Enabling Hydrogen in the European Aviation Market

Partners

Introduction

Aviation's contribution to the European economy is significant. In 2024, ACI Europe estimates that direct and indirect impacts of the aviation sector reached €851 billion, representing 5% of Europe's GDP, and supporting 14 million jobs, equivalent to 6% of total European employment[1]. While the economic benefits of aviation are clear, aviation has a negative impact on the environment, currently accounting for around 3% of CO_2 emissions – a figure that could rise to 22% by 2050.[2]

However, decarbonizing aviation is challenging because of its dependence on high-energy-density, moderate cost fuels and the long lifecycles of its assets. Several pathways are available to help reduce aviation's emissions, including the use of Sustainable Aviation Fuel (SAF), enhancing aircraft and operational efficiency, developing zero carbon emission aircraft, including hydrogen propulsion, and adopting carbon capture technology.

Hydrogen is a particularly promising fuel due to its high energy density and zero-carbon-emission combustion. However, transitioning to hydrogen in aviation faces substantial hurdles. These include the need for major infrastructure changes at airports, the introduction of new aircraft designs, the development of cryogenic fuel technologies, and a significant increase in green hydrogen production and distribution capabilities. For airlines, the financial implications of adopting hydrogen technology must therefore be carefully considered to assess its impact on profitability and to determine the most effective policies to support its adoption.

This study, powered by University College London's (UCL) 'Airline Behaviour Model' (ABM), analyses the extent to which the introduction of hydrogen as an aviation fuel, alongside conventional jet fuel and Sustainable Aviation Fuels (SAFs), could deliver potential environmental and economic advantages for the aviation sector.

Airline Behaviour Model (ABM)

The ABM assesses scenarios by determining how airlines compete to maximise their profit while consumers maximise their utility. By adjusting airfares and service frequency across their network, each airline iteratively responds to other airlines choices until a stable state is reached.

For the purposes of this study, the model has been used to assess the economic viability of hydrogen as a fuel in European aviation. By simulating airline decision-making processes under a range of scenarios where narrowbody hydrogen airliners* and sustainable fuels are available, the model predicts the size of the respective hydrogen aircraft fleet and how the airlines decide to use them, under different levels of government incentives and penalties related to carbon emissions. The industry outcome can then be estimated without any assumptions of airline behaviour beyond profit maximisation.

These scenarios are intended to explore strategies that will help decarbonise the European short-haul aviation market, whilst best preserving the societal and economic benefits it provides.

* A320/737 size

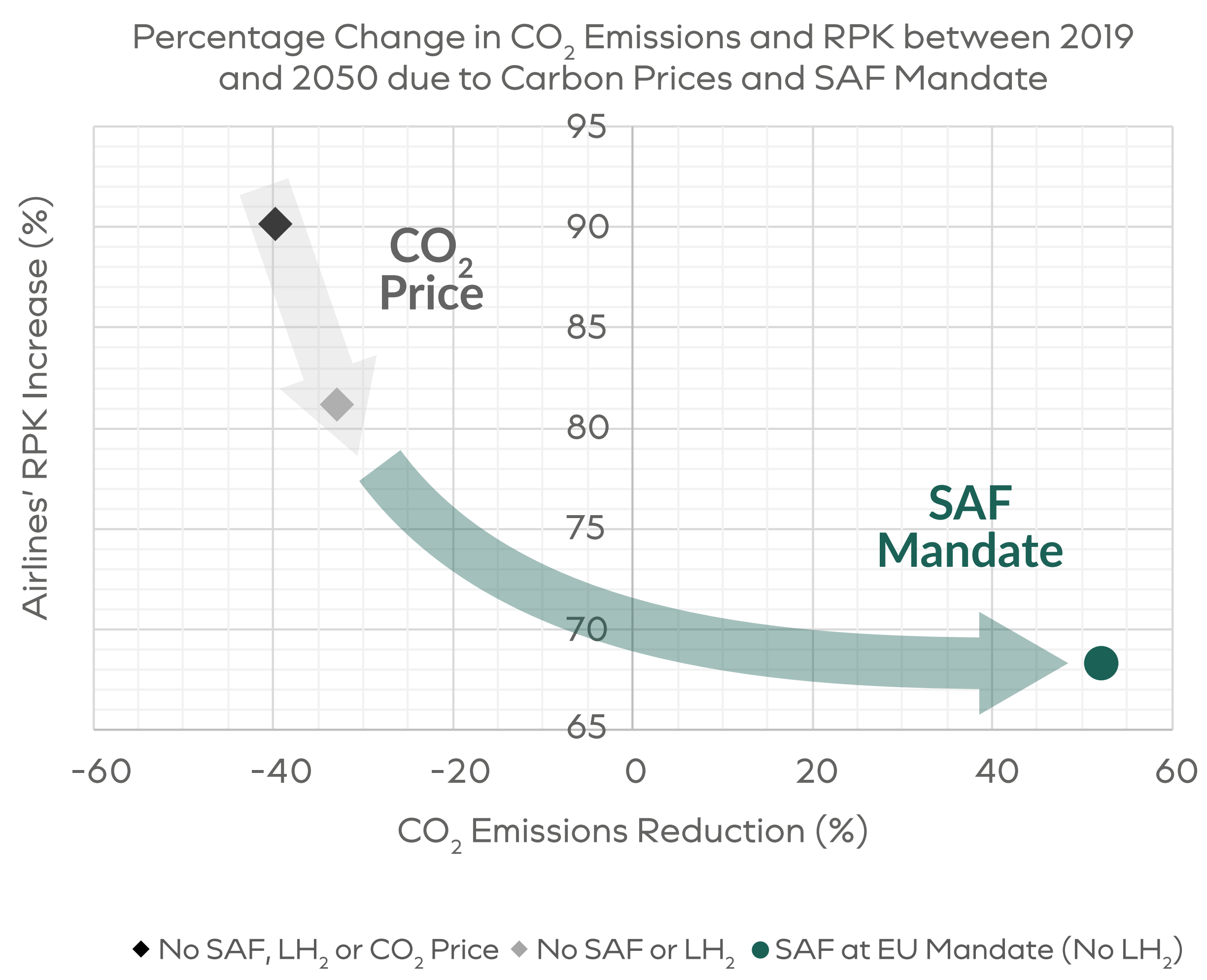
Input Assumptions

- Initial fleet composition based on current European data[3 4].
- Operating Costs of current aircraft and projected hydrogen concepts.
- Jet fuel & hydrogen prices based on IEA analysis[5].
- SAF mandate fuel proportions based on RefuelEU[6].
- All incentives and taxes are applied to both SAF and hydrogen in proportion to the carbon emissions of the fuel.
- Narrowbody hydrogen aircraft entry into service of 2035 due to industry perspective when modelling was conducted[7].
- Current airport capacities are maintained.

» Key Findings

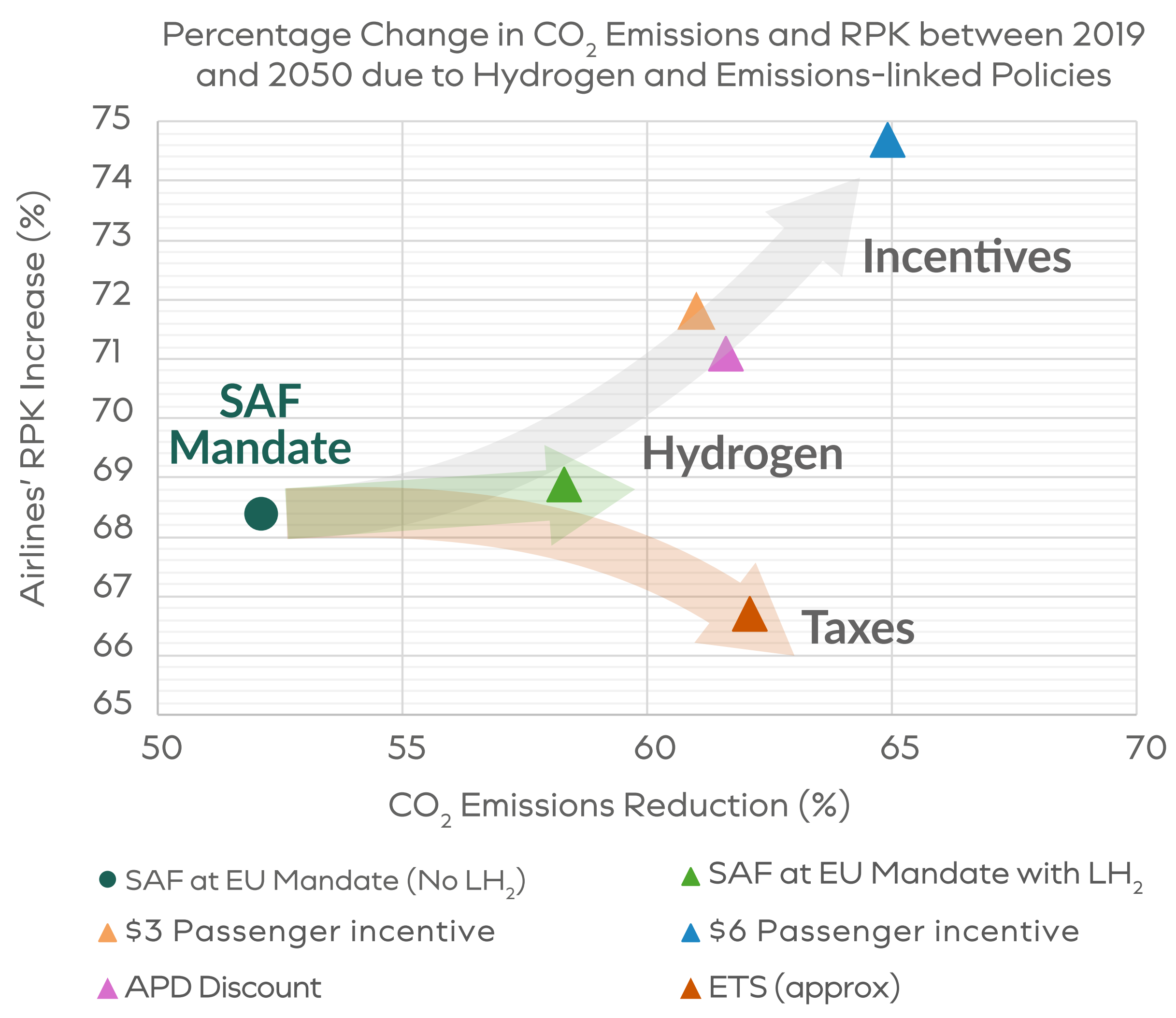
1. The existing EU SAF mandate, without the inclusion of hydrogen, would result in a 52% reduction in CO_2 by 2050 compared to 2019.

- This is due to a combination of the lower lifecycle emissions of SAF and the reduction in growth caused by the additional cost of the mandated 70% SAF fuel mix in 2050.
- If no SAF mandate was imposed, the total CO_2 emissions of the sector would increase by 40% between 2019 and 2050.
- The additional fuel cost introduced by a SAF mandate reduces growth of the sector, from a 90% increase in RPK from 2019 without a mandate to a 68% increase under a SAF mandate.



2. The introduction of hydrogen to the market would start to enable a simultaneous improvement in aviation growth and emission reductions.

- The introduction of hydrogen can further reduce CO_2 emissions while recovering some RPK growth potential lost due to the additional cost of SAF.
- As plotted, incentives applied on fuels in proportion to their emissions increase both the industry growth and the CO_2 reductions.
- Similarly, taxes in proportion to emissions could also reduce CO_2 but at the cost of industry growth.



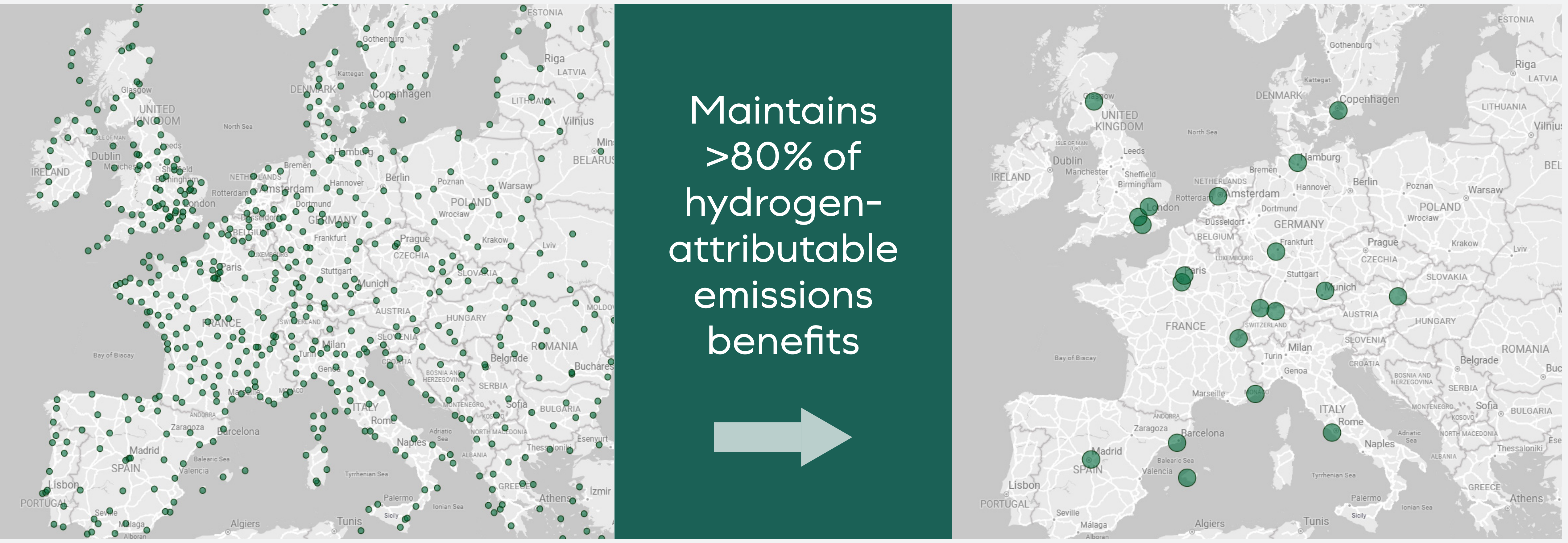
» Key Findings

3. Targeted infrastructure at a few hydrogen-equipped hub airports achieves similar emissions reductions to widespread hydrogen availability, illustrating a path to early adoption.

- Hydrogen aircraft with 2000 nmi range (to accommodate tankering) enable just 20 key hydrogen-equipped airports to deliver a level of hydrogen uptake and emissions savings very similar to the case where hydrogen is available at all airports.
- Most other European airports can be served from these 20 hydrogen-equipped hubs through tankering.
- Once factored into the aircraft design, the relative weight of hydrogen means tankering is achieved at minimal extra cost and CO_2 emissions.

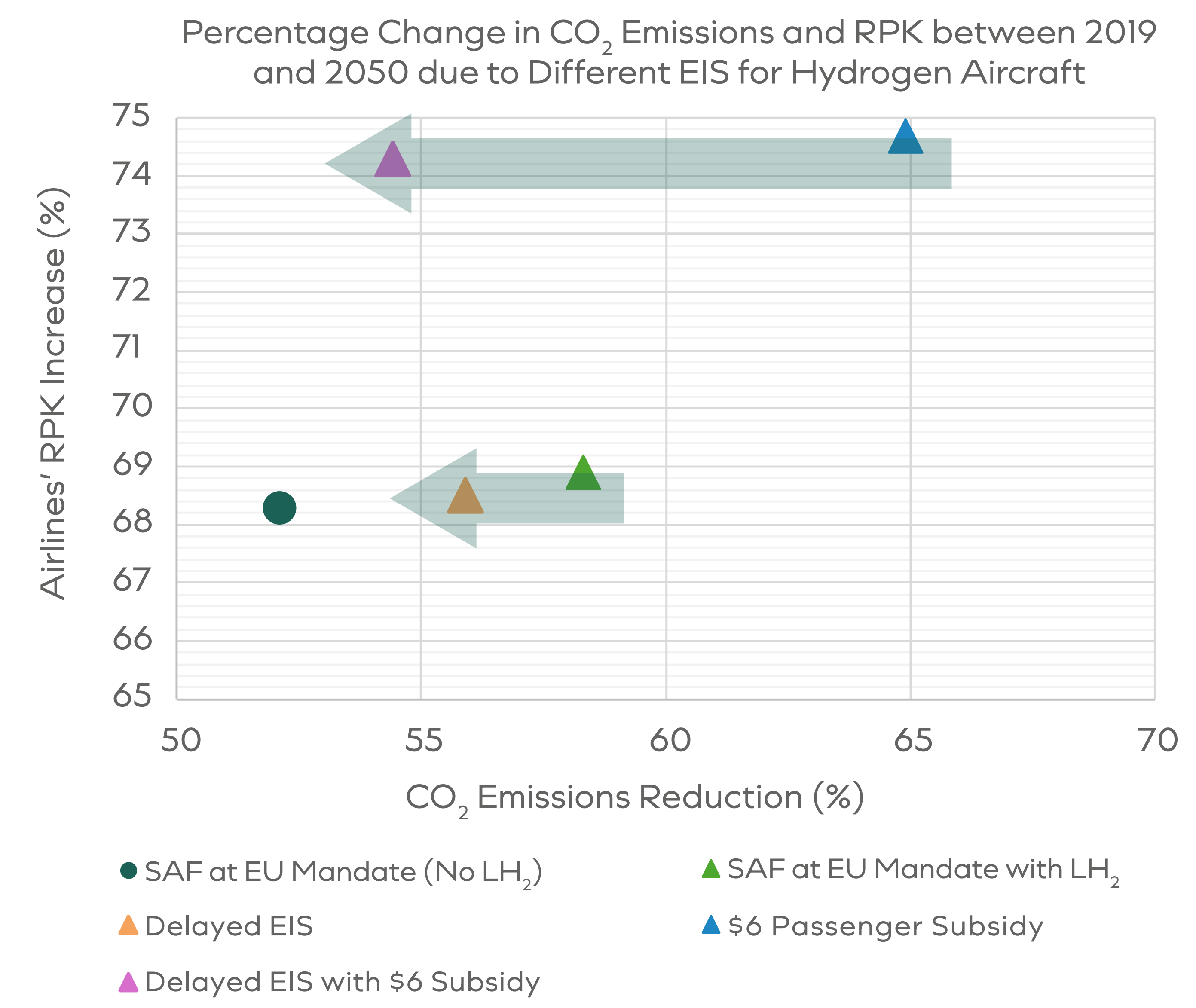
Hydrogen at all Airports

20 Hydrogen Hubs



4. The earlier novel technologies, such as hydrogen, can be introduced, the more opportunity they present for CO_2 reductions.

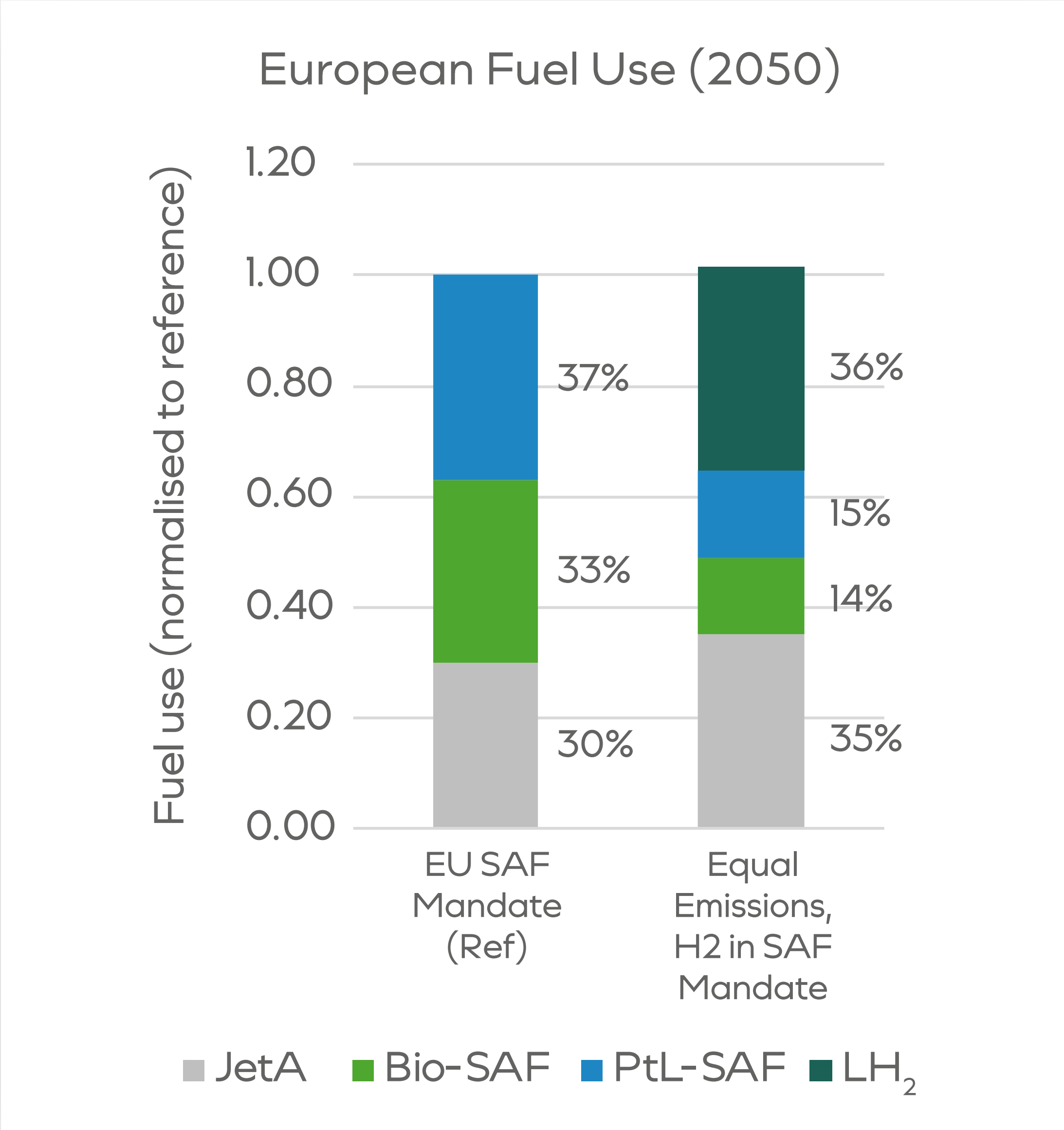
- In the model, shifting the entry into service (EIS) of a hydrogen narrowbody from 2035 to 2040 will lead to an increase in annual CO_2 emissions of 1 Mt by 2050, the equivalent of 2.5% of 2019 aviation emissions.



» Key Findings

5. Direct hydrogen uptake is stimulated when airlines can use hydrogen for part fulfilment of SAF mandates.

- In the current EU mandate, hydrogen as a direct fuel is referenced but the manner of its inclusion is not specified.
- The trade-off between the lower cost and emissions of hydrogen and the availability and performance of kerosene aircraft leads to a mixed fuel uptake with a higher hydrogen proportion, lower energy requirements[8] [9] and reduced costs.



If hydrogen can contribute to the SAF mandate:

~7%
increase in 2050 airline gross profit

~14%
reduction in 2050 electrical energy usage

Outlook

Decarbonising aviation will incur significant costs. However, there are substantial risks and potential costs associated with doing nothing. As such, the industry requires multiple solutions and pathways to reduce its environmental impact while sustaining growth, in order to maintain the economic prosperity and social benefits aviation brings to so many.

Hydrogen as an aviation fuel is promising but the nature of the technology means it requires new infrastructure and aircraft; hence its initial impact will likely be lower than a drop-in fuel. However, in principle, hydrogen's ability to enable emission reductions and industry growth simultaneously, while only requiring targeted airport infrastructure, make it a capable future fuel for European aviation.

While the results presented here focus on 2050—when SAF could have played a major role for several decades and hydrogen's potential contribution is more limited—this should not be taken as an indicator of hydrogen's ultimate potential. Beyond 2050, hydrogen may well emerge as an important solution for aviation decarbonisation.

This project analysed a range of illustrative potential scenarios, the outcomes of which highlight that hydrogen could have a vital role – alongside SAF and other solutions – in decarbonising a growing sector to preserve the benefits of flying for future generations.

Sponsors

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Technical Appendix

A.1 ABM Reference

The airline behaviour model is adapted from an earlier version that was applied to Australia, which has been improved for application to the European market. For further details on the original model see Doyme et al.[10]

A.2 Fuel Price Data

Fuel price data used in the baseline run of the ABM. The underlying data has been sourced from the IEA (5): Crude Oil Price, CO_2 Price, Synthetic Aviation Fuel Price and Gaseous Hydrogen Price. To convert between Crude Oil and Kerosene price, a conversion factor based on today's relative fuel prices has been used[11 12]. The minimum SAF blend has been sourced from the ReFuelEU Mandate[13 6]. The gaseous hydrogen price from the IEA has been converted into a liquid hydrogen price using liquefaction cost estimates from Dray et al[14].

	Model Input	2019	2030	2040	2050
Jet Fuel	Jet Fuel Price (USD/tonne)	720	350	280	240
	CO_2 price (USD/tonne CO_2)	0	130	205	250
	Total (USD/tonne)	720	760	930	1,030
	Total (USD/bbl)	93	98	119	133
SAF	SAF price (USD/tonne)	0	2,090	1,870	1,650
	SAF price (USD/bbl)	-	269	241	212
	Minimum SAF blend (%)	0	6	34	70
LH_2	LH_2 price (USD/tonne)	-	4,500	3.700	3,300
	Energy equivalent (USD/tonne)	-	1,620	1,330	1,190

A.3 Current Aircraft Fleet Data

There are nine main classes/types of conventional aircraft within the ABM, which each airline can choose to use anywhere in their network, subject to airport and fleet constraints. The aircraft classes are based on seat numbers, with the smallest class representing regional turboprops, the largest class comprising 747 and A380 aircraft, and 4 classes corresponding to the single aisle aircraft sizes most used within Europe. Non-fuel operating costs were primarily derived from US Department of Transportation Form 41 data[15], scaled if necessary to ensure that it matched with company reports (e.g. [16 17]). Fuel burn for each of the aircraft classes was estimated using Piano-X software[18]. Airport landing charges, passenger fees and enroute charges were obtained from the RDC database[19]. These feed into the passenger cost and flight operating cost which form part of the objective function. The fleet of aircraft available to each airline was determined using the FlightGlobal fleet database[3] together with Europe specific operations data from SABRE[4].

A.4 Hydrogen Aircraft Performance

The aircraft was designed to best replicate the performance of the A320neo family while taking account of the impacts on aircraft capability from the properties of hydrogen. The hydrogen concept was sized such that it could transport 240 passengers, similar to the A321neo, up to 800 NM while retaining the ability to transport an A320neo payload of 186 passengers up to a distance of 2,800 NM.

A.5 Hydrogen Aircraft Operating Costs

An approach from a paper by J. Hoelzen et al[20] was used. It takes historical data to build up empirical models for how the aircraft maintenance and capital expenditure change due to the introduction of new technologies. This approach estimates a 12% increase in operating cost due to CAPEX and an 11% increase due to aircraft maintenance, resulting in a 4% increase in total direct operating costs overall.

A.6 Hydrogen Aircraft Production Rates

To correctly constrain the Airline Behaviour Model, a maximum allowable delivery rate for the hydrogen concept aircraft needs to be imposed after its assumed 2035 Entry into Service (EIS) date, a date aligned to the Airbus ZEROe position prior to February 2025[7]. The rate selected is based on an average of the first 15 years of deliveries for Boeing 737 and Airbus A320 family aircraft, with the data sourced from Cirium[21].

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