation demand for synthetic SAF and the green hydrogen demand, a total supply of 1260 TWh electricity is required by 2050. Besides aviation fuels, the production results in other synthetic fuels (such as gasoil), which can be used in other sectors. Therefore, in Table 4, the total amount of renewable electricity is shown for both the synthetic SAF and the other synthetic fuels. In addition, the part of this total amount of renewable electricity that can be accounted to synthetic SAF only is indicated as well.

Table 4: Amount of renewable electricity required for the production of synthetic SAF and green hydrogen to meet the ReFuelEU Aviation mandate, based on the DLR Clean Sky 2 low traffic scenario and the 2021 ReFuelEU Aviation proposal

Renewable electricity [TWh]		2025	2030	2035	2040	2045	2050
For the production of the minimum amount of synthetic SAF	For synthetic SAF and other synthetic fuels (by-products)	0	22	184	297	394	978
	Accountable to synthetic SAF	0	11	90	145	193	478
For the production of green hydrogen for use as fuel		n/a	n/a	11	75	190	282

Renewable electricity [TWh]		2025	2030	2035	2040	2045	2050
Total	For green hydrogen for use as fuel, synthetic SAF, and other synthetic fuels (by-products)	0	22	195	372	584	1260
	For green hydrogen for use as fuel and accountable to synthetic SAF	0	11	101	220	383	760

Regarding SR 6c, the supply of renewable electricity and biomass should take into account European energy security. It is therefore recommended to encompass European availability and availability from non-European countries from which renewable electricity and biomass can be imported.

6.7 Limit potentially negative effects of cost increases

The increased use of alternative fuels will lead to cost increases towards 2050. If passed on to customers, cost increases will affect the demand for air travel and consequently also on the emissions by the European aviation. These cost increases may however also have unintended effects such as level playing field distortions and carbon leakage. For policymakers, the unintended effects of cost increases are relevant to understand in order to limit the negative effects.

SR 7 Follow-up the TRANSCEND study with an assessment on the impact of cost increases due to the increased use of alternative fuels on aviation demand and emissions, and possibly introduced policies to reduce negative effects

This recommendation is addressed to: policymakers, universities and research centres.

6.8 Carry out sensitivity and integrated scenario studies

In anticipatory studies, such as TRANSCEND, there are many parameters of which the values are uncertain. It is useful to know which parameters contribute most to the predicted climate impact reductions and other key outcomes, and also to what extent these parameters contribute. Important uncertainties could then be targeted in order to improve the accuracy and reliability of those estimations. This can also help to carry out further integrated scenarios studies to formulate more informed policies recommendations.

SR 8 Follow-up the TRANSCEND study with a sensitivity study and integrated scenario studies to identify the most effective and ensure the most stable policies

This recommendation is addressed to: policymakers, universities and research centres.

This recommendation aims to identify and possibly reduce uncertainties relevant to support consistent and future-proof decision making on, for example, strategic priorities and long-term policies and regulations.

6.9 Periodically re-assess to include the latest developments

The amount of renewable energy and the associated amount of renewable fuels that are required up to 2050 may change drastically over time. A combination of external factors may influence air travel demand. Internal aspects within the aviation sector, such as the development of new technologies, fleet composition, regulatory aspects and full climate impact, will also evolve. For policymakers, a regular update of the prospected energy demand will ensure that the targets set by ReFuelEU Aviation can be met with truly sustainable fuels.

SR 9 Periodically update studies such as TRANSCEND to include the latest developments

a Update the assumptions and predictions related to aircraft technologies, compatible alternative fuels and their climate impact.
This recommendation is addressed to: policymakers, universities and research centres

b Update the supply and demand amounts of SAF, hydrogen and renewable energy frequently to support long-term decision making on policies and regulations.
This recommendation is addressed to: policymakers, universities and research centres.

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Appendix A Abbreviations

ACRONYM	DESCRIPTION
AF	Alternative fuel
AR	Agricultural residue
ATAG	Air Transport Action Group
ATI	Aerospace Technology Institute
ATJ	Alcohol-to-jet
BADA	Base of Aircraft Data
CA	Clean Aviation
CAJU	Clean Aviation Joint Undertaking
CB	Cereal bran
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
CS	Cereal straw
CS2	Clean Sky 2
CU	Competing use
DLR	German Aerospace Centre
EC	European Commission
EIS	Entry into service
EJ	Exajoule (10^{18} J)
EP	European Parliament
EU	European Union
EU ETS	EU Emissions Trading System
EU27	European Union with 27 Member States (excluding the United Kingdom)
F(N)C	Logging residues from final fellings of (non-)conifer trees
FP	Fast Pyrolysis
FR	Forestry residue
FT	Fischer-Tropsch
Gt	Gigatonne (10^3 Mt = 10^9 tonne = 10^{12} kilogramme)
H_2	Hydrogen
H_2O	Water (vapour)
HEFA	Hydro-processed Esters and Fatty Acids
IATA	International Air Transport Association
JU	Joint Undertaking
LH_2	Liquid hydrogen
MS	Maize stover
MSW	Municipal solid waste

ACRONYM	DESCRIPTION
Mt	Megatonne (10^6 tonne = 10^9 kilogramme)
NLR	Royal NLR - Netherlands Aerospace Centre
nm	Nautical mile (1 nm = 1.842 km)
NO_X	Oxides of nitrogen
PtL	Power-to-Liquid
SS	Sunflower straw
SAF	Sustainable aviation fuel
SPK	synthetic paraffinic kerosene
TAS	True airspeed
T(N)C	Thinnings from (non-)conifer trees
TRANSCEND	Technology Review of Alternative and Novel Sources of Clean Energy with Next-generation Drivetrains
TUD	Delft University of Technology
TWh	Terawatt-hour
UCO	Used cooking oil
UK	United Kingdom
WtT	Well-to-tank

Appendix B Methodology

Appendix B.1 Alternative fuels

Appendix B.1.1 Non-EU countries considered for alternative fuel or feedstock imports

The analyses in Chapter 4 discern between alternative fuels sourced from a combined supply of EU and UK production, and of import from select non-EU countries. Table 5 provides an overview, for hydrogen and synthetic SAF based on EC (2020b) and Van der Sman et al. (2021), for bio- or waste-based SAF sourced from Ben Salah (2022).

Table 5: Non-EU countries considered for alternative fuel or feedstock imports

Country or region	Import supply for hydrogen and synthetic SAF	Import supply for bio- or waste-based SAF
Albania		Yes
Bosnia and Herzegovina		Yes
Moldova		Yes
Montenegro		Yes
North Macedonia		Yes
Northern Africa	Yes (e.g.)	
Serbia		Yes
Ukraine	Yes (e.g.)	Yes

Appendix C Additional results

Appendix C.1 EU traffic development scenarios

Chapter 2 presented global traffic development scenarios. On the next pages, this appendix shows these same figures, but specific to flights departing form airports in the EU (Figures 30, 31 and 32) and the EU + UK (Figures 33, 34 and 35).

EU

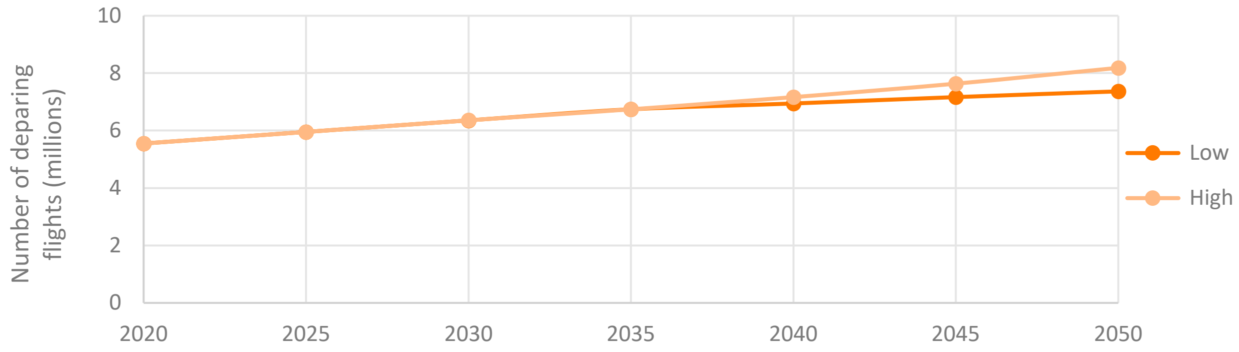

Figure 30: Traffic development (number of flights departing from EU27 airports) in the two traffic development scenarios considered

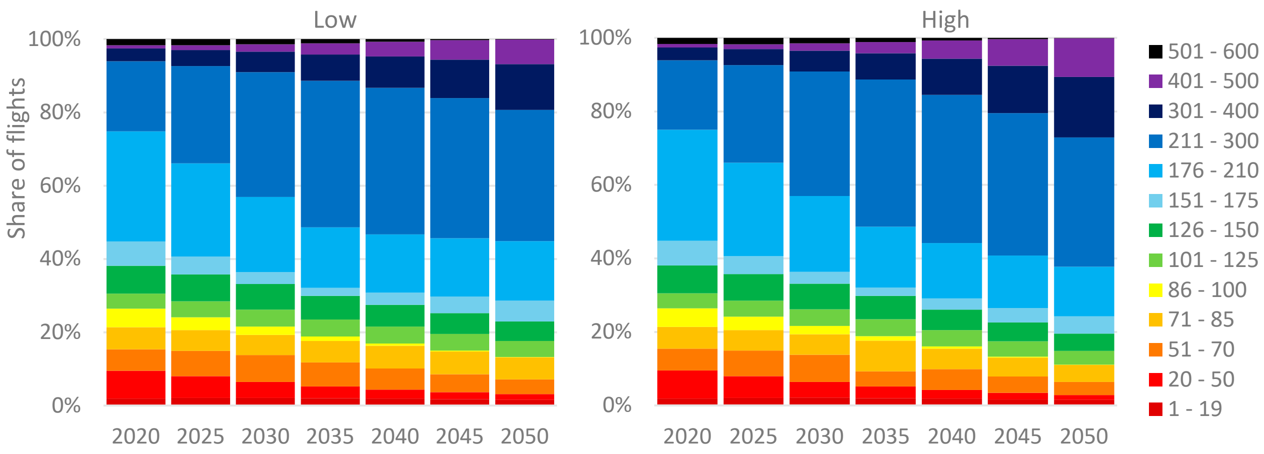

Figure 31: Fleet composition of flights departing from EU27 airports according to aircraft size class in the two traffic development scenarios considered

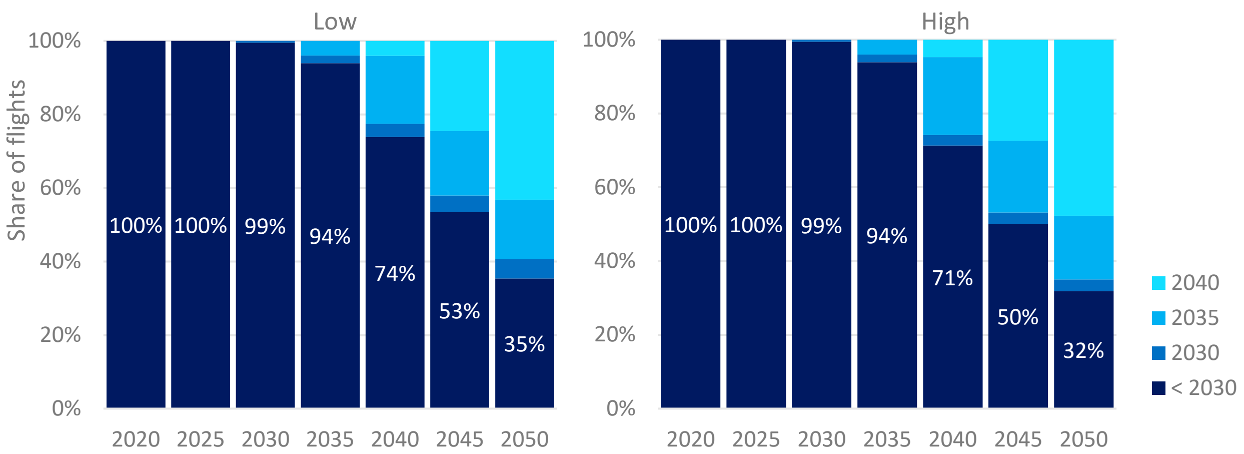

Figure 32: Fleet composition of flights departing from EU27 airports according to aircraft entry into service (EIS) year in the two traffic development scenarios considered (based on Gelhausen, Grimme, Junior, Lois, & Berster, 2022). Aircraft with EIS in 2030 or later are Clean Sky 2 aircraft

EU + UK

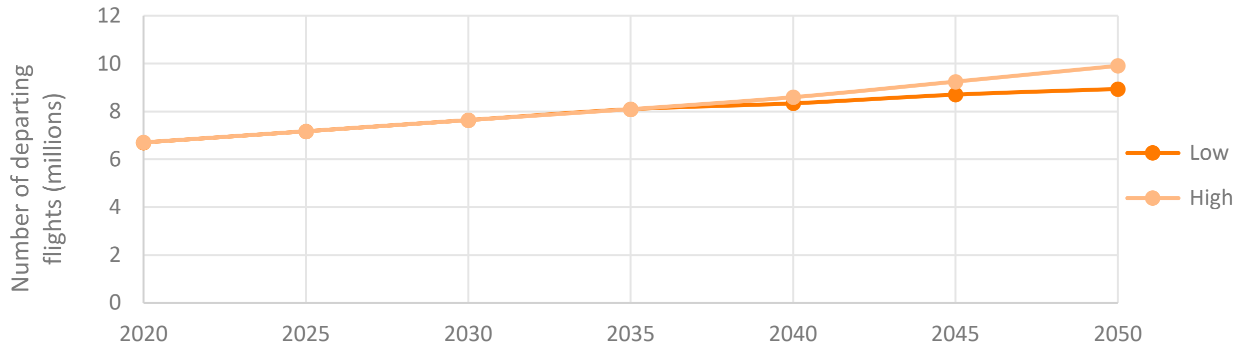

Figure 33: Traffic development (number of flights departing from EU + UK, airports) in the two traffic development scenarios considered

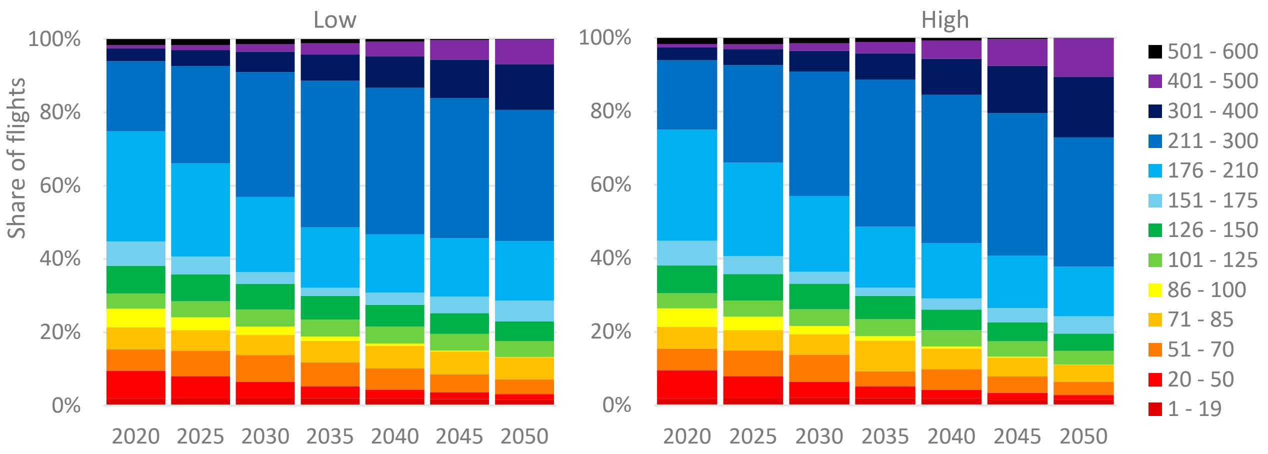

Figure 34: Fleet composition of flights departing from EU + UK, airports according to aircraft size class in the two traffic development scenarios considered

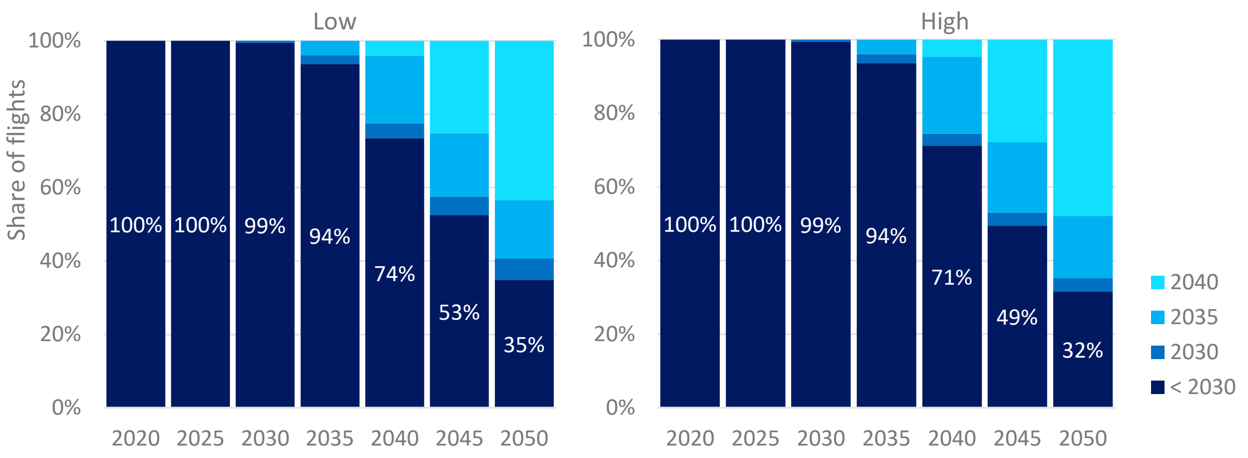

Figure 35: Fleet composition of flights departing from EU + UK airports according to aircraft entry into service (EIS) year in the two traffic development scenarios considered (based on Gelhausen, Grimme, Junior, Lois, & Berster, 2022). Aircraft with EIS in 2030 or later are Clean Sky 2 aircraft

Appendix C.2 EU energy and emissions projections

Section 3.3 showed the aircraft energy and emissions projections resulting from the global fleet-level assessment. Figure 36 in this appendix shows EU-specific figures; Figure 37 does this for the EU + UK.

EU

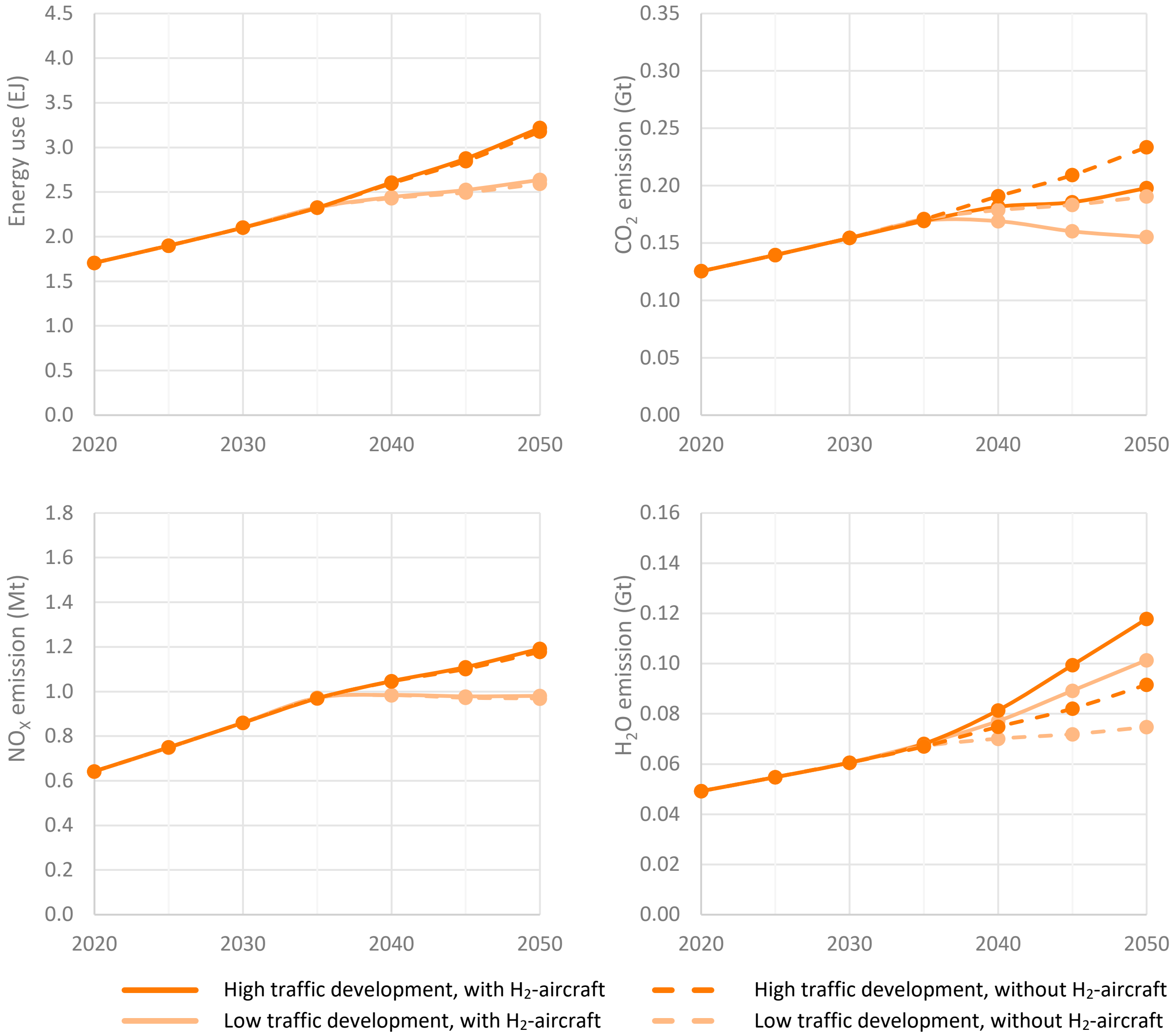

*Figure 36: Aircraft energy use and emissions by aircraft departing from EU27 airports under **high** or **low** traffic development, and with (solid lines) or without (dashed lines) hydrogen-powered aircraft*

EU + UK

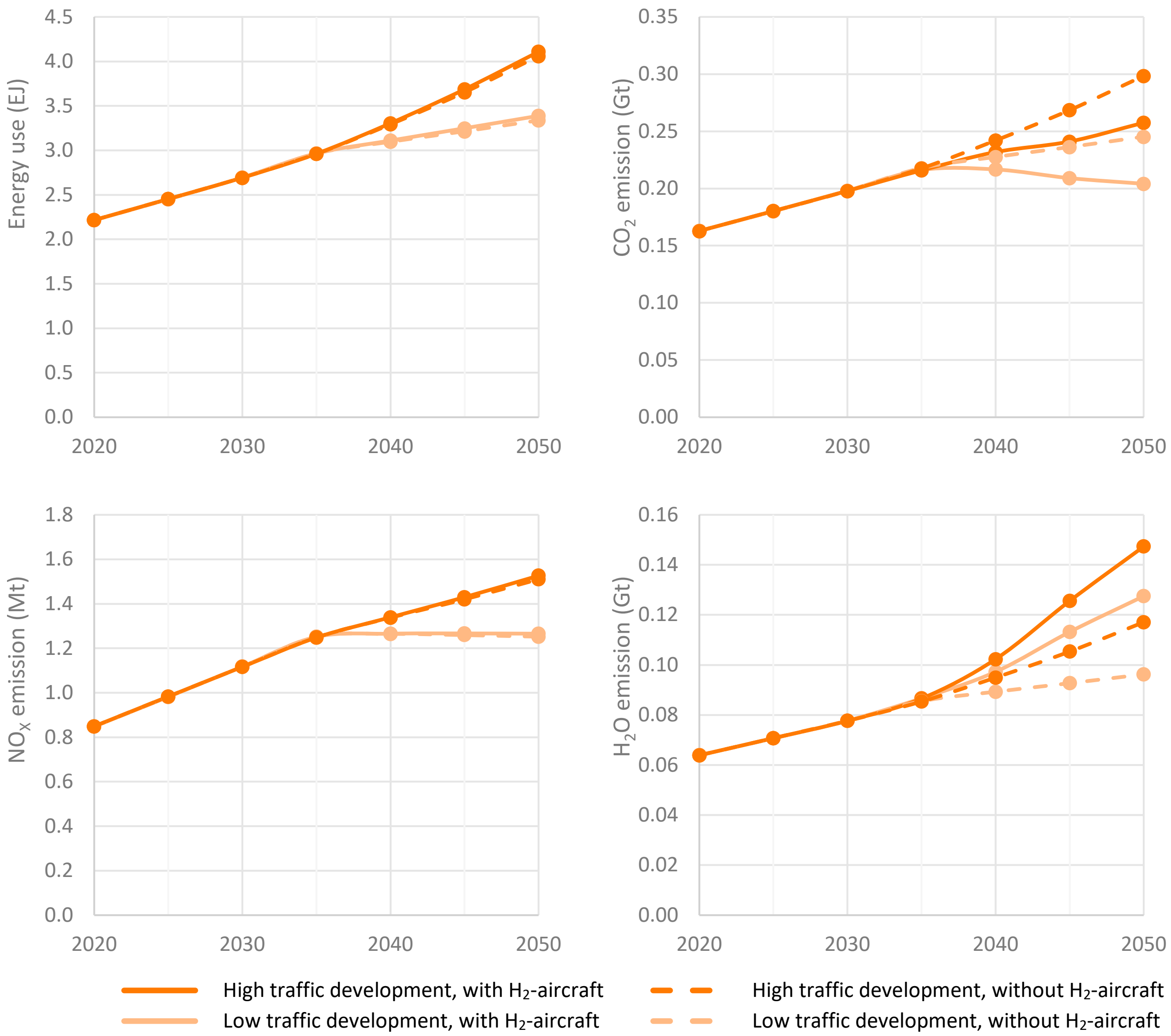

*Figure 37: Aircraft energy use and emissions by aircraft departing from EU + UK airports under **high** or **low** traffic development, and with (solid lines) or without (dashed lines) hydrogen-powered aircraft*

Appendix C.3 Fuel demand

Chapter 4 discussed, amongst others, supply and demand for (alternative) fuels. This appendix shows the supporting demand figures for various types of fuel for the different scenarios and horizon years.

EU

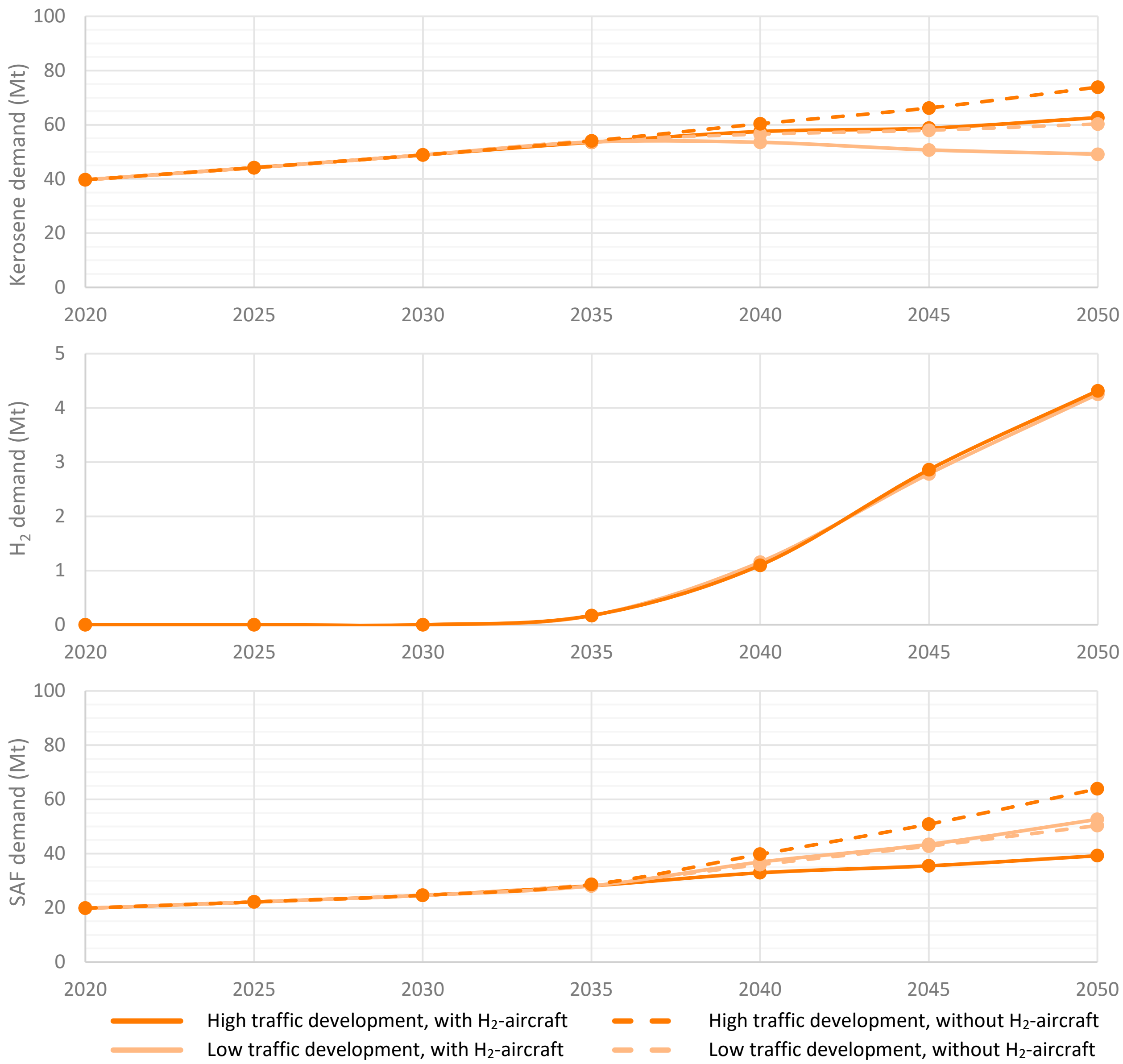

*Figure 38: Fuel demand (total kerosene, hydrogen and SAF) by aircraft departing from EU27 airports under **high** or **low** traffic development, and with (solid lines) or without (dashed lines) hydrogen-powered aircraft*

EU + UK

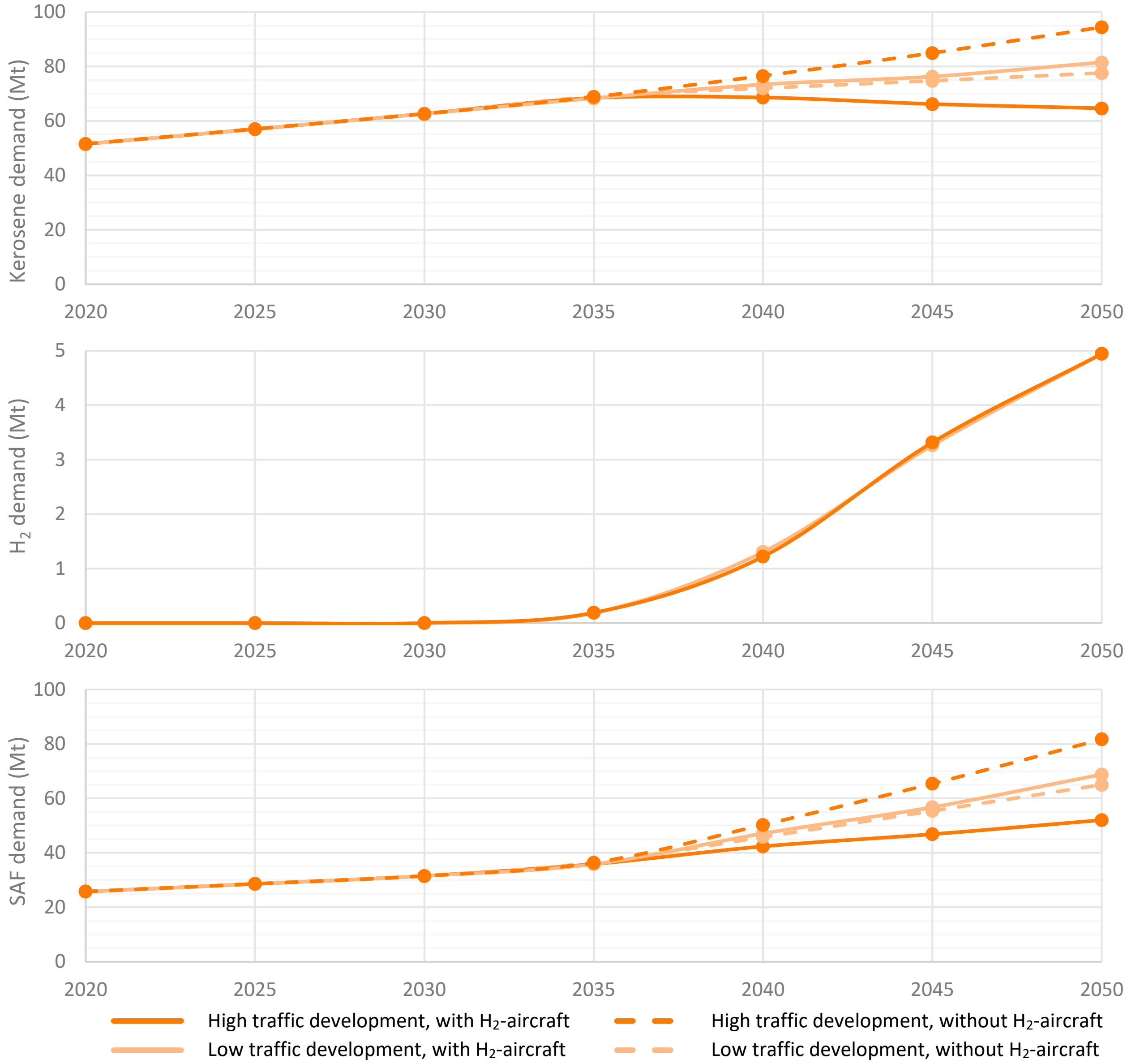

Figure 39: Fuel demand (total kerosene, hydrogen and SAF) by aircraft departing from EU + UK airports under ***high*** *or* ***low*** *traffic development, and with (solid lines) or without (dashed lines) hydrogen-powered aircraft*

Global

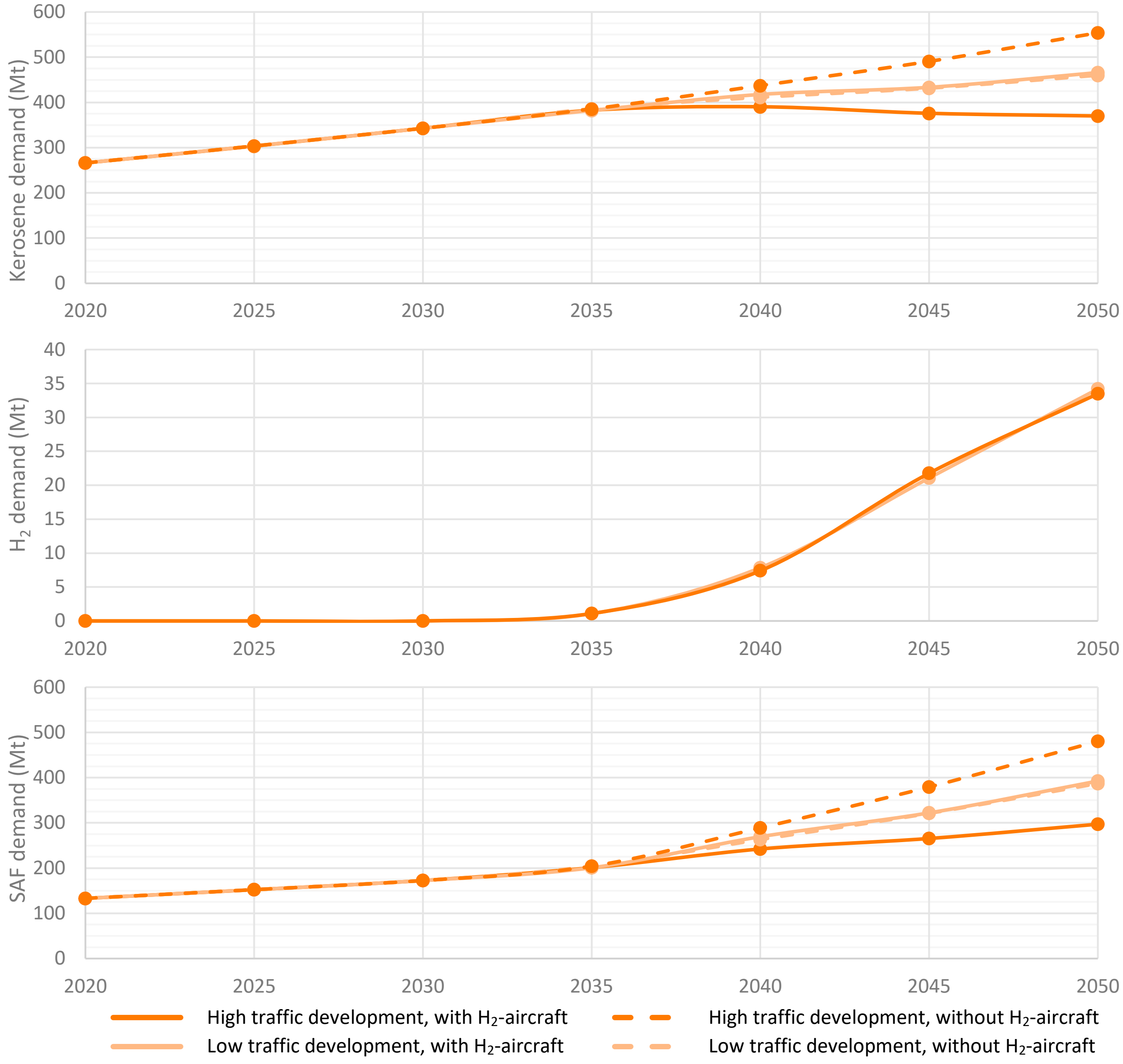

*Figure 40: Global fuel demand (total kerosene, hydrogen and SAF) under **high** or low traffic development, and with (solid lines) or without (dashed lines) hydrogen-powered aircraft*

Appendix C.4 Demand, supply, CO_2eq emissions impact and fuel cost without hydrogen-powered aircraft

The figures presented in this appendix show demand, supply, CO_2eq emissions impact and fuel cost in scenarios without hydrogen-powered aircraft. As hydrogen-powered aircraft are only introduced into the fleet from 2035, results for years up to and including 2030 are applicable to both scenarios with and without hydrogen-powered aircraft.

Synthetic SAF

Alternatively to Figure 20, Figure 41 shows total SAF demand and synthetic SAF supply (and CO_2eq emissions reduction) in a scenario without hydrogen-powered aircraft. Total SAF demand is in this case higher, but the supply of synthetic SAF and the net CO_2eq emissions reduction achieved by the use of synthetic SAF are as well.

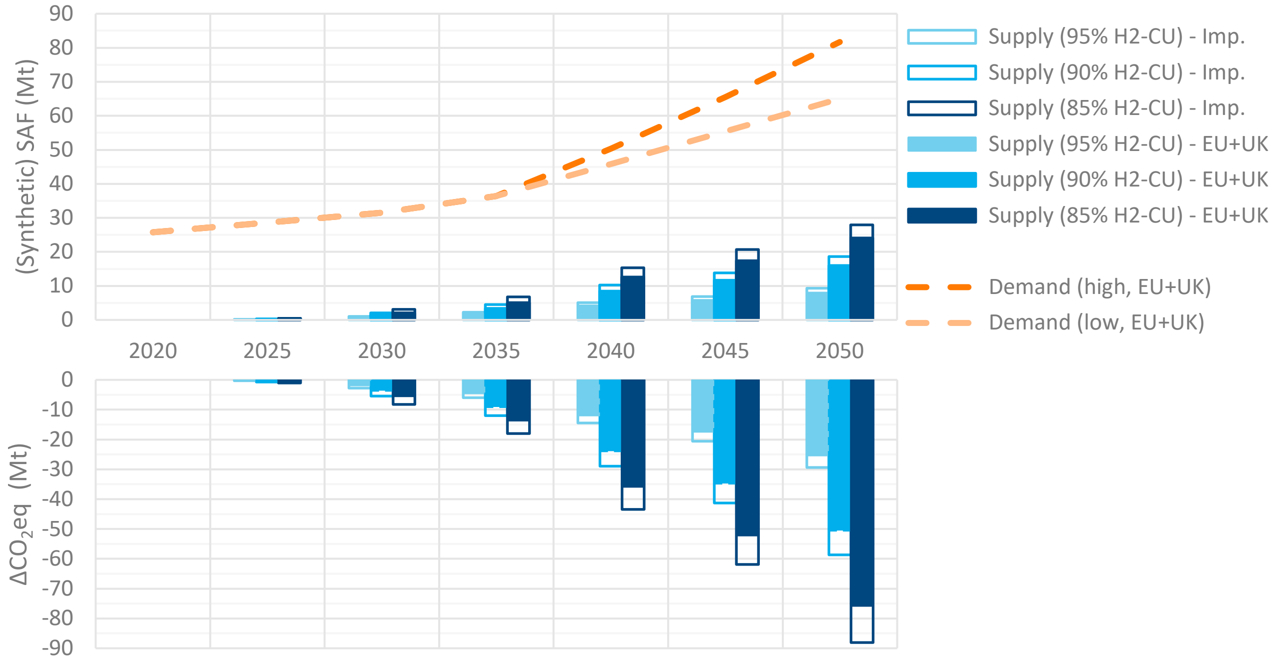

Figure 41: Synthetic SAF supply and total SAF demand (top) and associated net CO_2eq emissions reduction (bottom) in different traffic scenarios (without hydrogen-powered aircraft) and cases of competing use with supply from EU + UK only or with additional import from selected non-European production (Imp.

In case of 90% competing use, the gap to maximum SAF in 2050 varies from 37 Mt (low scenario) to 54 (high scenario), meaning that fuel blends consisting of 24% (low scenario) to 20% (high scenario) synthetic SAF. This is less than a third of the fleet-based blending limit shown in Figure 14, derived from anticipated regulatory and technological limits.

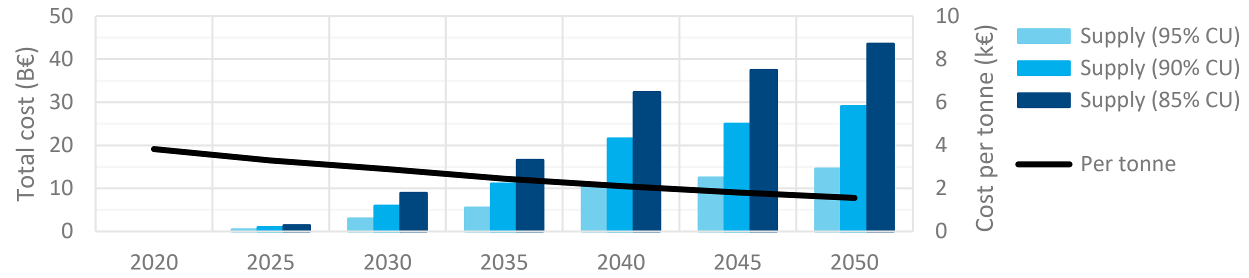

Figure 42: Total annual cost of synthetic SAF supplied from EU, UK and imported production in traffic scenario without hydrogen-powered aircraft and different cases of competing use (in billions of Euros) and cost per tonne (in thousands of Euros)

All SAF

Alternatively to Figure 22, Figure 43 shows total SAF demand and availability for bio- or waste-based and synthetic SAF combined, as well as the net CO_2eq emissions reduction both groups of SAF can realise, for traffic scenarios without hydrogen-powered aircraft.

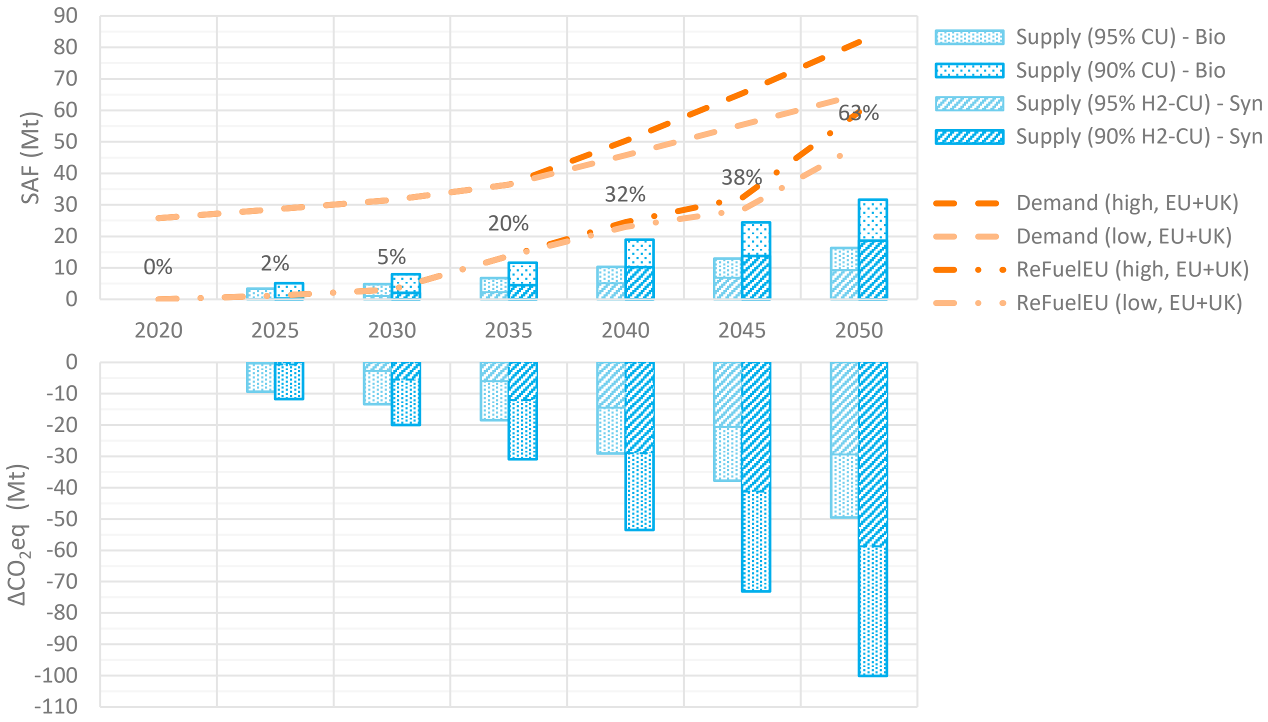

Figure 43: Total SAF supply and SAF demand (based on fleet-based blending limits or indicated ReFuelEU Aviation mandate; top) and net CO_2eq emissions reduction (bottom) in different traffic scenarios (without hydrogen-powered aircraft) and cases of competing use with EU, UK and imported supply

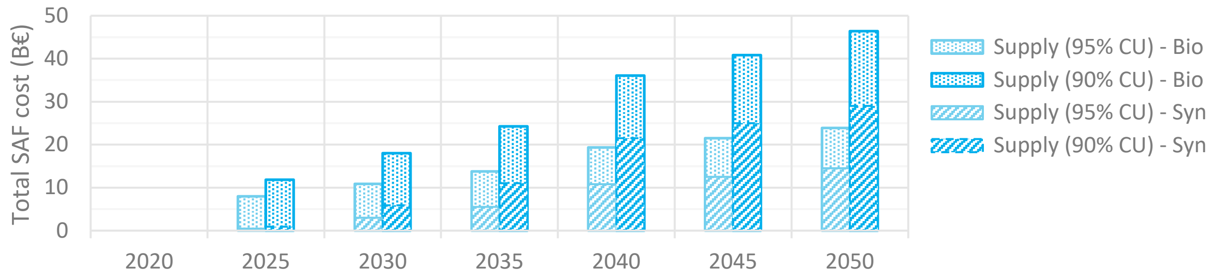

Figure 44: Total annual cost of SAF supplied from EU, UK and imported production in traffic scenario with hydrogen-powered aircraft and different cases of competing use (in billions of Euros)

All alternative fuels

Alternatively to Figure 24, Figure 45 shows the total CO_2eq emissions reduction delivered by SAF and hydrogen in traffic scenarios with hydrogen powered aircraft. Due to the lack of hydrogen-powered aircraft, hydrogen is not used directly as fuel and hence does not contribute to CO_2eq emissions reduction.

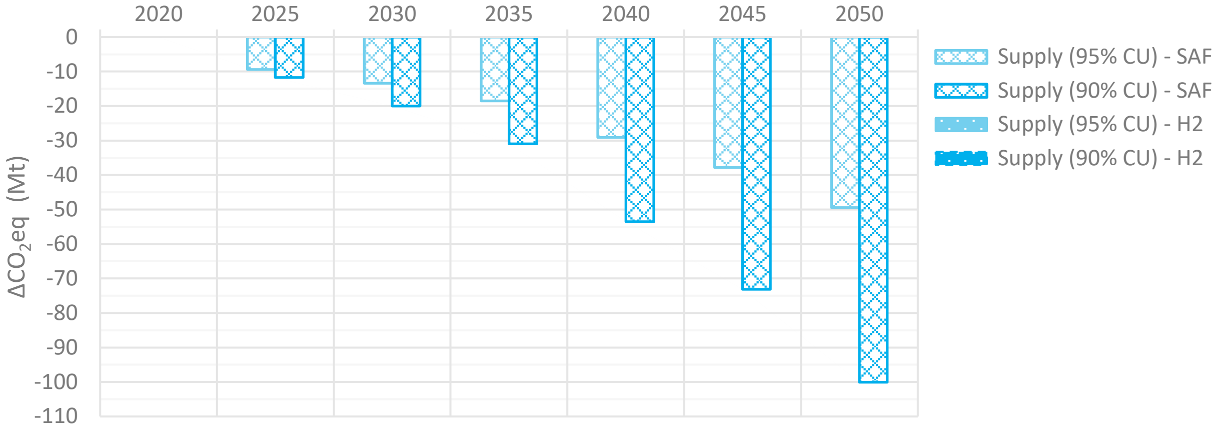

Figure 45: Total CO_2eq emissions reduction delivered by SAF and hydrogen in traffic scenarios without hydrogen-powered aircraft

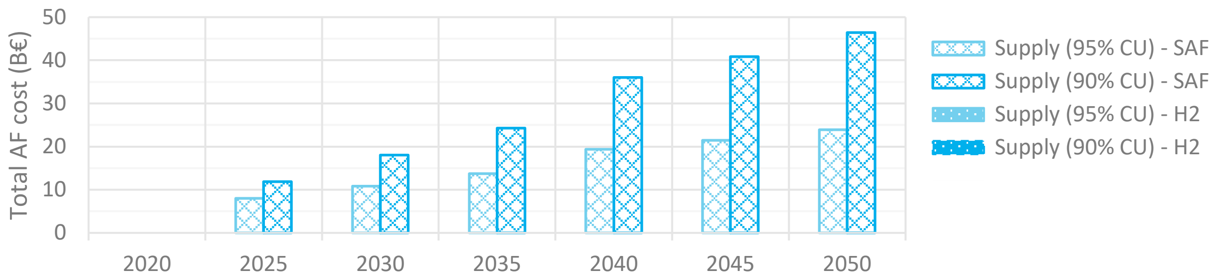

Figure 46: Total annual cost of alternative fuels supplied from EU, UK and imported production in traffic scenario without hydrogen-powered aircraft and different cases of competing use (in billions of Euros)

Appendix D Hydrogen availability

Green hydrogen availability was studied for 2025, 2030, 2040 and 2050. Focus was on European production (including the United Kingdom), but in additional, non-European production in Ukraine or Northern Africa – holding a trade potential to add to the supply of hydrogen in Europe – was considered as well.

Appendix D.1 2025 and 2030

European production (EU + UK)

The "2 × 40GW" initiative forms a main reference in the European outlook for hydrogen production in 2030. It refers to the European Commission's strategic objective (communicated in 2020) of installing 40GW of electrolyser capacity in the EU and another 40GW in neighbouring countries, contributing to trade potential (EC, 2020b). Hydrogen Europe has committed to this same target (van Wijk & Chatzimarkakis, 2020). By 2024, 6GW of electrolyser capacity should be available for European production.

Based on more recent analyses, the 40GW target for EU production seems feasible. Gas for Climate noted in December 2021 that almost 50GW has been announced for 2030 (Jens, Gräf, & Schimmel, 2021) and Wolf & Zander (2021) show that national capacity targets communicated by 11 of 27 EU Member States add up to 34.8GW capacity to be realised in 2030. An earlier report by the FCH JU notes ranges between 15 and 40GW (FCH JU, 2019), in line with a FCH JU study by Trinomics (2020), noting 13 to 56 GW.

Although fair agreement is found on total electrolyser capacity, the amount of hydrogen to be produced per GW differs per source: the EC indicates 40GW yields 10 Mt (0.25 Mt/GW) whereas Hydrogen Europe anticipates 4.4 Mt, at 0.11 Mt/GW (van Wijk & Chatzimarkakis, 2020). Trinomics (2020) assumes 4800 full load hours per year and then finds 2 to 8.8 Mt (0.15 Mt/GW). This range is comparable to 2021 estimates by Deloitte, ranging between 2 and 10 Mt of production, depending on ambition level (Villavincencio, 2021). A bottom-up study starting from the theoretical supply of renewable energy generation by the European Hydrogen Backbone and Gas for Climate finds 13.5 Mt, produced in the EU and the UK (Wang, et al., 2021).

The IEA Hydrogen Projects Database even further exceeds these estimates (IEA, 2021), as it currently lists 17.7 Mt of supply in EU countries to be possibly realised before 2030. The majority of these projects (13.9 Mt) is still in concept-stage and only a small part (0.2 Mt) is at or beyond a final investment decision.

Non-European production

Part of the 2 × 40GW objective is the realisation of 40GW of electrolyser capacity in e.g. Ukraine and Northern Africa. According to Hydrogen Europe, about 80% would be suitable for export to Europe (van Wijk & Chatzimarkakis, 2020). At 0.25Mt / GW, this would be another 8 Mt. IEA's Hydrogen Projects Database lists only 0.3 Mt of hydrogen projects in this same region. Deloitte does not (yet) anticipate imports in 2030.

Conclusions

For European production (EU + UK), realising approximately 40GW of electrolyser capacity as targeted by the EC (2020b) for 2030 is in line with earlier estimates and, based on more recent sources, seems feasible. At an average utilisation of 0.17Mt/GW, hydrogen output is 6.8 Mt in 2030. Scaling with electrolyser capacity, 2024 production should be at 1 Mt – interpolation to 2025 results in a figure of 1.4 Mt.

Literature shows estimates for green hydrogen imports to vary widely, from 0 to 8 GW. Based on the "2 × 40GW" strategy, 40GW of non-European electrolyser capacity, a conservative estimate of 50% trade potential and a utilisation of 0.17Mt/GW, 3.4Mt would be available for European use in 2030. Total hydrogen availability in the year 2030 would then be 10.2 Mt. For 2025, without any imports, total availability of green hydrogen is forecast to be 1.4 Mt.

Appendix D.2 2040

Few studies explicitly forecast hydrogen supply by 2040.

European production (EU + UK)
A study by Deloitte for Hydrogen for Europe anticipates European production to vary between 19 and 40Mt, depending on the ambition level (Villavincencio, 2021). Compared to 2030 values, these figures imply compound annual growth rates of 25% and 14%, respectively. Wang et al. (2021) forecast 63.1 Mt for 2040, produced in the EU and the UK. This is consistent with an annual growth rate of 17%. Lastly, IEA's Hydrogen Projects Database shows some additional projects for 2030 to 2040, increasing supply to 21 Mt (IEA, 2021). However, with a longer timeline, targeted projects for realisation in the 2030 to 2040 timeframe might not be studied concretely yet (and therefore not included in the database).

Non-European production
For 2040, Deloitte anticipates between 8 and 10 Mt of imported hydrogen (Villavincencio, 2021), depending on ambition level (lowest imports in highest ambition scenario). Again, anticipated projects by IEA's Hydrogen Projects Database in Ukraine and Northern-Africa are limited, at only 0.4 Mt (IEA, 2021). This is an increase of 25% with respect to the 2030 estimate.

Conclusions
Sources that explicitly estimate hydrogen availability from European (EU + UK) production in 2040 show substantial growth compared to 2030 – on average, some 20% per year. Based on 2030 numbers, this would yield a 2040 supply estimate of 42 Mt. That aligns with individual projections from literature, averaging 41 Mt. Estimates for the amount of hydrogen available in 2040 sourced from non-European production facilities averages 9 Mt, making a total of 51 Mt.

Appendix D.3 2050

As for 2040, relatively few studies explicitly forecast hydrogen supply by 2050. Demand projections are more widely available, but might not be representative, as they might not include hydrogen use in aviation.

European production (EU + UK)
Deloitte anticipates between 37 and 77 Mt to be available in 2050 (Villavincencio, 2021). As with shorter-term estimates from the same study, the range of values is explained by differences in ambition level. In both cases, the figures reflect a compound annual growth rate of about 7% with respect to 2040. Wang et al. (2021), too, note that growth rate, but in their case end up at a production of 120 Mt from facilities in the EU and the UK – a substantially higher value than forecast by Deloitte. Annual growth figures do align, however. Combining that with production figures from 2040, 2050 supply from European production would total some 80 Mt.

These wider ranges reflect the uncertainty associated to projections over this longer time period, also with respect to demand: Cihlar et al. (2020), for example, projects European hydrogen demand in 2050 to vary between 20 and 120Mt, whereas Trinomics (2020) forecasts a demand of 24 to 27 Mt in two different scenarios. On a global scale, IEA (2019) expects hydrogen demand for 2050 to total 135 Mt.

Non-European production

Literature also observes growth in imports from non-European production sites, but at a lower rate: some 2 to 4% per year, bringing average absolute estimates to 13 Mt (Villavincencio, 2021).

Conclusions

Literature notes continued increases in hydrogen availability from 2040, although the annual growth rate reduces to 7% (Villavincencio, 2021; Wang, et al., 2021). Based on 2040 supply figures, that would result in a total 2050 supply from European production of 83 Mt. Direct forecasts from these sources average 78 Mt. For this study, an intermediate value of 80 Mt is assumed. Supply from non-European sources also increases, to an estimated 13 Mt (Villavincencio, 2021). Combined, total hydrogen availability in Europe in 2050 would be 93 Mt.

Appendix E Cost of alternative fuels

Chapter 4 presents alternative fuels and the associated total annual costs. This appendix provides further explanation on how these costs are built up.

The cost are based on the expected minimum selling price per pathway and multiplied with the expected total supply per year. The minimum selling prices do not include investment cost for plants, infrastructure, equipment etcetera but it is assumed that these investment cost are passed on in the minimum selling price. Other market value costs (on top of the minimum selling prices) have been excluded as these are difficult to estimate. For these reasons, the minimum selling price of AF will therefore be called costs.

The expected costs of AF are estimations from other researches. These studies often focus on target years 2030 and 2050. No further research has been done on the costs in the intervening years by researchers. It has therefore been decided to calculate a price for the intervening years on the basis of an exponential increase/decrease.

Table 6: Cost of alternative fuels and fossil kerosene (€/tonne)

(Alternative) fuel	Pathway	2025	2030	2035	2040	2045	2050
Hydrogen	Alkaline Electrolysis	5,313	3,400	3,075	2,782	2,474	2,200
Bio- or waste-based SAF	Fischer Tropsch	2,287	2,058	1,848	1,659	1,490	1,338
Synthetic SAF	Power-to-Liquid	3,370	2,899	2,482	2,124	1,819	1,557
Fossil kerosene			600				690

Figure 47 shows the cost of alternative fuels and fossil kerosene on an energy-equivalent basis, i.e., per MJ.

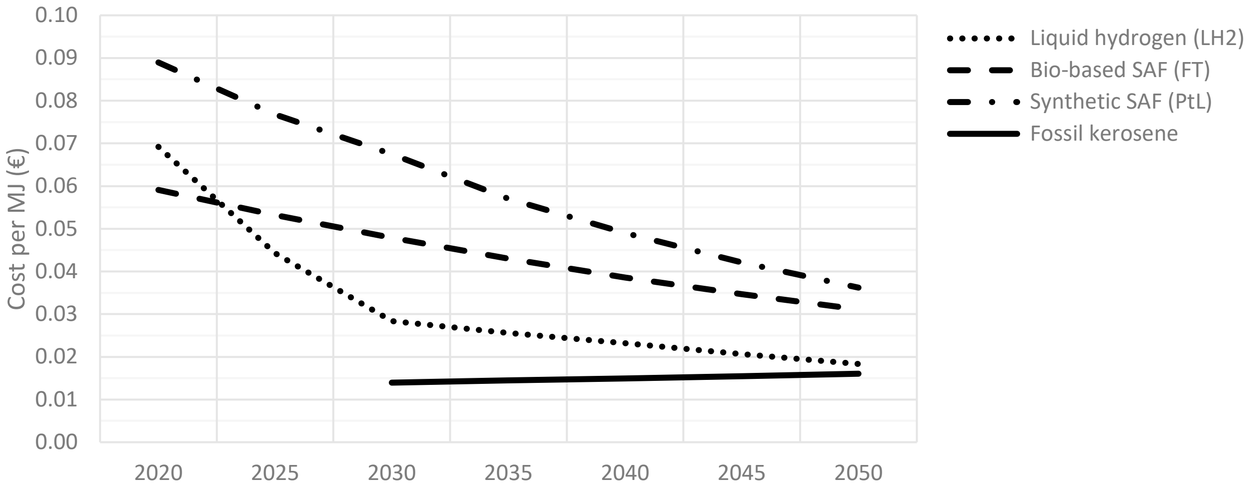

Figure 47: Cost of alternative fuels and fossil kerosene (€/MJ)

Hydrogen

In order to operate hydrogen-powered aircraft, liquid hydrogen is required for which the Alkaline Electrolysis pathway is applied. Table 6 shows that the costs of hydrogen using this pathway will be 3400 €/tonne in 2030. This amount is calculated by taking the average of different sources (Trinomics, 2020; McKinsey & Company, 2020; van Wijk & Chatzimarkakis, 2020). The scope of these sources differ from EU, import and EU + import.

The price is expected to fall to 2200 €/tonne in 2050. This price is an average calculated from 85% hydrogen produced in and 15% imported to the EU (McKinsey & Company, 2020), EU-produced and imported (van Wijk & Chatzimarkakis, 2020) and globally-produced hydrogen (IEA, 2019).

McKinsey and Flyzero both determined hydrogen costs for 2030. McKinsey concluded a price of 2800 to 3300 USD/tonne of H_2 in 2040 (McKinsey & Company, 2020). Applying an exchange rate of 1.12, the average is equivalent to 2723 €/tonne. Because it has been determined in Destination 2050 that the costs of McKinsey are relatively low compared to other sources (1900 €/tonne compared to 2200 €/tonne in 2050), this scaling up has also been applied for the prices of 2040. Secondly, Flyzero determined a price of 2700 $/tonne (FlyZero, 2022). This adds up to an average minimum selling price for hydrogen of 2782 €/tonne in 2040.

Bio- or waste-based SAF

The indicated cost of Fischer Tropsch SAF in Table 6 has been calculated by means of two feedstock prices concluded by (de Jong, et al., 2017). In this study, the cost of FT was researched for both forestry residues (1670 €/tonne) and wheat straw (2445 €/tonne). Together this amounts to an average of 2058 €/tonne in 2030.

For 2050 no cost indication for FT has been found in other researches. However, in Destination 2050 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) an average minimum selling price for bio- or waste-based SAF of all combinations (production process + feedstock) is determined for 2030 and 2050. Here it can be seen that the price of bio- or waste-based SAF decreases to 65% of the 2030 price in 2050. Based on this price decrease, an estimate has been made for the expected FT costs in 2050.

Synthetic SAF

For power-to-liquid (FT) multiple sources determined the costs for 2030. These price expectations lie in a range of 1144 €/tonne (German Environment Agency, 2016) to 3125 €/tonne (Pavlenko, Searle, & Christensen, 2019). The average of four price expectations corresponds to 2071 €/tonne. Since technological learning is required due to the use of pioneering plants which require technological learning, the costs are assumed to be 40% higher than average (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). This results in 2900 €/tonne for synthetic SAF in 2030. For 2050, the cost are 1577 €/tonne (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021).

Fossil kerosene

Table 6 also shows the expected costs for fossil kerosene since the cost premium of AF is calculated compared to fossil kerosene. The cost for this type of fuel will be 600 €/tonne in 2030 and 690 €/tonne in 2050 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021).

Appendix F Total well-to-tank energy requirements for liquid hydrogen and synthetic SAF production

Both liquid hydrogen and synthetic SAF are ultimately produced mainly from renewable electricity. In order to make this energy demand more tangible, this appendix estimates total well-to-tank (WtT) energy requirements for the supply of LH_2 and synthetic SAF projected in Sections 4.2 and 4.3.2.

This analysis is based on hydrogen and synthetic SAF quantities derived in this work and process efficiencies published by McKinsey (2020, p. 44): 58% for the production of liquified green hydrogen and 29% for the production of synthetic SAF based on an average of industry carbon capture (35%) and direct air carbon capture (22%). In the production of synthetic SAF, other synthetic fuels (such as gasoil) are produced as well. This is because even when the cracking process is optimised for synthetic SAF, the product slate can only be tuned for a fuel output that is approximately 50% synthetic SAF (i.e., aviation fuel) (Sustainable Aviation UK, 2020). That means that whereas the energy-to-SAF efficiency varies between the aforementioned 22 and 35%, the energy-to-fuel efficiency is higher. Following McKinsey (2020), this study assumes energy-to-SAF efficiencies. However, an efficiency of 22% is used, as the potential for industry carbon capture might be limited, and is likely to decrease to zero by 2050.

Figure 48 compares total well-to-tank energy requirements for LH_2 and synthetic SAF production in scenarios with and without hydrogen-powered aircraft. Figures 49 and 50 show the results for each of these scenarios individually and indicate the energy requirements per alternative fuel (i.e., for production of LH_2 or synthetic SAF).

Figure 48 shows that in a scenario without hydrogen-powered aircraft, total WtT energy requirements are higher than in a scenario without hydrogen-powered aircraft. The difference grows with the share of energy consumed by hydrogen-powered aircraft in the fleet, which grows with time. By 2050, the difference is approximately 250 TWh – equivalent to 33% in case of 90% CU and 90% in case of 95% CU.

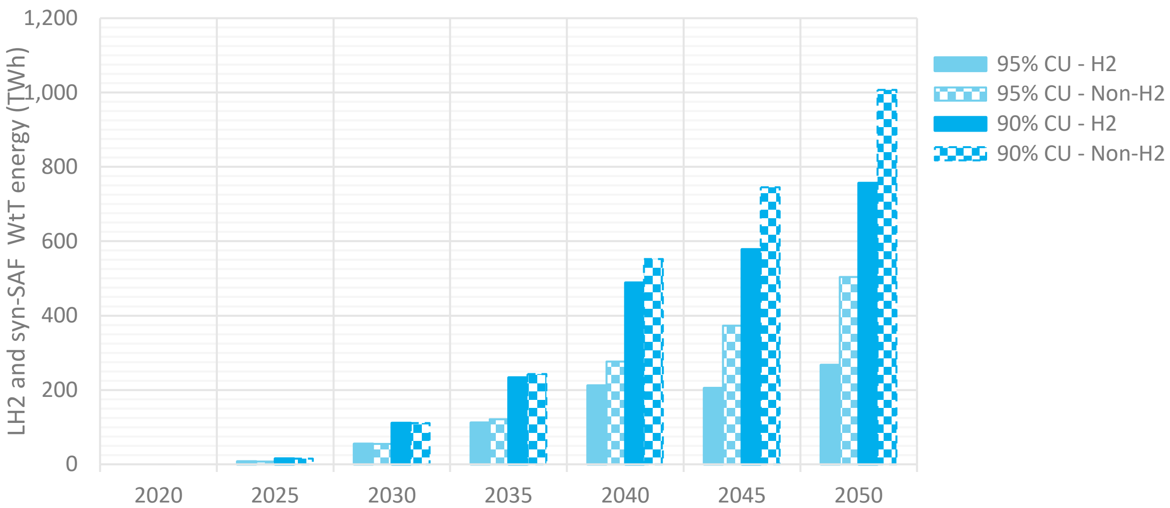

Figure 48: Total well-to-tank energy requirements for production of available LH_2 and synthetic SAF in scenarios with and without hydrogen-powered aircraft and different cases of competing use with EU, UK and imported supply

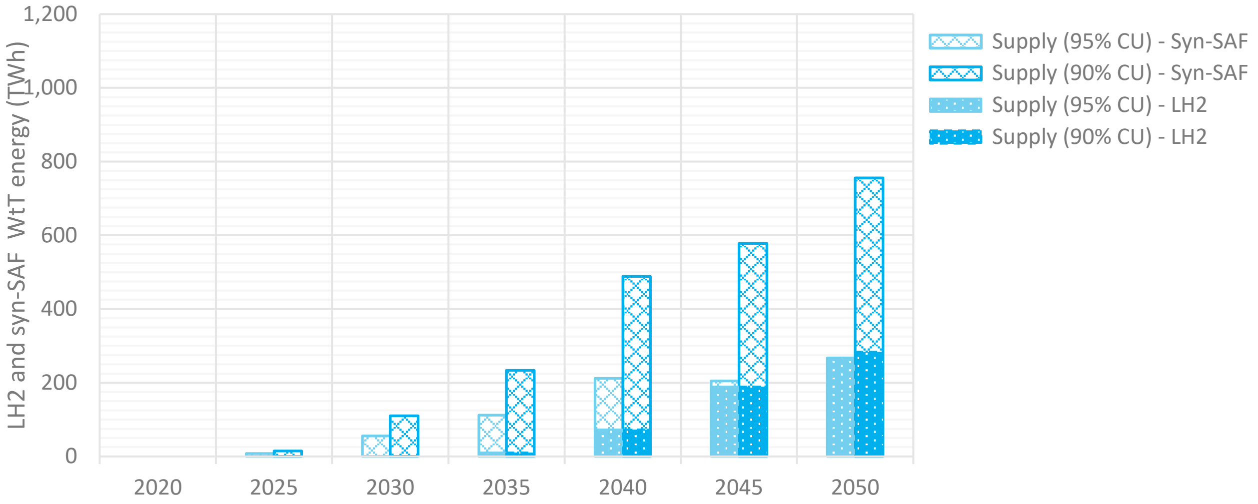

Figure 49: Total well-to-tank energy requirements for production of available LH_2 and synthetic SAF in a scenario with hydrogen-powered aircraft and different cases of competing use with EU, UK and imported supply

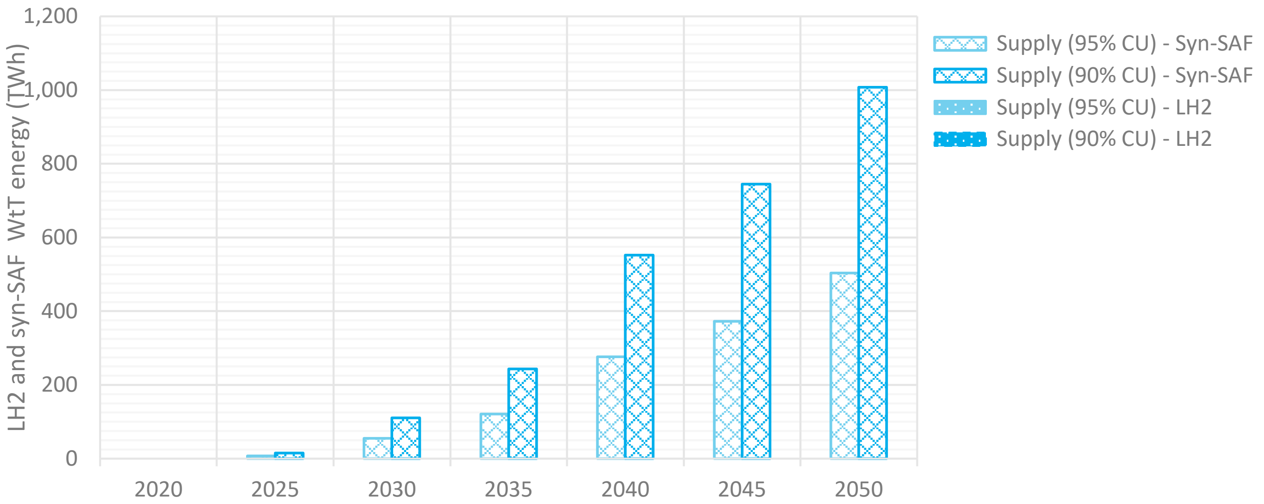

Figure 50: Total well-to-tank energy requirements for production of available LH_2 and synthetic SAF in a scenario without hydrogen-powered aircraft and different cases of competing use with EU, UK and imported supply

Appendix G SAF and well-to-tank energy requirements to meet ReFuelEU Aviation

Section 4.3.3 identified a substantial gap between available supply and demand of SAF after 2030 – compared to the total demand for SAF limited only by technological and regulatory limitations, as well as compared to the ReFuelEU Aviation blending mandate. Analysing that problem from the other side, this appendix estimates the amount of fuel as well as well-to-tank energy (for producing these fuels) to meet the ReFuelEU Aviation mandate. It does so for flights departing from EU and UK airports in the low traffic scenario (presented in Chapter 2) and the ReFuelEU Aviation regulation as proposed by the European Commission on July 14th, 2021 (EC, 2021).

Appendix G.1 Demand for SAF and green hydrogen

For the scenario including hydrogen-powered aircraft, Table 7 first shows the total kerosene demand of flights departing from the EU and UK airports. Following, it shows the total amount of SAF (bio- or waste-based and synthetic). Based on the ReFuelEU Aviation sub-mandate for synthetic SAF, it computes the minimum amount of synthetic SAF. Due to limitations of bio- and waste-based SAF availability, following from limitations in feedstock availability, more synthetic SAF might be required to meet the overall ReFuelEU Aviation blending levels.

Besides the amount of (synthetic or other) SAF, the table shows the amount of green hydrogen – for use as feedstock for synthetic SAF, for use as fuel in hydrogen-powered aircraft, and the total. Comparison of Table 7 to Figure 15 (in Section 4.2) shows that especially in 2050, the anticipated supply of green hydrogen (in a 90% competing use scenario) is lower than the 14 Mt required.

Table 7: (Minimum) amounts of bio-based SAF, synthetic SAF and green hydrogen to meet the ReFuelEU Aviation mandate, based on the DLR Clean Sky 2 low traffic scenario and the 2021 ReFuelEU Aviation proposal

	2025	2030	2035	2040	2045	2050
Total amount of kerosene [Mt]	**57.0**	**62.7**	**68.4**	**68.6**	**66.2**	**64.6**
ReFuelEU Aviation mandate for SAF	2%	5%	20%	32%	38%	63%
Total amount of bio-/waste-based and synthetic SAF	1.1	3.1	13.7	22.0	25.2	40.7
ReFuelEU Aviation sub-mandate for synthetic SAF	0%	0.7%	5%	8%	11%	28%
Minimum amount of synthetic SAF [Mt]	0	0.4	3.4	5.5	7.3	18.1
Green hydrogen for use as feedstock for minimum amount of synthetic SAF [Mt]	0	0.2	1.7	2.7	3.6	9.1
Green hydrogen for use as fuel [Mt]	n/a	n/a	0.2	1.3	3.3	4.9
Sum of green hydrogen for use as fuel, and as feedstock for minimum amount of synthetic SAF [Mt]	0	0.2	1.9	4.0	6.9	14.0

Appendix G.2 Demand for renewable electricity

Building upon the analysis in Appendix G.1, Table 8 shows the demand (or: required availability) of renewable electricity that corresponds to the quantities of green hydrogen and synthetic SAF derived in Table 7. The amount of energy required for the production of synthetic SAF is computed using two efficiencies:

- The efficiency of 22% corresponds to the conversion of renewable energy to synthetic SAF. This is the same efficiency as used in the computations in Appendix F.
- The efficiency of 45% corresponds to the conversion of renewable energy to all synthetic fuel, of which part is SAF.

In both cases, and consistent with Appendix F, the efficiencies assume the carbon required for the fuel is sourced using direct air capture (DAC).

Table 8: Amount of renewable electricity required for the production of synthetic SAF and green hydrogen to meet the ReFuelEU Aviation mandate, based on the DLR Clean Sky 2 low traffic scenario and the 2021 ReFuelEU Aviation proposal

<table>
<tr><th colspan="2">Renewable electricity [TWh]</th><th>2025</th><th>2030</th><th>2035</th><th>2040</th><th>2045</th><th>2050</th></tr>
<tr><td rowspan="2">For the production of the minimum amount of synthetic SAF</td><td>Renewable electricity [TWh]</td><td>0</td><td>22</td><td>184</td><td>297</td><td>394</td><td>978</td></tr>
<tr><td>For synthetic SAF and other synthetic fuels (by-products)</td><td>0</td><td>11</td><td>90</td><td>145</td><td>193</td><td>478</td></tr>
<tr><td>For the production of green hydrogen for use as fuel</td><td></td><td>n/a</td><td>n/a</td><td>11</td><td>75</td><td>190</td><td>282</td></tr>
<tr><td rowspan="2">Total</td><td>For green hydrogen for use as fuel, and synthetic SAF, and other synthetic fuels (by-products)</td><td>0</td><td>22</td><td>195</td><td>372</td><td>584</td><td>1260</td></tr>
<tr><td>For green hydrogen for use as fuel and accountable to synthetic SAF</td><td>0</td><td>11</td><td>101</td><td>220</td><td>383</td><td>760</td></tr>
</table>

Appendix H SAF Facility announcements

Producer	Country	Amount [tonnes/year]	Production start	Source
SkyNRG	The Netherlands	100,000	2025	SkyNRG (2019)
Neste	The Netherlands	500,000	2023	Neste (2021b)
Altalto Immingham Limited	United Kingdom	N/A	2024	Altalto (2022)
Total Energies	France	500,000	2021	Total Energies (2021)
	France	N/A	2021	Total Energies (2021)
	France	170,000	2024	Total Energies (2021)
	Belgium	150,000	n/a	Total Energies (2022)
Shell	The Netherlands	410,000	2024	Shell (2021)
Austrian Airlines and OMV	Austria	1,500	2022	OMV (2021)
Total		**1,831,500**		

Appendix I Acknowledgements and disclaimer

TRANSCEND’s Advisory Board included representatives from European Commission, EASA, Dutch Ministry of Infrastructure and Water Management, Joint Undertakings BBI, Clean Sky 2/Clean Aviation, and Fuel Cells and Hydrogen/Clean Hydrogen, IATA, KLM, Airbus, Safran, and SkyNRG. The representatives are acknowledged for their valuable advices.

Many experts contributed to the expert workshops organised by TRANSCEND for alternative aviation fuels and hydrogen-powered propulsion. The experts are acknowledged for their valuable feedback on preliminary results provided to them.

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This report reflects only the author's view and the JU is not responsible for any use that may be made of the information it contains.

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