Report

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Aviation: technologies and fuels to support climate ambitions towards 2050

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CONTENTS

GLOSSARY

ADS-B Automatic Dependent Surveillance – Broadcast

AIM Aviation integrated model

ANSP Air navigation service provider

APR Aqueous phase reforming

APU Auxiliary power unit

AR Aspect ratio

ATC Air traffic control

ATM Air traffic management

BPR Bypass ratio

BWB Blended wing body

CAGR Compound annual growth rate

CCO Continuous climb operations

CCUS Carbon capture, utilisation and storage

CDO Continuous descent operations

CFRP Carbon fibre reinforced polymers

CM Commissioning and ramp-up

CMC Ceramic matrix composites

CO Construction

CO_2e Carbon Dioxide equivalent

CORSIA Carbon offsetting and reduction scheme for international aviation

DAC Direct air capture

DOC Direct operating cost

EEA European economic area

EFTA European free trade area

EIS Entry into service

EJ Exajoule

ETJ Ethanol-to-jet

ETS Emissions trading scheme

FAME Fatty acid methyl ester

FT Fischer-Tropsch

GDP Gross domestic product

GGR Greenhouse gas removal

GHG Greenhouse gas

GPS Global positioning system

GTP Global temperature potential

GWP Global warming potential

HEFA Hydroprocessed esters and fatty acids

HLF Hybrid laminar flow

HTL Hydrothermal liquefaction

HVO Hydrotreated vegetable oil

IATA International Air Transport Association (the trade association for the world's airlines)

ICAO International Civil Aviation Organisation (the UN body responsible for aviation)

ILUC Indirect land use change

LCAF Lower carbon aviation fuel

LCFS Low carbon fuel standard

LCOE Levelized cost of energy

L/D Lift-to-drag ratio

LFC Laminar flow control

LH2 Liquid hydrogen

LNG Liquefied natural gas

LPG Liquefied petroleum gas

LRC Long-range cruise Mach number

LTAG Long-term aspirational goal

MRC Maximum-range cruise Mach number

MSW Municipal solid waste

MTJ Methanol-to-jet

MTOW Maximum take-off weight

NLF Natural laminar flow

nm Nautical miles

NOx Nitrogen oxides (NO and NO_2)

OEM Original equipment manufacturer

OWE Operating weight empty

PD Project development and financing

PEM Polymer electrolyte membrane (electrolysis)

PM Particulate matter

PPS Powerplant system

PTL Power-to-liquid (synthetic kerosene produced using electricity and CO_2)

PV Photovoltaic

RCF Recycled carbon fuels

RED Renewable energy directive

RES-T Renewable energy share in transport

RFNBO Renewable fuel of non-biological origin

RFS Renewable fuel standard

RJ Regional jet

RMS Root mean squares

RPK Revenue passenger-kilometre

RVSM Reduced vertical separation minimum

SA Single aisle

SAF Sustainable Aviation Fuel

SAR Specific air range

SFC Engine specific fuel consumption

SOx Sulphur oxides

SPK Synthetic paraffinic kerosene

SSP Shared Socioeconomic Pathways (IPCC scenarios of socioeconomic global changes up to 2100)

TA Twin aisle

TKM Tonne-kilometre

TRL Technology readiness level

UCO Used cooking oil

UHBR Ultra high bypass ratio

UN United Nations

USD US dollars

VLA Very large aircraft

EXECUTIVE SUMMARY

The climate ambition of the Paris Agreement sets long-term goals to substantially reduce global greenhouse gas (GHG) emissions to limit the global temperature increase in this century to 2 degrees Celsius while pursuing efforts to limit the increase even further to 1.5 degrees. It requires achieving net-zero GHG emissions by 2050, which can only be met with a significant contribution from aviation. In response to this ambition and changes in customer demand, individual airlines have started to set net-zero GHG emissions goals by 2050, as have global aviation bodies such as IATA and ICAO (IATA, 2022; ICAO, 2022). Achieving net-zero emissions requires a radical transformation of the entire aviation sector, affecting each main source of GHG emissions.

This study addresses what such a transformation could look like. It is based on a transparent analysis of the fuels and technology pathways available for aviation to reduce its GHG emissions and integrated modelling of overall system outcomes when these fuels and technologies are adopted, including a bottom-up analysis of the implications for the fuels/refining industry.

Technological improvements to aircraft alone will not be sufficient to reduce the aviation sector’s GHG emissions due to anticipated increases in demand. Without significant changes in attitudes towards flying, demand growth will continue to be correlated with global income growth. Bio-based kerosene can substantially contribute to aviation fuel decarbonisation, but supplying the aviation industry with 100% sustainable aviation fuel (SAF) would require vast quantities of biomass feedstock, and it is uncertain whether feedstock supply can match aviation demand (see **Figure 1,** below). Additional constraints exist for some biomass pathways around sustainability criteria and land availability. Therefore, decarbonizing the aviation sector will likely strongly depend on other technologies such as Power-To-Liquid (**PTL**), which require an abundance of renewable power.

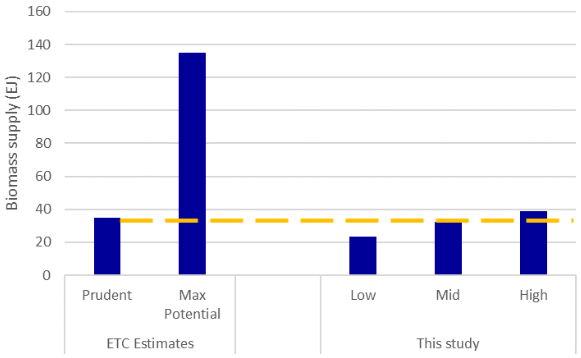

Figure 1 Comparison of modelled biomass supply scenarios against ETC estimates of feedstock potential (ETC, 2020)

Under the high scenarios[1] developed for this study, PTL kerosene makes up between 54-63% of total fuel supply in 2050, in scenarios where hydrogen aircraft are available and scenarios which rely on drop-in fuels respectively (**Figure 2**). The results of this study indicate that 5.4-32.4 EJ (1,500-9,000 TWh) of electricity is required across the full range of scenarios modelled (A through to F). In the high scenarios, this is greater than total global renewable electricity generation in 2020 (~7,500 TWh from 2,700 GW installed capacity; IEA, 2020a & IRENA, 2021). This would require substantial additional renewable electricity production above what is required to decarbonise other parts of the economy. Even meeting the level of ambition in the low scenario, which still requires 63% SAF by 2050 in the total fuel mix, would require a dramatic increase in uptake, and the contribution of multiple SAF production pathways. Today, SAF accounts for only approximately 0.01% of total jet fuel consumption and is almost exclusively hydroprocessed esters and fatty acids, or HEFA (WEF, 2022). Therefore, policy support will be required in order to sufficiently accelerate development.

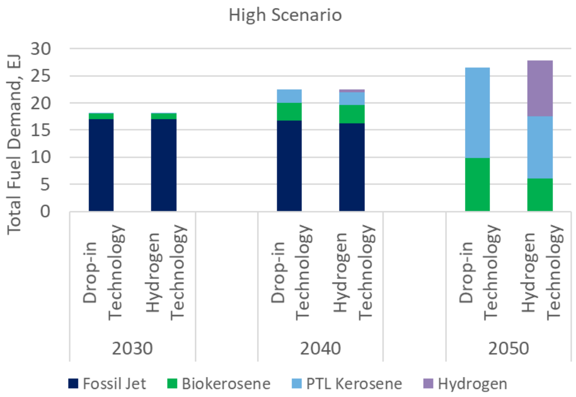

Figure 2 Total fuel demand (energy basis) in the high scenarios

Another important element of aviation decarbonisation is the necessity for a very substantial and rapid infrastructure roll-out in order to put in place the required SAF supply. For aviation alternative fuel production, over 6000 plants (worldwide) by 2050 are needed in the high scenario. The reason for the large quantities of plants required is that biofuel and PTL production facilities operate at smaller scales

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[1] **Scenarios**: Each scenario consists of a combination of a technology roll-out case, a demand case including policy characteristics, and a fuel supply case, which are together used to project the amount and composition of the global aviation fuel supply in future years.
High scenarios: These scenarios assume high demand growth driven by high income growth, low oil prices, and limited long-term impact of the COVID-19 pandemic (see chapter 4 and **Table 4** for more details on scenarios). They also assume a high level of policy ambition on aviation decarbonisation. These conditions lead to a particularly large demand for alternative aviation fuels.
Low scenarios: These scenarios assume low demand growth driven by low-income growth, high oil prices, and changes in attitudes to aviation. They assume a lower (though still significant) level of policy ambition on aviation decarbonisation. These conditions lead to a more moderate demand for alternative aviation fuels.
Hydrogen and drop-in scenarios: for each demand scenario, we look at aviation decarbonisation both via drop-in fuels alone and via a combination of drop-in fuels and hydrogen aircraft.

than fossil refineries; biofuel plant scale is limited by the feedstock sourcing radius and complex feedstock supply chains which can be costly.

In the case that hydrogen aircraft are used in addition to drop-in fuels, this will place additional strain on airport infrastructure, due to the need for new on-site hydrogen storage or pipelines, and changes to existing infrastructure to cope with the extreme cold temperatures of liquid hydrogen, and other hazards. Depending on the time of first availability of different sizes of hydrogen aircraft, the total hydrogen aircraft uptake into the fleet could be limited to only approximately one-third of the global fleet by 2050. This is a consequence of the long lifetimes of existing aircraft, and applies even if new hydrogen-fuelled aircraft are cost-competitive with new kerosene fuelled ones.

The projected whole aviation system net CO_2[2] emissions using the scenarios and technology packages defined in this study are shown in **Figure 3**, below. These suggest significant CO_2 emission reductions are possible, but it will be very challenging for the aviation sector to achieve net zero ambitions without relying on additional market-based-measures, e.g., offsets, or greenhouse gas removal (GGR) technologies, e.g. using carbon capture and storage on the SAF production plants. This is because, although the combustion CO_2 emissions of SAF are considered to be zero, there are still emissions associated with the production of SAF. In 2050 the weighted average GHG intensity of SAF lies in the range 4-7 gCO_2e/MJ based on this analysis. The weighted average is lower in the high supply scenario due to the increased penetration of PTL kerosene which has emissions of only 1 gCO_2e/MJ when produced from renewable power.

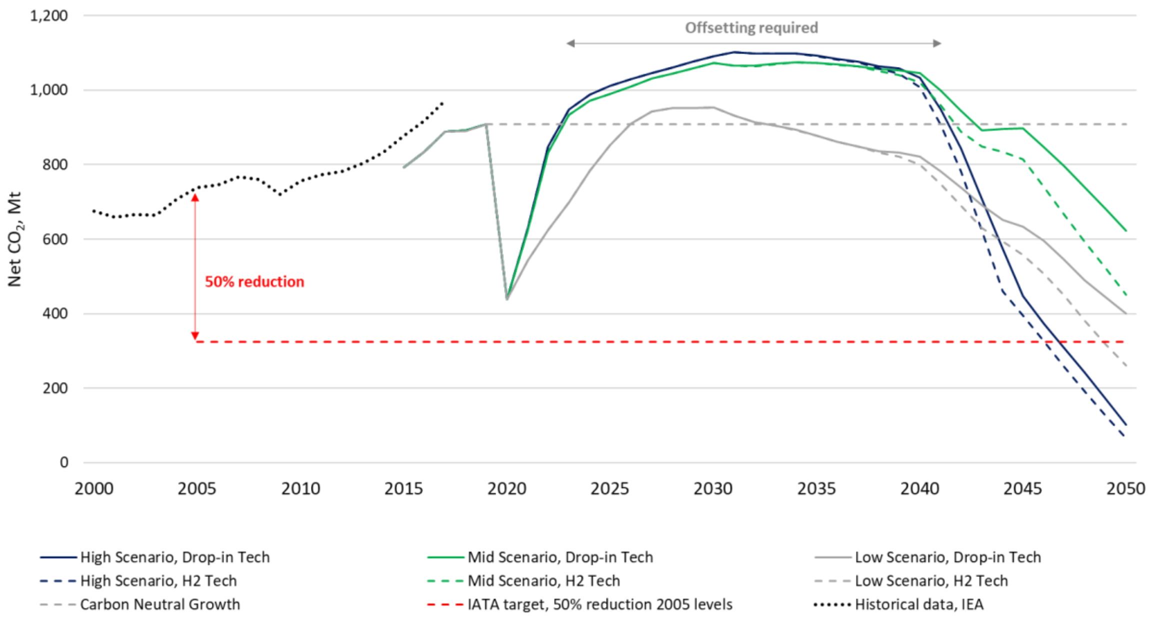

Figure 3 Net CO_2 emissions from the aviation sector. Note, IEA's data includes military flights, which are excluded from this analysis

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[2] refers to CO_2e, covering CO_2, N_2O and CH_4 in line with the UN's definition of GHGs, and does not include non-CO_2 aviation emission impacts at altitude (e.g. NOx, contrails, etc).

Our analysis highlights that the sector cannot rely on a single solution, and a range of measures, including aircraft developments, Air Traffic Management (ATM) and operational improvements, and alternative fuels from multiple pathways, especially SAF and hydrogen, will be required to approach global decarbonisation ambitions. Our projections suggest that approximately one-third to half of CO_2 emissions reductions in the sector under scenarios with significant decarbonisation can be achieved by improved energy efficiency of the air transportation system (via new aircraft models and improvements in operational efficiency). Demand reduction from the increased costs of using alternative fuels can contribute up to 20% of emissions reductions, with the remaining 50+% of emissions reductions arising directly from SAF and/or hydrogen use. Although aircraft fuel efficiency improvements will likely happen without policy support, given the likely increased costs of using SAF and hydrogen over fossil kerosene, policy support will likely be needed for significant alternative fuel uptake.

Significant decarbonisation in the aviation sector is possible. However, to achieve this goal it is crucial to have firm and effective long-term policy in place soon, to give the industry proper direction and to signal that the necessary policy drivers and support will be in place.

1. INTRODUCTION

In 2019, the aviation sector directly employed 11.3 million people worldwide. If also accounting for the associated indirect, induced, and catalytic jobs, aviation enabled a total of 87.7 million jobs, which translates into a gross world product of $3,500 billion (ATAG, 2020): equivalent to a national GDP level between that of the UK and Germany. Yet, aviation is more than can be expressed by sober economic statistics. It is a lifeline for countries that almost entirely depend upon tourism, an enabler of international trade, and an icon of technological progress, globalisation, and prosperity.

However, in order to generate these benefits, in 2019, the global aviation industry consumed around 363 billion litres of jet fuel and was responsible for 914 $MtCO_2$ in direct emissions (IATA, 2020). Passenger aviation, including aircraft carrying belly freight, accounted for 92% of these emissions, with the remaining 8% being attributable to freighter flights (ICCT, 2020). If future fuel use and emissions growth is only half the historical (1980-2019) rate of 2.8% per year, global aviation fuel demand and CO_2 emissions would increase by around 50% by 2050.

Such growth would be in stark contrast to what is needed to mitigate climate change. The Paris Agreement calls for limiting the rise in mean global temperature to well below 2°C above pre-industrial levels, and preferably limiting the increase to 1.5°C. This target requires achieving net-zero greenhouse gas emissions by 2050 which can only be achieved with a significant contribution from aviation. Already in 2009, IATA, the aviation industry's trade body, set a sector target of reducing CO_2 emissions by 50% over 2005 levels by 2050, and has recently updated this ambition to net zero CO_2 by 2050 (IATA, 2022). In the meantime, individual airlines have started to set their own net-zero CO_2 emissions goals by 2050.

Whereas more modest reductions could continue to be realized by incremental improvements, as during the past five decades, such drastic abatement requires a radical transformation of the entire aviation sector, affecting each determinant of CO_2 emissions. This report illustrates how such strong reductions could be achieved, along with the implications for stakeholders of the aviation value chain, particularly the fuels industry.

A number of different analyses have been published in recent years that explore the opportunities and challenges of global aviation deep decarbonization. Other studies taking a global view include ATAG (2021) and Shell (2021). In addition, NLR (2021) took a European perspective, whereas Sustainable Aviation (2020) focussed on the UK. Common to all studies is the goal of complete sector decarbonization by 2050 and the understanding that there is no silver bullet for satisfying this objective; rather all factors affecting CO_2 emissions reduction need to be exploited, i.e., aircraft fuel efficiency improvements, advancements in air traffic control and aircraft operations, low-carbon aviation fuels, demand reductions as a result of introducing more expensive aviation fuels or as a consequence of carbon taxes, and offsets.

This study differs from others in several ways:

Transparent, integrated modelling of the global aviation system down to an individual flight itinerary level, considering regional differences and system feedbacks such as the (demand-related) rebound effect.

Transparent aircraft deployment pathways, considering emerging technologies and related time constants (**described in detail in the appendices to this report**), based on internally consistent assumptions:

- Detailed bottom-up analysis of sustainable aviation fuel production pathway capacities; and
- A focus on implications for the fuels/refining industry

This report is structured as follows. **Section 2** describes key aviation sector characteristics which are critical to understanding the challenges the industry faces when trying to strongly reduce CO_2 emissions. **Section 3** explores options for reducing CO_2 emissions, including aircraft technology-related efficiency improvements and alternative aviation fuels. **Section 4** introduces the modelling methodology for a global aviation systems model (AIM), which is used to project what would be required to achieve future aviation CO_2 emissions targets under a range of scenarios, and the characteristics of the technologies and fuels that are used as modelling inputs. Modelling outcomes are presented in **Section 5** discussed in **Section 6**, and a summary of conclusions is given in **Section 7**.

Additional supporting material for this study, discussing modelling assumptions in more detail and providing additional results, is also available in **the report appendices**.

2. KEY AVIATION SECTOR CHARACTERISTICS

2.1. STRONG DEMAND GROWTH

Models of human spatial interaction behaviour follow the principle of Newton's law of universal gravitation. Namely that the attractive force between two masses is determined by the product of the masses, the squared distance between them, and a parameter (the gravitational constant). In analogy, the amount of intercity travel between two urban areas depends mainly on the size of the city populations, the income levels, the airfare, and the respective elasticities. Based upon the change in these variables and the size of the elasticities, it can be readily determined that historical aviation growth was a result mainly of income growth, followed by declining airfares and then the growing population.

Using similar "gravity" models, **Figure 4** illustrates the projected growth in revenue passenger-km aggregated to the world total along with the observed revenue passenger-km travelled (RPK). Starting with Airbus and Boeing market projections in the late 1980s, air transportation demand was predicted to grow, and has grown, at a rate of around 5% per year, a doubling every 15 years. Projections by aircraft manufacturers and ICAO anticipated a continuation of that trend at almost the same growth rate, but the emergence of the COVID-19 pandemic in 2020 resulted in a drop of global RPK by two-thirds relative to the 2019 level. Most recent Airbus and Boeing market forecasts anticipate only slightly reduced 2040 RPK levels compared to the pre-COVID-19 projections (blue symbols in **Figure 4**).

Figure 4 also depicts this study's range of demand scenarios, which span a larger range compared to demand scenarios underlying the Waypoint 2050 study (ATAG, 2020) and that of the Shell (2021) study. This study's demand scenarios are discussed in more detail in **Section 4.3**; each utilises different global scenarios for income, population and energy prices, leading to a High scenario which implies demand growth will return to pre-COVID-19 growth rates, a Mid scenario where growth rates are close to post-COVID-19 industry projections, and a Low scenario where growth rates diverge from historical trends. These differences are driven mainly by differences in income growth between the scenarios, which are derived from the IPCC Shared Socioeconomic Pathway (SSP) scenarios (O'Neill et al, 2013); for the Low scenario, demand growth is additionally assumed to decouple from income growth due to ongoing changes in attitudes to aviation.

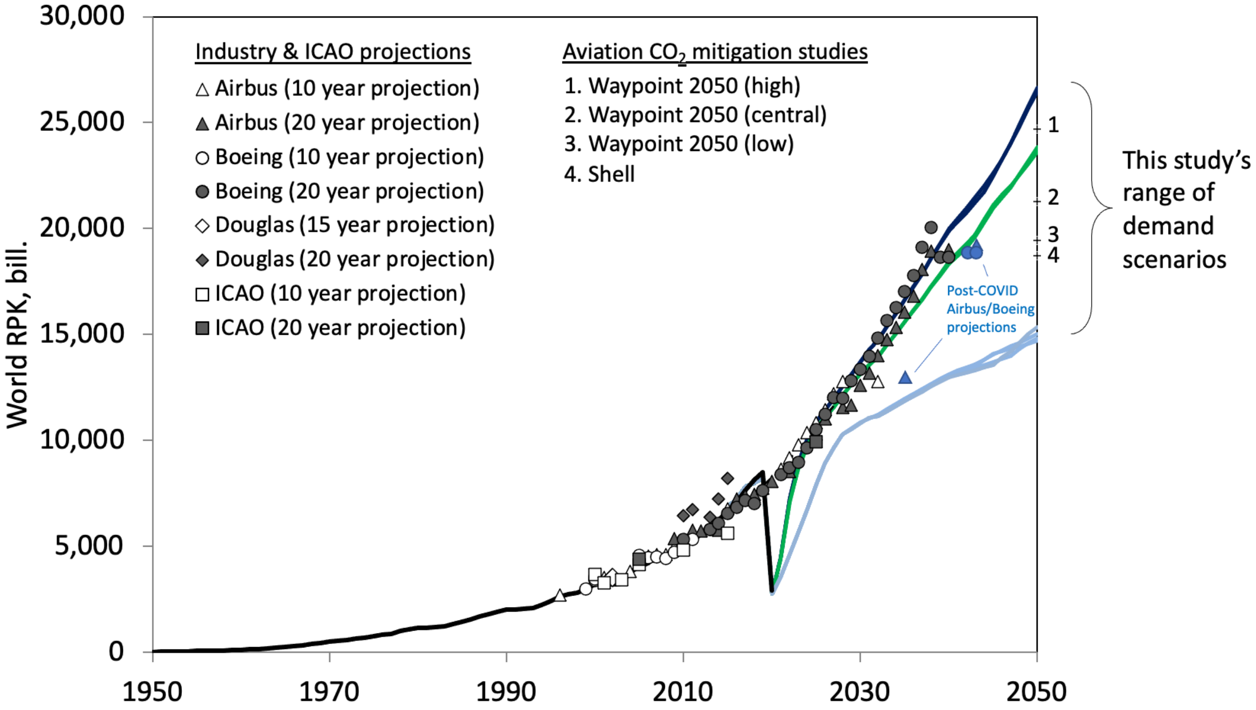

Figure 4 World revenue passenger-km travelled (RPK), observed (black continuous line) and projections by industry and ICAO (symbols) and this study (coloured continuous lines). Adapted from Schafer and Waitz (2014)

2.2. DEPENDENCY ON HIGH-DENSITY ENERGY SOURCES

Because any extra aircraft weight consumes additional fuel or—along with extra space—can generate revenue, aviation depends heavily on high energy-density fuels per unit weight and volume. This stringent requirement rules out many alternative fuels, such as alcohols, due to their much lower gravimetric and volumetric energy density compared to kerosene. Along the same line of reasoning, the currently very low energy density of batteries is not expected to reach the level required for narrow-body aircraft to cover meaningful stage lengths by mid-century. Hence, this study does not consider all-electric aircraft: instead, the focus of the study is on drop-in SAF and liquid hydrogen as alternative aviation fuels (see **Appendix 1**).

2.3. LONG TIME CONSTANTS

When deciding whether to purchase new aircraft, airlines compare the business case of new aircraft designs to a continued use of their existing fleet that may already be fully depreciated. Other factors that airlines consider include the uncertainty in how the new aircraft will perform in commercial service, and potential extra expenditures for crew training and changes in maintenance procedures when rolling out new aircraft types. This implies that airlines are typically interested only in aircraft that offer significant reductions in operating costs compared to those vehicles already in their fleet.

Aircraft manufacturers manage production risk by responding to these airline demands. It can take many years for the upfront development costs to be recovered after a new aircraft enters the market, so aircraft programs are considered to be sustainable if they break even within the first decade of entry into service. Aircraft manufacturers thus bundle multiple enhanced technologies, which jointly provide a significant benefit compared to existing aircraft types. In addition to operating cost reductions, the composition of these bundles depends upon market needs and the likely moves by competitors. Because the technologies forming the bundle are identified at the concept level and then further developed into prototypes, tested and demonstrated, the associated innovation process is lengthy. Developing a new aircraft is thus a long process (10-20 year) and a capital-intensive ($20-30 billion) one. Considering the roughly 15 years development time for a new aircraft model, the reference aircraft (see **Appendix 2**) considered in this study with entry-into-service dates between 2011 and 2017 are likely to experience two successive generations, one in 2030-35 and another one in 2045-50 (see **Section 3.1**).

The long-time constants are not limited to aircraft development. The average operating lifetime of today's commercial aircraft – the timespan by which 50% of an aircraft cohort is scrapped – is about 30 years (Dray, 2013). This implies that around half of those aircraft introduced today will still be operating in 2050. Combined, these long-time constants mean that the time between identifying promising concept technology bundles and their significant market impact is around 40-50 years.

2.4. LOW AIRLINE PROFITABILITY

Over much of the history of commercial aviation, airlines have experienced low profitability. For example, between 2000 and 2020, US airlines experienced net losses in seven out of 21 –years (MIT Airline Data Project, 2022). The most drastic losses occurred in 2020 due to the drop in demand and operations as a result of the COVID-19 pandemic.

However, pandemics and other shocks are only one reason for the low sector profitability. Stiff competition by low-cost carriers on short-haul routes and especially by Persian Gulf-based state airlines on long-haul routes have depressed airfares in both segments. Moreover, in contrast to the competitive airline market, there is little competition in the upstream components of the aviation value chain—airports, air traffic control, and aircraft manufacturers (Economist, 2014).

The low profitability becomes a concern when airlines experience higher fuel costs, for example as a consequence of reducing CO_2 emissions. In 2019, the International Air Transport Association (IATA), the aviation industry's trade body, computed that the airline profit per passenger was $6.12 – not enough to buy a Big Mac in Switzerland (IATA, 2019). The operating cost structure implies that, all other things remaining equal, a 15% increase in fuel costs would completely wipe out these profits if not passed through onto ticket prices. As this study will show, the expected increase in fuel costs as a result of reducing CO_2 emissions could be significantly greater than 15% and lasting, thus potentially resulting in a restructuring of the airline market.

2.5. MARKET FORCES AS A DRIVER FOR FUEL EFFICIENCY IMPROVEMENTS

The introduction of jet engine aircraft during the 1950s allowed airlines to increase productivity (seat-km per hour) while – at the same time – reducing operating costs. The higher energy intensity and lower operating costs of jet engine aircraft resulted in an increase in the fuel cost share of direct operating costs from originally around 20% for piston engine aircraft to 25-30% for early jet engine aircraft (FAA, 1966). The two oil crises during the 1970s then led to a doubling of the fuel share of direct operating costs (Lee et al., 2001), which sparked further and continuous efforts to increase aircraft fuel efficiency.

Overall, the US aircraft fleet energy intensity has decreased from 5.6 MJ per RPK in 1969 to 1.4 MJ per RPK in 2019, a 75% reduction which translates into an average of 2.7% per year. As the lifecycle CO_2 intensity of jet fuel has historically remained largely unchanged, the depicted decline in aircraft fleet energy intensity corresponds to that in lifecycle CO_2 intensity.

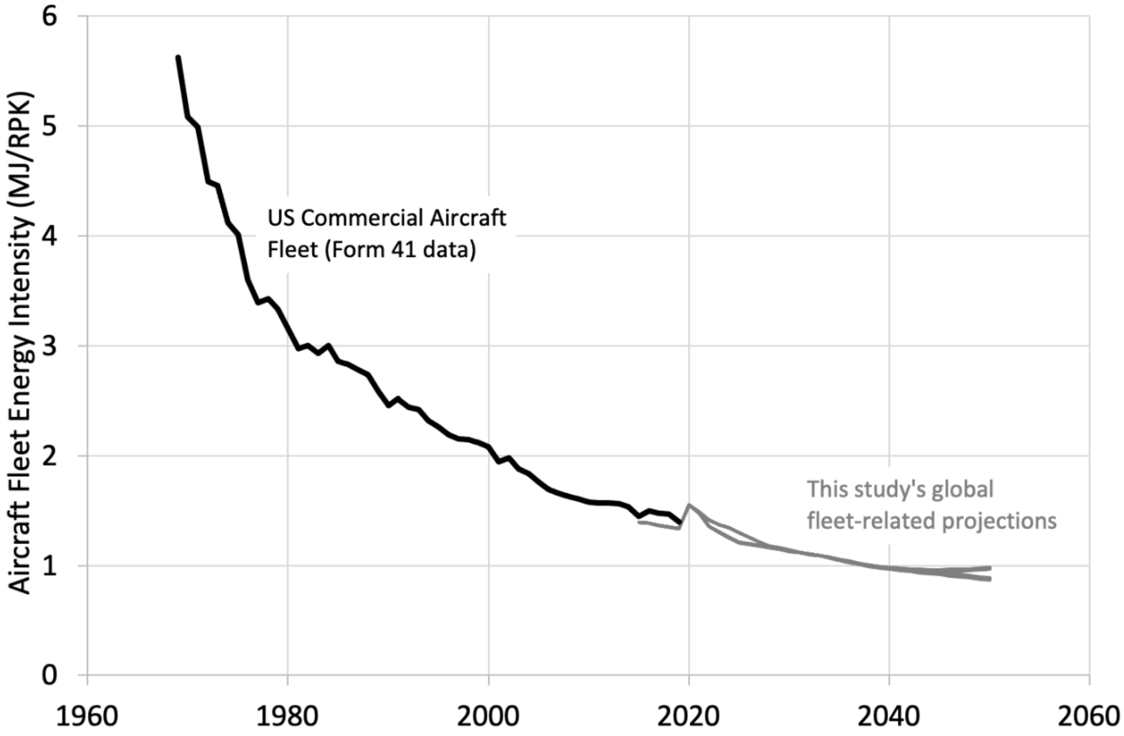

Figure 5 Historical trend in aircraft fleet energy intensity, US (1969-2019) and project world (2020-2050). Data source: Lee et al. (2001), US Form 41

The overall decline in **Figure 5** can be broken down into three stages. The first stage, lasting from 1969 to the early 1980s, was a result mainly of introducing more fuel-efficient turbofan engines that replaced the early turbojet engines. During that period, aircraft energy intensity declined at a rate of around 5% per year. The second stage, lasting from the early 1980s to around 2005, was a result of a number of factors, including incremental improvements in engine efficiency and reductions in aerodynamic drag and structural weight (Lee et al., 2001). In addition to incremental technology improvements, reductions in energy intensity during that period can also be attributed to the deregulation of the US air transportation sector, which allowed airlines to operate routes that are more profitable, partly due to high passenger load factors. The latter also contributed to a reduction in energy intensity. During that period, the energy intensity of the US aircraft fleet declined at about half the rate of the first period, that is, around 2.5% per year. The final period, starting at around 2005, was also determined by incremental improvements of all three determinants of aircraft energy intensity. It experienced the lowest reduction in aircraft energy intensity, that is, around 1.3% per year, or half the rate of the second period. It is apparent that the change in energy intensity reduction has declined over time, as the low-hanging fruit have been harvested and design trade-offs become more apparent.

Figure 5 also depicts this study's projected future levels of energy intensity of the global aircraft fleet through 2050. For all demand scenarios, energy intensity increases during the COVID-19 pandemic period due to reductions in load factor, with the time extent of this increase depending on the assumed extent of pandemic-related disruption. After 2040, two distinct trajectories can be identified; for scenarios with hydrogen aircraft, smaller reductions in energy intensity are projected than for scenarios with only kerosene aircraft because the additional weight associated with hydrogen tanks makes hydrogen aircraft flights less energy-efficient. However, this additional energy use has limited associated CO_2 emissions, because liquid hydrogen is assumed to be produced with renewable power (see **Section 3.2**). Compared to hypothetical scenarios with a similar level of demand but with energy intensity held constant at base year values, by 2050 we would anticipate around a 30-35% reduction in aviation energy use from energy efficiency improvements.

2.6. NON-CO_2 EFFECTS AT ALTITUDE

Burning 1 kg of jet fuel generates around 3,160 grams of CO_2, 1,290 grams of water vapour, 15 grams of nitrogen oxides (NOx), 1.2 grams of sulphur oxides (SOx), less than 0.6 grams of carbon monoxide (CO), less than 0.01 grams of unburned hydrocarbons, and 0.028 grams of particulate matter (Dickson, 2014; Stettler et al., 2013; Skowron et al., 2021).

Due to their abundance and long lifetime in the atmosphere, CO_2 emissions are the most important aviation greenhouse gas (GHG). However, other climate effects of aviation exist, mainly because of the effect of NOx (which reduces atmospheric methane but produces ozone) and of linear-shaped contrails that can transition to cirrus clouds (Lee et al., 2021). Due to their uncertainty, these combustion-related non-CO_2 climate effects are not considered in this study. However, we do account for non-CO_2 greenhouse gas emissions in the fuel production stage (i.e. N_2O and CH_4, in line with the UN definition of GHGs).

Beyond offering reduced CO_2 emissions, the sustainable aviation fuels discussed in **Section 3** have the potential of reducing aviation's non-CO_2 emissions. The full extent of non-CO_2 impacts of SAF is an area of ongoing research and currently remains inconclusive, especially in relation to NOx and contrails. Biomass feedstocks typically have a very low sulphur content, which lowers the sulphur content in the final blended fuel and thus reduces SOx emissions compared to fossil-only jet fuel. In addition, particulate matter emissions could be reduced due to the reduced aromatic content of SAF (EC, 2020; de Jong, 2017). Both reduced SOx and PM emissions during take-off and landing can also improve local air quality (ICAO, 2016). For hydrogen aircraft, there are no combustion-related CO_2 emissions, but non-CO_2 impacts are uncertain. NOx emissions will be determined by future hydrogen aircraft engine designs, but could be lower than for kerosene aircraft. A wide range of potential contrail impacts is projected in the literature, from greater than to less than those of an equivalent kerosene aircraft (e.g., Grewe et al., 2017).

2.7. POLICY

Aviation emissions are already targeted by national, regional, and global policy. The largest-scale current policies are ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and aviation's inclusion in Emissions Trading Schemes (ETS) including the EU ETS, UK ETS and Swiss ETS. These schemes primarily reduce net aviation emissions via airline purchases of allowances and/or offsets which are used to reduce emissions in other sectors. CORSIA applies to emissions of international flights between participating countries relative to a baseline currently set using year-2019 emissions (e.g., ICAO, 2019b; ICAO, 2022b). For 2021, global international aviation CO_2 was below the CORSIA baseline, leading to no CORSIA offset obligations, but this might change as demand recovery proceeds. ICAO also sets a carbon standard for new aircraft, but at its current level this is not anticipated to stimulate significant changes in aircraft design (ICCT, 2016).

To address aviation fuel CO_2 intensity, blending mandates for aviation SAF have also been proposed . These include RefuelEU (EC, 2021) and a UK SAF mandate (DfT, 2021). RefuelEU initially proposed a 63% SAF blend by 2050[1] for EEA departing flights and has subsequently (July 2022) increased this target to 85%, while the UK mandate, which is at an earlier stage of development, specifies up to 75% use in UK departing flights by 2050. There are already some national SAF mandates in place in countries including France (since 2021) and Norway (since 2020). Other policies promote SAF use via a reduction in carbon costs when using SAF (UK ETS, EU ETS, CORSIA) or via credits associated with SAF use (e.g., SAF has opt-in status in the US Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS)). However, the EU ETS, Swiss ETS and UK ETS collectively only apply to flights within the EEA/EFTA region (e.g. EC, 2013), within the UK, and between the EEA/EFTA region and the UK, accounting for less than 10% of global aviation CO_2 emissions.

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[1] Note that SAF blends above 50% assume that current blend certification limits can be relaxed, either via fuel additives or changes in aircraft fuel systems (Zschocke et al., 2012). Some of the scenarios examined in this report are based on the initial RefuelEU proposal of 63% SAF blends by 2050.

3. TECHNOLOGIES AND FUELS CONSIDERED

3.1. AIRCRAFT TECHNOLOGIES, ATM AND OPERATIONAL STRATEGIES

Three key factors affect aircraft range and energy use and are captured in the Breguet range equation (**Appendix 2**): the aircraft lift-to-drag ratio or aerodynamic efficiency; engine specific fuel consumption or the amount of fuel burnt per unit of thrust; and the empty weight of the aircraft. The higher the lift-to-drag ratio, the lower the engine specific fuel consumption, and the lower the empty weight of the aircraft, the lower the aircraft energy intensity. Using an extended version of the Breguet range equation, which also accounts for contingency fuel and diversion fuel requirements, the fuel burn improvements of 24 strategies were assessed based on the options below.

The menu of options for reducing aircraft fuel burn consists of (i) airframe-related technologies, which directly address the lift-to-drag ratio, aircraft drag, or aircraft empty weight, (ii) engine-related technologies, which aim at increasing engine efficiency, (iii) fuel-related technologies that reduce aircraft CO_2 emissions directly, (iv) air traffic management related technologies that improve flight procedures, and (v) operational technologies and techniques, i.e., measures that the airlines themselves can apply when operating their fleet in the air and on the ground. A list of all examined strategies, the projected entry into service (EIS) date, and more detailed descriptions are summarised in **Table 1**. The EIS data is based upon literature studies and expert judgement.

Table 1 Aircraft fuel burn and CO_2 mitigation strategies examined in this study[2]

Strategies	EIS date	Comment
Airframe related technologies		
1 Reduced design cruise Mach no. by 0.06	2045	All commercial aircraft types
2 High aspect (AR) ratio wings	2030	All commercial aircraft types
3 Ultra-high AR strutted wings	2040	Reductions in wing sweep enable this design only for slower, i.e., regional and short-haul aircraft
4 Natural and hybrid laminar flow	/	Technology does not operate robustly with real-world manufacturing processes and flight ops
5 Flying wing or blended wing body (BWB)	2040	Wing size dictates cabin height and limits design to medium and long-haul aircraft
6 Composite materials	Now	All commercial aircraft types. Further benefits possible as composites are used more broadly and composite-specific design processes evolve.
Engine-related technologies		
7 Ultra-high bypass ratio (UHBR) turbofan	2030	Already under development
8 Open rotor	/	Significant technical challenges and limited fuel burn benefits over UHBR
Fuel-related technologies		
9 Hybrid electric propulsion	/	Required decline in propulsion system weight unlikely before 2050
10 All electric propulsion	/	Required decline in propulsion system weight unlikely before 2050

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[2] See **Appendix 2** for more details

11 Sustainable drop-in fuels	Now	Already under development
12 Hydrogen propulsion	2035	Technically viable
13 Liquefied natural gas (LNG) propulsion	/	Technically viable but not considered due to low availability of biogas feedstock
14 Fuel cells as APU replacement	/	Weight penalty increases fuel burn; other ground-based options available
Air trafic management technologies		
15 Reduced taxi time	Now	Progressive improvements in taxi time offsets delay due to traffic growth
16 Cruise climb	/	Negligible benefit
17 Continuous Climb & Descent	Now	
18 Optimum track	2030	
19 Reduced contingency fuel	Now	Already in use
20 Reduced diversion hold	2025	Will require regulatory approval
Operational strategies		
21 Formation flying	2025	
22 Long range cruise to max. range cruise speed / Mach no. reduction	/	Already in use
23 Engine inoperative taxi	/	Being superseded by E-tug
24 E-tug	Now	
25 E-taxi	/	Extra weight of motors increases fuel burn and offsets taxi fuel flow benefit

The benefit of the strategies in **Table 1** will depend upon the size of the aircraft and its operational characteristics, which are determined by the market within which it operates. As shown in **Table 2**, this study uses four reference aircraft to assess technology characteristics, jointly covering all major market segments. Aircraft with year 2000 technology form the basis of this classification. The 2015 aircraft types were modelled based upon available data about specific aircraft model performance and costs in each size class for this generation (e.g., Airbus A320neo; see **Appendix 2** of this study for tables of assumptions for these aircraft).

To respond to the airline requirements for new aircraft models to offer significant reductions in operating costs over their predecessors, the most promising technologies and operational strategies were bundled into packages, depending upon their technology readiness level, fuel burn / CO_2 reduction potential, suitability for specific aircraft size classes, and level of complementarity to each other. The combined fuel savings benefit was then determined using the root mean squares approach (see **Appendix 6**). The resulting fuel burn reduction over the year 2000 levels are also shown in **Table 2** for the next two future aircraft generations, 2030-2035 and 2045-50. The corresponding results for liquid hydrogen aircraft are shown in **Appendix 2** this report. For those aircraft, the change in fuel burn is more uncertain, as it depends on the on-board liquid hydrogen (LH2) storage characteristics, an area that has remained subject to research for commercial aircraft. At the same time, that metric is of secondary importance, given the objective of significantly reducing CO_2 emissions.

Table 2 Reference aircraft and projected fuel burn reductions over year 2000 performance

Market Segment	Representative aircraft for year 2000 (2015)	Seat Count	Avg. stage length (nm)	Approx. % of global aviation CO_2, 2015	% Fuel burn change over year 2000 technology, EIS 2030-35	% Fuel burn change over year 2000 technology, EIS 2045-50
Regional	E-190AR (E2-190)	98	500	7	-28.6	-35.5
Short haul	A320-200 (A320 NEO)	150	1,000	48	-30.4	-38.3
Medium haul	A330-300 (B787-9)	295	3,500	19	-23.6	-57.0
Long haul	B777-300ER (A350-1000)	368	4,500	26	-25.7	-52.5

Table notes: Details of which technology options were included in each market segment and generation are given in **Table 3**. Additional fuel burn reductions, which result from the chosen ATM and operational strategies in **Table 1**, are excluded. These range from 2.2% (long-haul) to 12.9% (regional) in 2020 to 7.0% (medium-haul) to 14.3% (regional) in 2040 (see **Appendix 2**). CO_2 percentages are calculated by representative aircraft size rather than distance.

The fuel burn reductions for the next (2030-2035) aircraft generation are similar across all aircraft types, as they build upon similar technologies. In contrast, the generation after next (2045-2050) rely on different technologies particularly between the two smaller and the two larger aircraft size classes, which leads to marked differences in fuel burn reduction. Whereas the E-190AR and A320 aircraft can be designed with a higher aspect ratio wing because of their relatively lower cruise speed, a flying wing layout would be impossible due to the limited wing depth that would not allow for a stand-up cabin. In contrast, the A330-300 and B777-300ER offer sufficient height for a stand-up cabin in the wing but are flying too fast for a very high aspect ratio wing. These results point to the importance of developing the flying wing technology to deliver high levels of fuel burn improvement suitable for long haul operations.

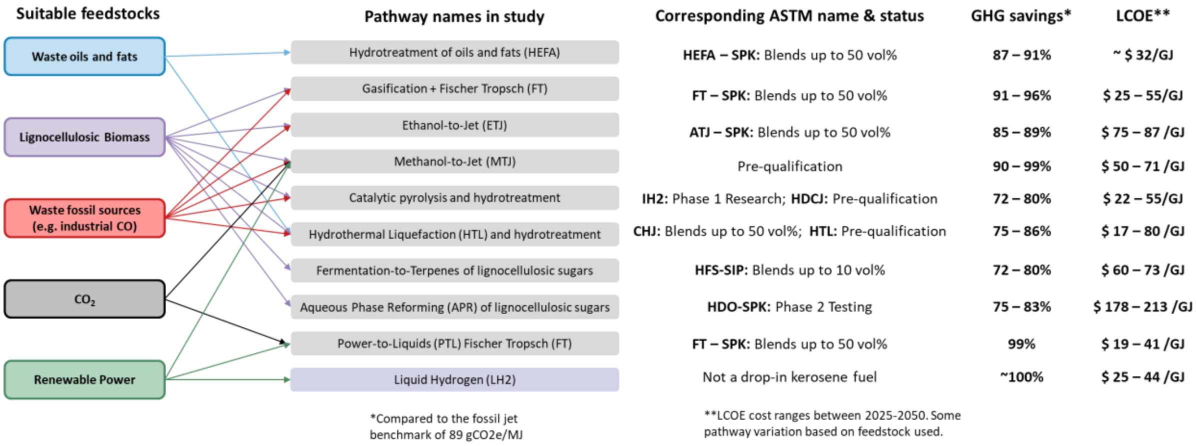
Compared to a hypothetical scenario where aviation energy intensity is frozen at base year values, we would expect energy efficiency improvements to result in 30-35% reductions in fuel use by 2050. Of this reduction, we would expect a roughly equal split in 2050 between fuel use reductions due to operational and air traffic management measures; fuel use reductions due to new aircraft models up to and including the current generation of aircraft; and fuel use reductions due to future generations of aircraft.

3.2. ALTERNATIVE AVIATION FUELS

There are several alternative aviation fuels that could be adopted to reduce aviation emissions associated with fuel-use. These can be categorised as drop-in liquid fuels and non-drop-in fuels. Drop-in fuels have similar properties to fossil jet fuel, meaning that no significant modifications to existing infrastructure, aircraft and engines are required. On the other hand, uptake of non-drop-in fuels will require significant modifications and investment.

Drop-in Sustainable Aviation Fuels (SAFs) are produced from renewable feedstocks, including biomass and renewable hydrogen, as well as recycled waste fossil carbon (if it leads to sufficient CO_2 emissions reduction), and have a similar composition and performance to that of fossil jet fuel. Whilst there is some variation in properties such as energy density, the potential impact of these differences has also been estimated (see the appendices to this report for details).

Currently, most SAF technology pathways are at an early stage of development, with HEFA the only commercialised route. Nonetheless, a number of routes are already certified under ASTM International's D7566 standard (D1655 for co-processed fuels), which are highlighted in **Figure 6**.



Pathway names in study	Corresponding ASTM name & status	GHG savings*	LCOE**
Hydrotreatment of oils and fats (HEFA)	**HEFA – SPK:** Blends up to 50 vol%	**87 – 91%**	**~ $ 32/GJ**
Gasification + Fischer Tropsch (FT)	**FT – SPK:** Blends up to 50 vol%	**91 – 96%**	**$ 25 – 55/GJ**
Ethanol-to-Jet (ETJ)	**ATJ – SPK:** Blends up to 50 vol%	**85 – 89%**	**$ 75 – 87 /GJ**
Methanol-to-Jet (MTJ)	Pre-qualification	**90 – 99%**	**$ 50 – 71 /GJ**
Catalytic pyrolysis and hydrotreatment	**IH2:** Phase 1 Research; **HDCJ:** Pre-qualification	**72 – 80%**	**$ 22 – 55/GJ**
Hydrothermal Liquefaction (HTL) and hydrotreatment	**CHJ:** Blends up to 50 vol%; **HTL:** Pre-qualification	**75 – 86%**	**$ 17 – 80 /GJ**
Fermentation-to-Terpenes of lignocellulosic sugars	**HFS-SIP:** Blends up to 10 vol%	**72 – 80%**	**$ 60 – 73 /GJ**
Aqueous Phase Reforming (APR) of lignocellulosic sugars	**HDO-SPK:** Phase 2 Testing	**75 – 83%**	**$ 178 – 213 /GJ**
Power-to-Liquids (PTL) Fischer Tropsch (FT)	**FT – SPK:** Blends up to 50 vol%	**99%**	**$ 19 – 41 /GJ**
Liquid Hydrogen (LH2)	Not a drop-in kerosene fuel	**~100%**	**$ 25 – 44 /GJ**

*Compared to the fossil jet benchmark of 89 gCO2e/MJ

**LCOE cost ranges between 2025-2050. Some pathway variation based on feedstock used.

Figure 6 Schematic of the alternative aviation fuels considered in this analysis. GHG savings are given relative to the CORSIA benchmark. LCOE represents production costs, in 2020 USD

The GHG savings shown in **Figure 6** are calculated based on literature values, which were selected to align as closely as possible to CORSIA GHG calculation methodology[3]. Under CORSIA, fuels can be credited or penalised with a land-use factor, which has not been considered in this analysis. However, feedstocks included in this study have been limited to those considered a waste or residue, in which case the land-use factor is zero. The level of GHG savings achievable is given as a range to account for differences in feedstock, as well as anticipated improvements between now and 2050, for example using low carbon hydrogen in place of fossil hydrogen for upgrading of fuels.

Figure 6 provides an estimate of the range of levelized costs of production for the different fuel routes between 2025 and 2050 (de Jong, 2015; ICCT, 2019; IEA 2020b). Due to the early stage of development of these routes, the production costs of alternative aviation fuels are much higher than fossil jet prices. Choice of feedstock has a sizable impact on the overall production cost of fuels. For example, municipal waste can provide plant operators with a zero-cost, or even negative cost, whilst other feedstocks such as Used Cooking Oil come at a much higher cost to the plant. Over time the production costs will decrease, owing to scale-up efficiencies and process improvements. Furthermore, routes which rely on renewable electricity – PTL FT, liquid hydrogen and e-Methanol-to-Jet – might see dramatic reduction in feedstock cost as the availability of low-cost renewable power increases. Nonetheless, some routes will remain expensive in 2050, and

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[3] Note, under this methodology embodied emissions are not included within the system boundary (for example, emissions associated with producing wind turbines). This means that GHG savings for renewable hydrogen can be considered 100%, **as long as** renewable electricity is used during electrolysis and liquefaction.

will likely require policies which support the uptake of alternative aviation fuels in order to effectively penetrate into the fuel mix.

Non-drop-in fuels

Several candidate fuels could, in theory, be used in clean-sheet new aircraft designs. These include LNG, electricity, and liquid hydrogen. All require significant redesign of aircraft and changes to existing infrastructure.

For LNG to be considered “low carbon” it would need to be derived from renewable sources: i.e., either upgraded from biogas or synthesised using renewable hydrogen. Both come at an efficiency and cost penalty compared to their direct uses, which is exacerbated by the need for liquefaction. While renewable methane is already being produced from biogas at scale, this has a pre-existing use in the shipping and heavy-duty vehicle sectors. As such, considering the cost of re-designing aircraft and powertrains, the adoption of LNG as an aviation fuel is highly unlikely.

Electrification of short-haul aircraft is at a nascent stage of development, and in 2019 the first small-scale, short distance commercial all-electric flights began. However, electrification of the aviation industry is highly unlikely for medium or long-haul flights in the next few decades, largely due to battery limitations. While this study acknowledges that there may be some opportunities for small, regional aircraft to adopt hybrid electric technology, it is unlikely to be realised in any significant volume by 2050, nor to impact most aviation emissions that are generated by the market segments which the analysis focuses on.

In contrast, there is scope for the use of liquid hydrogen as an aviation fuel, and it is feasible that liquid hydrogen aircraft could enter into service by 2035 (Airbus, 2021). Although significant infrastructure and aircraft modifications would be required, many industries are investigating hydrogen supply chains and technologies, which could accelerate development. Hydrogen production costs from renewable energy are projected to decrease from ~28-63 USD/GJ in 2019 to ~10-28 USD/GJ in 2050 (IEA, 2020c). Hydrogen can be produced with minimal emissions through the electrolysis of water using a renewable power source. This has several advantages over biofuel production pathways in terms of feedstock/energy potential and plant scales. Importantly, hydrogen combustion does not directly generate CO or CO_2 emissions, although there may be indirect climate effects due to the creation of cirrus clouds from contrails. In addition, although the combustion of hydrogen produces NOx, it is unclear to what extent relative to burning kerosene.

3.3. TECHNOLOGY PACKAGES

Following the assessment of aircraft-based fuel burn and CO_2 emissions mitigation strategies in **Section 3.1** and the analysis of alternative aviation fuels in **Section 3.2, Table 3** summarises the selected technology and fuel combinations further explored in this study. Building upon four reference aircraft and using the most promising technologies from **Table 1**, two distinct aircraft families are considered: a drop-in fuel family that can use either fossil kerosene or SAF and a LH2. The characteristics of both aircraft families are projected for two future generations, being 15 years apart.

Owing to the very large cost and resource requirements of new aircraft programs (see **Section 2.3**), the entry-into-service (EIS) date of medium & long-haul aircraft is assumed to be phase-displaced by five years relative to regional and short-haul aircraft. This allows manufacturers to better balance their capital requirements and resources over time, i.e., one programme is being ramped up while the other is running down.

Whereas the entry-into-service date of the next evolutionary aircraft generation is expected to be 2030, liquid hydrogen aircraft are unlikely to be available before 2035. It is assumed that LH2 would be introduced first on less complex, smaller aircraft and then progress to larger aircraft later. This decision will nonetheless pose challenges to the industry in terms of managing fast aircraft manufacturing rates common to smaller aircraft. The chosen aircraft technologies in **Table 3** are then complemented by the subset of promising air traffic management and operational measures from **Table 1**.

Table 3 Chosen aircraft technologies for the drop-in fuel and LH2 aircraft families

	2030	2035	2040	2045	2050	2055
	Generation N+1			Generation N+2		
Drop-in fuel family	Regional, short-haul	Medium & long-haul		Regional, short-haul	Medium & long-haul	
Hydrogen family		Regional, short-haul	Medium & long-haul		Regional, short-haul	Medium & long-haul
Wing	15 AR			20 AR	BWB (drop-in) 20 AR (LH2)	BWB (LH2)
Engines	UHBR			UHBR & flying slower		
Composite materials	Apply to 50% of components by weight			Apply to 100% of components by weight		

Table notes: AR: wing aspect ratio, BWB: blended wing body aircraft, UHBR: ultra-high bypass ratio engines

As discussed in **Section 2.3**, airlines are only interested in new aircraft designs that offer significant reductions in operating costs compared to those vehicles already in their fleet. Of particular interest are the direct operating costs (DOCs), which consist of crew, fuel, maintenance, ownership or depreciation, and other expenditures. These were estimated in the following way. (See **Appendix 6** for details).

- Aircraft ownership / depreciation costs were calculated via capital costs of the respective aircraft designs. The latter were estimated using the Development and Procurement Cost of Aircraft (DAPCA) model, originally developed at RAND and further improved by Raymer (2012), using the respective aircraft empty weight, maximum cruise speed, and a production run of 500 aircraft. Because DAPCA does not include engine costs, an engine cost model was developed that explains the engine list price as a function of maximum thrust, cruise engine specific fuel consumption, and certification year. A typical discount of 70% was used to arrive at the engine research, technology and production costs.
- Crew, maintenance, and other expenditures were estimated following Harris (2005), using US Form 41 data from the top-10 airlines operating in the US.
- Airport and en-route charges were estimated using aircraft weight and passenger number-based relationships from Jenkinson (2001).

Figure 7 depicts the resulting DOCs in US$(2020) per flight hour by DOC category for the four aircraft size classes using (synthetic) liquid fuels for today's conditions, for Generation N+1 (2030/35) and for Generation N+2 (2045/50). Fuel costs are based on a fuel price of $5 per gallon ($CO_2$ costs not included). Although capital costs of the Generation N+1 aircraft are projected to increase above the current aircraft, the savings in all other expenditure items are anticipated to decline more strongly (particularly fuel costs), thus leading to a decline in total DOC. However, in practice, airlines will not accept an increase in capital costs compared to the previous-generation aircraft and manufacturers will thus have to absorb these extra production costs through a larger production run (greater than 500). Hence, the DOC reduction experienced by airlines would be larger than shown. See **Appendix 6** for details.

Because of the projected strong reduction in aircraft energy intensity, the share of fuel costs to total DOC declines from one generation to the next. For example, assuming a synthetic liquid fuel price of $5 per gallon, for the medium-haul, A330 type of aircraft, fuel costs account for around 50% in the reference case, around 42% in the Generation N+1 aircraft, and only around 30% in Generation N+2. See **Appendix 6** for the estimated DOCs of hydrogen aircraft.

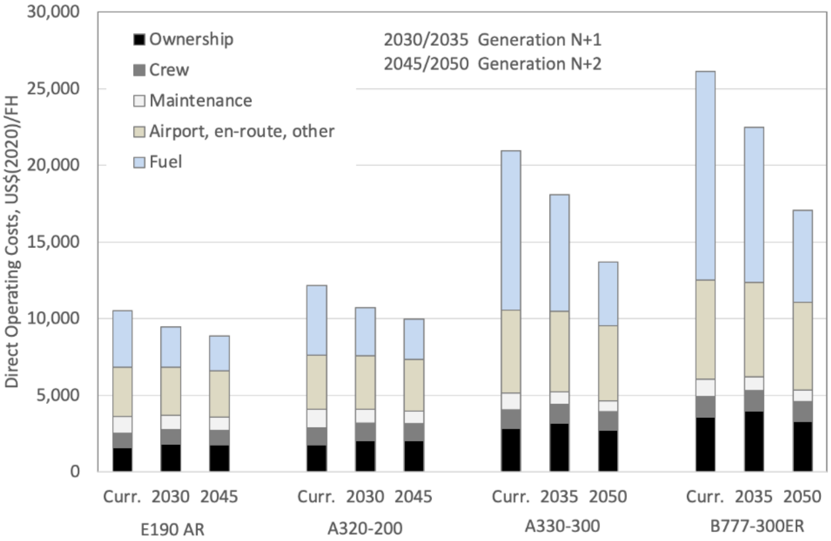

Figure 7 Estimated DOCs in US$(2020) per flight hour for the four aircraft size classes using synthetic liquid fuels for today's generation, Generation N+1, and Generation N+2. The underlying jet fuel price is $5 per gallon

4. MODELLING METHODOLOGY

This section summarises the Aviation Integrated Model (AIM), which was used to project the potential global impact of the uptake of the various technologies and fuels described in **Section 3**. Six different scenarios for combinations of demand, fuel supply, policy and aircraft technology were explored using AIM, which are also described in the following sections. Further information on the modelling methodology and scenarios is given in the Appendices to this study.

4.1. THE AVIATION INTEGRATED MODEL (AIM)

AIM is a global aviation systems model which simulates interactions between passengers, airlines, airports and other system actors into the future, with the goal of providing insight into how policy levers and other projected system changes will affect aviation's externalities and economic impacts.

4.1.1. AIM structure

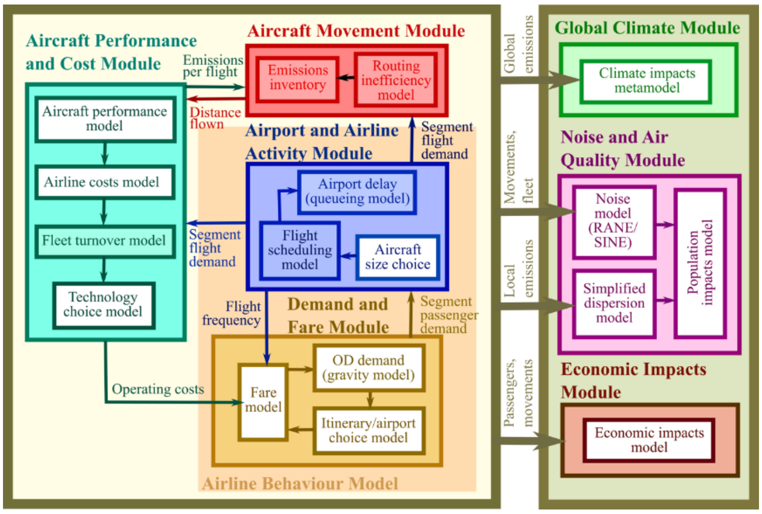

Figure 8 AIM model structure

AIM models passenger and freighter flights across a global network consisting of flights between 1,169 airports (878 cities or airport regions). As shown above, the Demand and Fare Module simulates total city-pair demand (e.g., London-Sydney), the itineraries passengers choose to use between those cities (e.g., Heathrow-Hong Kong International-Sydney Kingsford Smith), and the fare they are charged to do so. The Airport and Airline Activity Module simulates airlines' choice of aircraft size and schedule to meet this passenger demand, and any resulting airport-level congestion, and the Aircraft Movement Module simulates the air routes flown for these flights, including en-route inefficiency. The Aircraft Performance and Cost Model then simulates fleet turnover, airline technology choices, and the resulting airline operating costs. These estimates of operating costs in turn affect the fares that are charged, so these modules are iterated until a converged solution is achieved and output metrics, including demand, emissions, technology and fuel use, can be calculated. This structure allows AIM to assess the impact of new policies and/or technology packages on demand, operations, ticket prices and multiple other system metrics, both globally and down to the flight segment or itinerary level. Because of these capabilities, AIM has been used for aviation policy and technology assessment in a wide range of contexts, including for the UK Department for Transport (e.g., ATA & Clarity, 2018), EC DG CLIMA (e.g., ICF et al. 2020), and the International Energy Agency (IEA, 2020c).

As described in **Section 3**, new technologies and fuels affect aircraft fuel use, operating cost, and potentially other per-flight characteristics such as turnaround time or the typical number of seats on an aircraft. These characteristics are used as input parameters to AIM. Further information on how the costs and benefits of each new aircraft design and operational intervention are quantified is given in the appendices to this study.

The impact of these parameters in reducing sectoral emissions is uncertain, and many factors affect how they translate into emissions savings. Some key uncertainties include:

- Future demand growth.
- Supply of alternative fuel. For a given constrained supply of alternative fuel, a smaller percentage of aviation fuel demand can be supplied at higher demand growth rates.
- Future developments in oil price (both in terms of absolute levels and year-to-year variation).
- The potential of hydrogen aircraft to reach high technology readiness level (TRL) and proceed to widespread use and the level of policy support.
- The future development of global environmental and aviation-related policy.

To address these uncertainties, two different sets of technology roll-outs, and three different cases for developments of future trends and policy are defined, spanning a wide range of possible futures for global SAF demand. These are combined to make a total of six **scenarios** (A-F) for future developments. These scenarios are intended to be aspirational, highlighting the effort that will be required to meet different aviation emissions targets: as such, they are not projections. Each scenario consists of a set of **technology roll-outs** defined by the technology analysis in **Section 3**; a **demand case**, including policy ambitions, various demand drivers and trends; and a **SAF supply case** aimed at meeting the projected demand. The different inputs to these scenarios are discussed below. Further information on how the scenarios were generated and quantified, and additional sensitivity cases, are included in the appendices to this report.

4.2. TECHNOLOGY ROLL-OUT

The defined technology packages discussed in **Section 3.3** above lead to two sets of technology rollouts. The ATM and operational measures assessed in **Section 3.1** are used for both.

- **“Drop-in” technology:** new aircraft generations enter service on the expected industry schedule and drop-in SAF is part of the fuel supply, with uptake stimulated by blending mandates; and
- **“H2” technology:** New aircraft launches are delayed by 5 years with the first hydrogen-fuelled aircraft entering service in 2035 (see **Table 3**). Both drop-in SAF and liquid hydrogen are part of the fuel supply, with uptake stimulated by blending mandates (for SAF) and aircraft design/purchase standards (for hydrogen aircraft).

These two technology rollouts are used as input into AIM. Due to the initially high costs associated with hydrogen and some SAF pathways compared to fossil-derived kerosene, this study explores the case where adoption of SAF, or SAF and hydrogen aircraft, is stimulated by mandate policy and assesses the resulting impacts on ticket prices, rather than exploring cases where airlines have a free choice about which technologies to use.

4.3. DEMAND CASES

The following demand cases are explored:

- **High Demand:** assumes high income growth, low oil prices, and limited long-term impact of the COVID-19 pandemic. Rapid aviation growth similar to historical levels shown in **Figure 4** resumes as soon as the pandemic is over and, unless additional policy action is taken, significant growth in emissions is likely. Long-term population and income growth are derived from the IPCC SSP1 scenario (O'Neill et al. 2018), adjusted for COVID-19 impacts, with global GDP/capita around 2.2 times greater than year-2015 values by 2050. Oil prices follow the IEA SDS scenario (IEA, 2021) at just below $60 (year 2020 USD) by 2050, and short-term pandemic recovery is taken from the 'Upside' scenario in IMF (2021). Additionally, an ambitious global SAF mandate, rising to 100% by 2050, is assumed. This combination of drivers and policy is likely to result in particularly high SAF production requirements, which will be very challenging to meet.
- **Mid Demand:** assumes population and income follow central-case trends, leading to aviation demand growth that is close to the post-COVID-19 industry projections shown in **Figure 4**. Long-term population and income growth are derived from the IPCC SSP2 scenario (O'Neill et al. 2013), adjusted for COVID-19 impacts, with global GDP/capita around 1.9 times year-2015 values in 2050. Short-term pandemic recovery follows the IMF (2021) 'baseline' scenario. Oil prices follow the IEA SDS scenario (IEA, 2020a) as in the High Demand case. A global SAF mandate at levels initially suggested for RefuelEU (EC, 2021a), reaching 63% SAF by 2050, is assumed[4] .While still challenging, lower SAF volumes are required compared to the High Demand case.
- **Low Demand**: assumes economic growth is on the low end of the projections given in **Figure 4** and additionally aviation passenger demand growth is suppressed by changes in attitudes to aviation arising from societal changes in the wake of the COVID-19 pandemic and/or increased environmental concerns about flying. Long-term population and income growth are derived from the IPCC SSP3 scenario adjusted for COVID-19 impacts, with global GDP/capita around 1.4 times year-2015 values in 2050, and short-term pandemic recovery follows the IMF (2021) 'downside' scenario; additionally, income elasticities are assumed to decrease over time as demand growth decouples from GDP/capita growth (by factors derived from DfT, 2017). Oil prices rise over time and are over $120 (year 2020 USD) in 2050, following the IEA STEPS scenario (IEA, 2020a). A global SAF mandate at levels initially suggested for RefuelEU (EC, 2021a), reaching 63% SAF by 2050, is assumed. The lower level of demand results in lower SAF requirements necessary to meet ambitious emissions goals.

For each of these demand cases, initial model runs are used to assess the amount of SAF that is likely to be needed to satisfy demand, and to develop a

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[4] Note, this refers to the initial proposal by the European Commissions in July 2021.

corresponding set of supply characteristics. This process is discussed in the next section.

As well as the mandate policies described above, current policies (e.g. the EU, Swiss and UK ETS; CORSIA) are assumed to remain in operation at their planned specification as of the start of 2022 to 2050[5]. The assumptions used regarding these policies are discussed in the appendices to this study. However, these existing policies have relatively little impact on outcomes as the high mandated SAF uptake reduces airline obligations to offset or purchase allowances.

4.4. FUEL SUPPLY CASES

The amount of SAF required is dependent on level of policy ambition and resulting demand, so SAF supply cases were developed jointly with the demand and policy cases (**Section 4.3**). This allowed a wide range of levels for future SAF requirements to be explored. As the bottom-up analysis of the fuel supply is not integrated with the AIM system model, the fuel supply for each set of demand and policy cases was determined following an iterative process, assuming that low-carbon fuel supply would scale with and in response to demand to 2050. A baseline set of supply characteristics, based upon work previously conducted by E4tech for Sustainable Aviation UK (2020), was first used as an input into AIM. The difference in fuel supply and demand from the AIM model was observed, and the ramp-up model adjusted accordingly, to ensure an aviation fuel supply by 2050 of ~5-10% greater than projected aviation industry demand at a given level of policy ambition for each demand case. Supply modelling variables were adjusted to enable greater SAF supply volumes.

This process was repeated for each demand and policy case, resulting in three accompanying sets of supply characteristics that are used as inputs to the AIM model. As such, it should be noted that these combinations of demand, supply, policy and technology are not projections, but rather scenarios where demand for SAF is met by a corresponding increase in available supply.

4.4.1. Drop-in fuels

A range of feasible fuel production pathways were identified (see **Section 3.2**), along with associated supply, cost, and emissions characteristics, and how these are likely to vary over time. For SAF pathways, cost curves were constructed for typical blended fuel costs for a given global amount of SAF required.

The build rates for each of the drop-in fuel production pathways were determined using a bottom-up methodology, which estimates the current potential deployment of SAF based on an extensive database of fuel production facilities globally. Various scenarios were modelled for how drop-in fuel supply could develop in the future based on potential new facility build rates.

In the near term, the build rate is based on the number of active developers within each fuel pathway, the technology readiness of each developer, and operational and planned plants. On this basis, the future supply capacity of a pathway is projected on a plant-by-plant basis, using the following factors:

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[5] These specifications reflect the aviation policy situation at the time this study was carried out; note that some have subsequently been updated, typically towards greater stringency (for example, a reduction in the CORSIA baseline; ICAO 2022b).

- ***Project timeline***: How long it takes to build each plant
- ***Lifetime***: How many years each plant operates for
- ***Plant capacity***: How large each plant is
- ***Utilisation rate***: How many hours per year a plant operates for
- ***Initiation rate***: How many commercial projects can be started each year, e.g., via technology licences
- ***Launch points***: How soon after a previous project start is it feasible for the next project to start
- ***Success rate:*** How many of these plants and developers might fail/be unsuccessful

Given the large degree of uncertainty in how these factors will evolve and vary to 2035, ***slow and fast growth*** of the industry were modelled to project the potential production volumes. The slow and fast growth cases differ in terms of the initiation rate, the launch-point, and the success rate.

Beyond 2030, technologies are assumed to have reached commercial maturity once a certain number of plants have been deployed. At this point the market is projected to move from an introductory phase to a growth phase, where the number and scale of plants proliferates in response to demand. In the year of commercialisation for each pathway, the model switches from a plant-based ramp-up to a market growth model, at a pre-determined compound annual growth rate (CAGR). The year at which this occurs is determined as the year at which the market growth rate would exceed a ramp-up growth rate equivalent to four additional full-scale commercial plants in operation per year.

Based on the demand and policy cases used within AIM, the following SAF supply cases were explored:

- **Low supply** resulting in a SAF supply of 10.8 EJ (~250 Mtonnes) in 2050, increasing from ~1 EJ (~25 Mtonnes) in 2030. Both biofuels and PTL routes make up this supply but biofuels are relied upon to 2030, accounting for 92% of the total SAF supply. Post-2030, as PTL pathways reach commercialisation, biofuels account for 67% of the SAF supply. During the initial ramp-up period, project development timelines are typical of those currently observed for projects with similar technologies, at similar scales and stages of commercialisation. Upon reaching commercialisation, biofuel production pathways grow with a CAGR of 15%. This rate is equivalent to the historic growth rate of US corn ethanol production capacity between 2000 and 2016, and was chosen due to similarities in market behaviour and technological challenges. For PTL FT pathways, the post-commercialisation market growth rate is 21%: in line with the rate of growth for combined wind and solar power between 2009 and 2018 (~22%) (IRENA, 2019) as deployment of additional renewable capacity is seen as a likely rate-limiting step.
- **Mid supply** resulting in a SAF supply of 17.5 EJ (~400 Mtonnes) in 2050, with a supply of 1.2 EJ (~27 Mtonnes) in 2030. Roughly 90% of the 2030 supply is from biofuels, decreasing to 56% in 2050. The increase in supply to 2030 is achieved by slightly reducing the project development timeline during the ramp-up phase, which leads to faster commercialisation. The biofuel market growth rate upon commercialisation remains at a 15% CAGR, while the rate of growth for PTL fuels increases to a 23% CAGR to meet demand.

- **High supply** resulting in a in a SAF supply of 30.6 EJ (~700 Mtonnes) in 2050, from a supply of 1.2 EJ (~27 Mtonnes) in 2030. The ramp-up phase to 2030 remains the same as for the mid supply case, with reduced project development timelines, where biofuels account for 90% of SAF in the first decade. However, market expansion after commercialisation occurs at a much faster rate, mostly due to the rapid scale-up of PTL FT, which account for roughly 63% of SAF in 2050. The PTL market grows at an accelerated CAGR of 36% between 2030 and 2040, before reducing to a CAGR of 23% between 2040 and 2050. Although much higher than the other cases, a CAGR of 40% has been observed with the growth of the solar PV industry since 1990, providing a potentially relevant proxy for early-stage growth (JRC, 2019). Biofuel growth rates are slightly increased to above historic levels, at 16% CAGR.

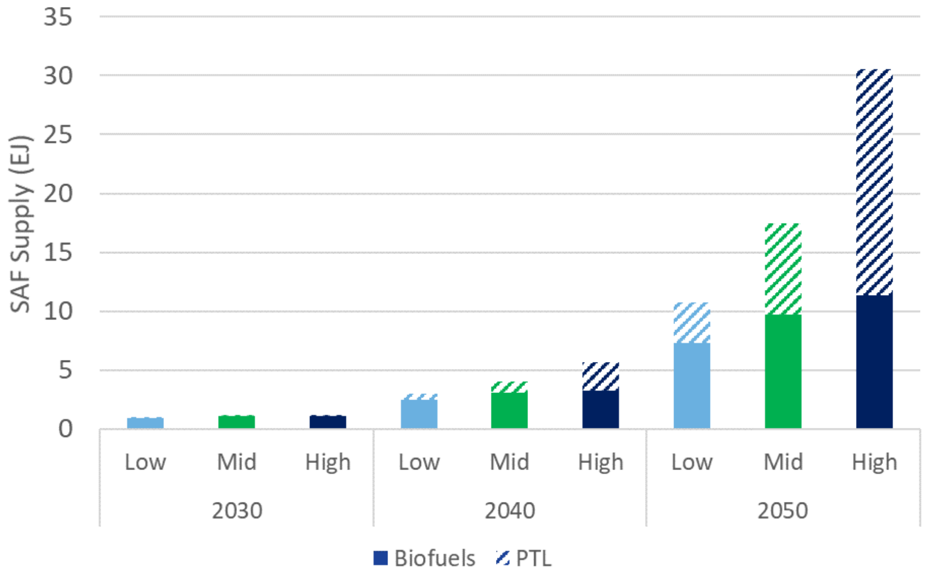

Figure 9 SAF supply comparison

The following assumptions are relevant to all SAF supply cases:

- During the introductory phase, plant development timelines differ according to the stage of commercialisation.
- The HEFA pathway, unlike other fuel pathways, is constrained by the limited feedstock availability of waste oils and fats. A cap of 44 Mt of available feedstock is assumed, based on an Ecofys study (2019). Higher potentials are available in literature, such as an estimate of 170 Mt in the World Economic Forum Clean Fuels Clean Skies study: however, higher estimates typically include the use of energy crops on marginal and degraded land, which is yet to be proven at scale and subject to high uncertainties regarding yields, therefore energy crops are not considered in this analysis. Additionally, other studies indicate that practical available potential of waste oils is far lower, such as CE Delft (2021).
- PTL pathways are assumed to be capable of scaling up faster than biofuel pathways. There are few constraints on the electrolyser industry in terms of growing its manufacturing capabilities in the future. Similar to renewable energy industries, such as solar PV and wind power, studies have indicated that manufacturing processes are easily scalable, requiring relatively low investment in terms of critical components, and minimal production lines

required to reach relatively high levels of demand (NOW GmbH, 2018). There are also fewer constraints regarding feedstock availability and geographical restrictions. The main consideration is the additional renewable energy capacity required for PTL fuels, and how this affects the wider market.

- Biofuel facilities, on the other hand, are limited by the availability of low-cost suitable feedstock local to the plant, and specialist equipment and knowledge may be required for feedstock transportation and conversion.

4.4.2. Fossil jet fuel

It was assumed that the supply of fossil jet fuel would react in response to demand: therefore, supply was not capped or projected. However, future projections of aviation emissions require projections of fossil jet fuel emissions and cost. Jet A prices are derived directly from each demand case (**Section 4.3**) based on historical relationships between oil price and jet fuel price. Fuel lifecycle emissions were generally maintained at year-2019 values, but a decrease over time in the refining emissions of fossil kerosene is assumed (by 30% compared to year-2020 values, or around 2 gCO_2e/MJ), reflecting anticipated decarbonisation measures in the refining sector (Concawe, 2019). Further emissions reduction could be achieved through efforts upstream, particularly by reducing methane emissions. However, most lifecycle emissions for fossil jet arise during combustion (73.2 gCO_2e/MJ vs. 86.7 gCO_2e/MJ including fuel lifecycle emissions): as such, use of fossil jet would still contribute significantly to net CO_2 emissions.

4.4.3. Hydrogen

The non-drop-in nature of hydrogen as an aviation fuel means that fleet turnover is likely to be a stringent constraint on the speed of any hydrogen transition. Separate constraints exist around the provision of fuel infrastructure, including hydrogen production plants and airport refuelling infrastructure. Given that it is likely any future scenario with widespread use of hydrogen aircraft will also see widespread hydrogen use in other sectors, this study assumes that the key bottleneck on amounts of hydrogen supplied to aviation is fleet turnover rather than production capacity, and additional constraints on hydrogen supply are not applied.

4.5. SUMMARY

Table 4 shows a summary of each modelled scenario within this report. Each scenario consists of a combination of a technology roll-out case, a demand case including policy characteristics, and a fuel supply case.

Table 4 Summary of the modelled scenarios

Scenario	Technology roll-out	Demand case	Supply case
A: Low (drop-in)	New aircraft, drop-in SAF, and operational measures	Long-term economic growth and demand growth is suppressed. High oil prices, ReFuelEU SAF mandate applied globally.	Standard project development timelines during ramp-up phase. 15% CAGR for biofuels, 21% CAGR for PTL fuels during market expansion phase.
B: Low (H2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of demand case.		
C: Mid (drop-in)	New aircraft, drop-in SAF, and operational measures	Economic growth follows central-case trends, aviation demand trends follow post-COVID-19 industry projections. Low oil prices, following IEA SDS scenario. ReFuelEU SAF mandate applied globally.	Accelerated project development timelines during ramp-up phase. 15% CAGR for biofuels, 23% CAGR for PTL fuels during market expansion phase.
D: Mid (H2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of demand case.		
E: High (drop-in)	New aircraft, drop-in SAF, and operational measures	High economic growth: high income growth, aviation demand trends follow pre-COVID-19 industry projections. Low oil prices, following IEA SDS scenario. Ambitious global SAF mandate, rising to 100% in 2050.	Accelerated project development timelines during ramp-up phase. 16% CAGR for biofuels, 36% market growth CAGR between 2030-2040, 23% CAGR between 2040-2050 during market expansion phase.
F: High (H2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of demand case.		

5. RESULTS

This section presents the key results of the modelling for the scenarios presented in **Section 4**.

5.1. DEMAND AND FLEET EVOLUTION

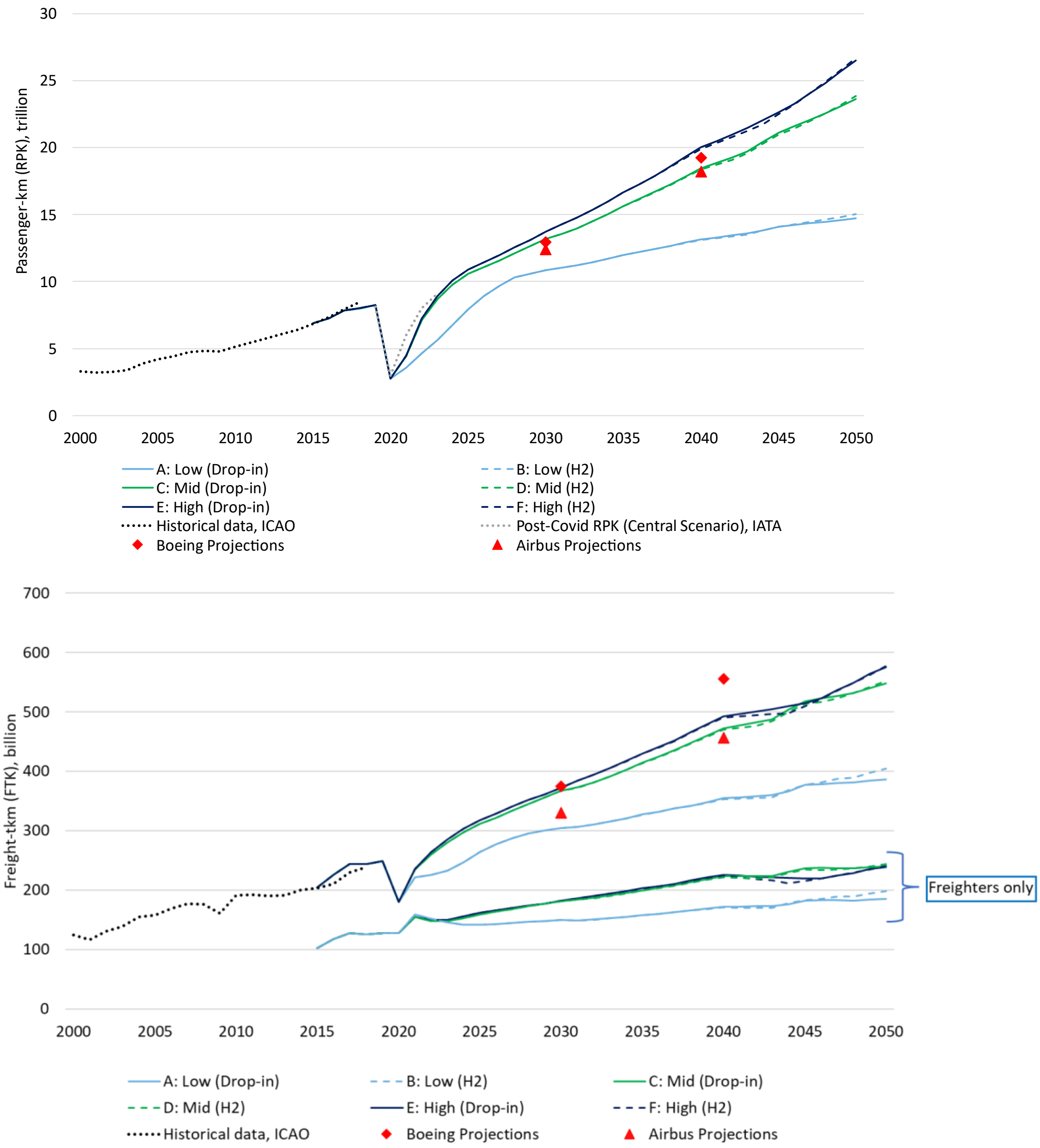

Figure 10 Demand for aviation expressed in passenger-km (upper graph) and freight-tkm (lower graph)

The AIM model does not impose a fixed level of demand: instead, it assesses macroeconomic and policy inputs to determine the demand. Across the range of explored economic inputs, **Figure 10** shows an increase in aviation demand over time, for both passenger and freight travel. This is the case even in the low scenario, which deviates significantly from historic trends and economic growth, as described in **Section 2.1**. This growth is not evenly distributed around the world but concentrates more on world regions where income growth is projected to be more rapid and where aviation systems are currently less mature. The demand in both the medium and high scenario are well aligned with industry projections (Airbus, 2021b; Boeing, 2021). **Figure 10** also projects that belly freight (i.e., in passenger aircraft) will continue to account for approximately half of freight demand.

Due to the anticipated growth in demand, the number of aircraft in the fleet will need to increase, as shown in **Figure 11**. The aircraft design process, and the way that new generations of aircraft designs come into the market, are discussed in the Appendices to this report.

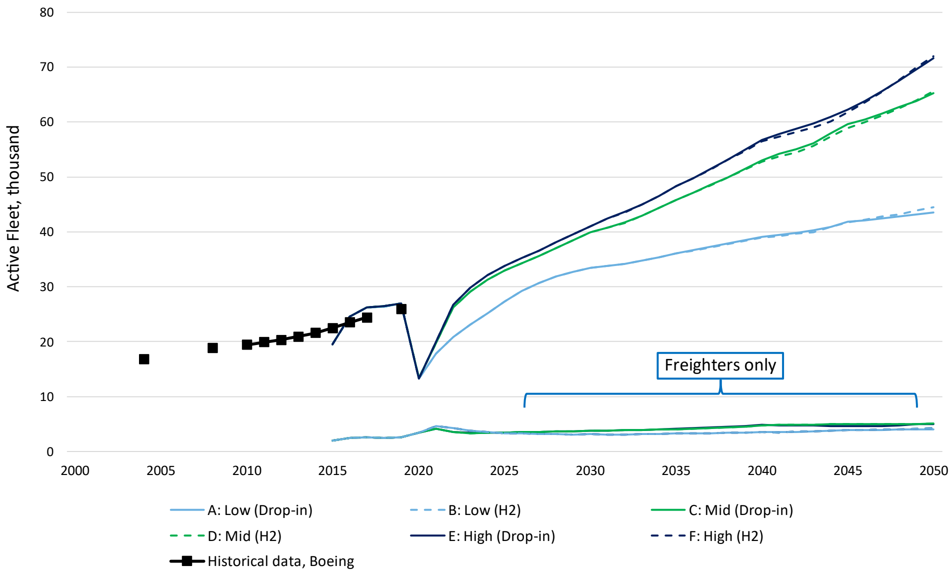

Figure 11 Active Fleet (thousands). Figures for freighters only shown below

The benefits of new aircraft designs are constrained by the time they take to come into the fleet. New aircraft are bought both to serve new demand and to replace older aircraft that have been retired. **Figure 12** shows the modelled fleet composition for the scenarios considered in this study. A typical aircraft lifetime to scrappage is 30 years (Dray, 2013). This means that, in the absence of any radical change in retirement behaviour, many aircraft entering the fleet now (Generation 'N' in **Table 3** and **Figure 12** – e.g. the Airbus A320neo, Airbus A350, or Boeing 777X) will still be operating in 2050. These are the best-available aircraft today, and do not have the benefits of the new technologies introduced in the N+1 (2030+) and N+2 (2045+) generations. Aircraft in these generations which are still operating in 2050 will have more limited opportunities to reduce emissions, beyond operational measures, retrofits, and uptake of SAF.

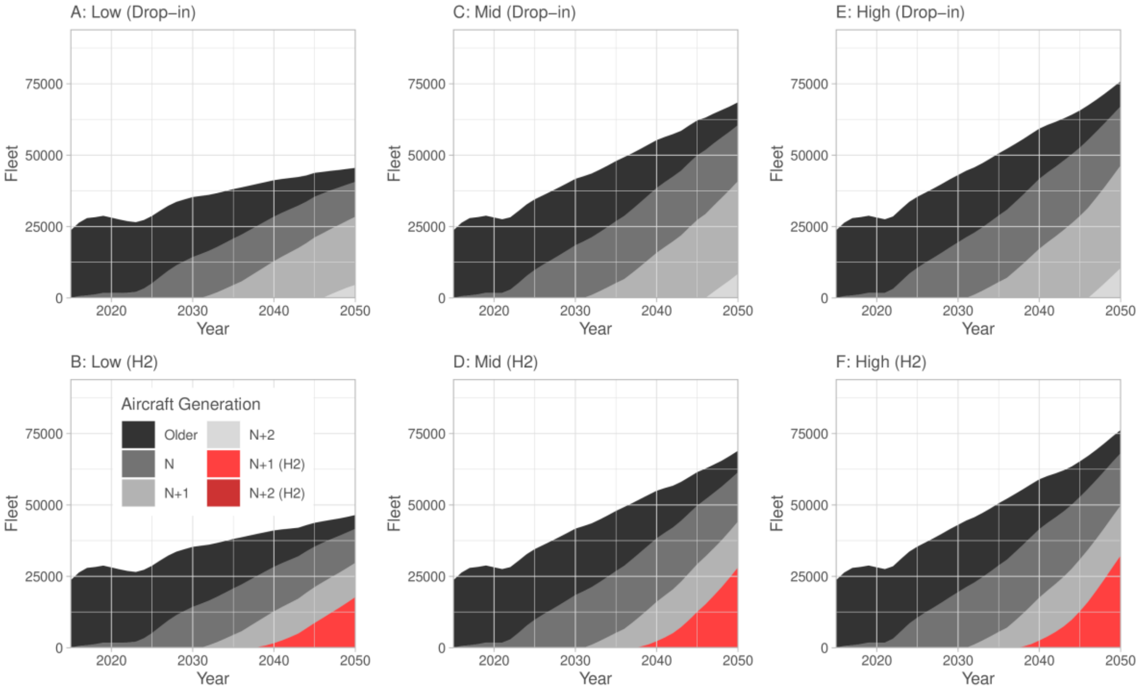

Figure 12 Aircraft fleet by generation of aircraft design and scenario

For scenarios with faster demand growth, more new aircraft are needed to serve new demand, and so new aircraft designs can become a larger proportion of the fleet earlier than in scenarios with slower demand growth. However, this effect is relatively small. For the drop-in fuel cases modelled, pre-2030 aircraft designs are around 40% of the year-2050 fleet. Although these aircraft can take advantage of the operational emissions mitigation measures discussed in **Section 3**, radical emissions reductions require SAF use. For the hydrogen scenarios, year-2050 hydrogen aircraft account for approximately 38-42% of year-2050 fleets. This is lower than the fraction of new technology aircraft in the conventional technology scenarios, since there is a 5-year delay assumed in bringing hydrogen designs to market, and an additional 5-year phase-in time assumed for purchase requirements. This still represents an aggressive scenario for hydrogen aircraft adoption, as hydrogen fuel is assumed mandatory in new purchases after this point and delays associated with infrastructure provision are not modelled. The hydrogen use in these scenarios acts to reduce the SAF requirement in the remaining fleet. However, hydrogen aircraft alone cannot produce significant reductions from current CO_2 emission levels in these scenarios due to the relatively slow rate of fleet turnover. Significant amounts of kerosene SAF are required in all scenarios to reach emissions goals.

5.2. FUEL SUPPLY COMPOSITION

Graphs in this section present the overall composition of fuel supply, showing the ramp up of SAF (biofuels and PTL fuels) and liquid hydrogen through to 2050.

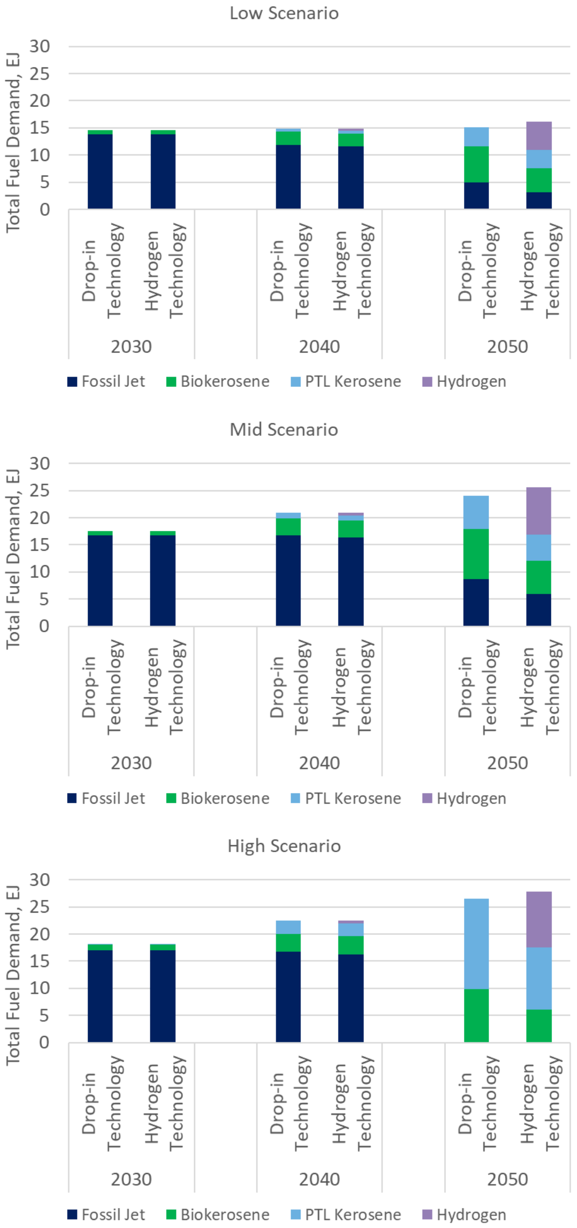

Figure 13 Total fuel demand (energy basis) in each scenario

In general, supply and use of lower cost biokerosene pathways is relatively consistent across the different scenarios modelled. As demand increases, the reliance on PTL fuels is increased due to the constraints on biomass plant scales and supply chains as discussed in **Section 4.4.2**. In the scenario where hydrogen aircraft are used, their impact on fuel demand becomes significant only after 2040, as before this time only small numbers of hydrogen aircraft are in operation. Sectoral energy demand increases in hydrogen scenarios since hydrogen aircraft are less energy efficient, due to the additional weight of hydrogen tanks.

PTL costs are assumed to decrease over time due to projected decreases in the costs of renewable electricity and direct air capture (see the different pathways in **Appendix 5**). By 2040, projected PTL costs are below some of the higher-cost biokerosene pathways modelled. As such, reductions in drop-in kerosene SAF demand from increasing hydrogen aircraft use are projected to result in lower capacity build-up after 2040 for higher-cost biokerosene pathways, most notably Alcohol-to-Jet.

5.3. CO_2 SAVINGS

The decarbonisation ambition level for the aviation sector has been evolving toward a net zero target by 2050:

- Since 2009, IATA has had an ambition to achieve 50% reduction on 2005 levels by 2050.
- In 2016, ICAO adopted CORSIA, with the (current) ambition of stabilising aviation's net CO_2 emissions relative to 2019 levels, from 2021 (carbon neutral growth). For CORSIA's pilot phase, CORSIA's baseline is set at 100% of year-2019 emissions. For subsequent phases, the planned baseline is now 85% of year 2019 emissions (ICAO, 2022b).
- However, in October 2021, IATA approved a revamped goal of achieving net-zero carbon emissions by 2050, in alignment with the Paris Agreement (IATA, 2022).
- In October 2022, ICAO adopted a Long-Term Aspirational Goal (LTAG) for international aviation of net zero emissions by 2050.

Figure 14 shows the net CO_2[6] emissions for each of the scenario's A-F, compared to the IATA 50% reduction goal, carbon neutral growth and net zero CO_2. Carbon offsets are captured within the net CO_2 emissions and arise from implementation of the EU ETS and CORSIA (at levels reflecting policy ambition at the start of 2022). Note that the historical data shown includes military aviation.

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[6] **Direct CO_2 is** all CO_2 produced by combustion in aircraft engines and does not account for reductions in CO_2 from SAF production. **Fuel lifecycle CO_2** additionally includes CO_2 from the fuel production process which, in the case of SAF, significantly reduces totals. **Net CO_2** is direct CO_2 adjusted both for the reduction in fuel lifecycle emissions of SAF, and offsets and allowances via CORSIA and emissions trading which result in emissions reductions in other sectors. CO_2 here refers to CO_2e, covering CO_2, N_2O and CH_4 in line with the UN definition of GHGs, but does not include non-CO_2 aviation emission impacts at altitude (e.g. NOx, contrails, etc).

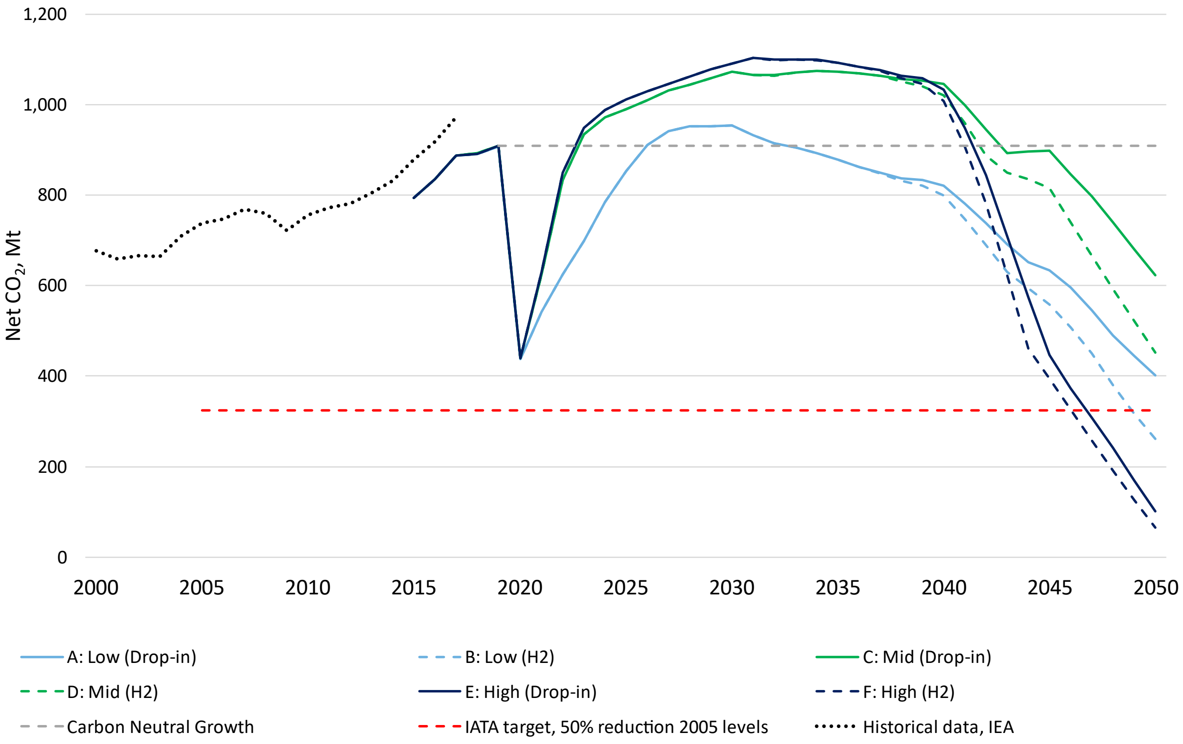

Figure 14 Net CO_2 emissions from the aviation sector. Note, IEA's data includes military flights, which are excluded from this analysis

Hydrogen scenarios result in slightly reduced emissions compared with their corresponding SAF-only counterparts. However, limited additional mitigation occurs until 2040, due to uptake constraints. From 2040-onwards, significant numbers of hydrogen aircraft enter the fleet (**Section 5.1**): this reduces the amount of drop-in fuels required, and hence drives sectoral emissions down.

The CORSIA ambition of carbon-neutral growth compared to 2019 levels is not achieved in all scenarios until 2045 based on emissions reductions within the sector. However, carbon offsets are allowed under CORSIA, which could accelerate the speed in which carbon-neutral growth is achieved, though this was outside the scope of the analysis. In the low scenario this is met, bar a small overshoot between 2026 – 2032, whilst in the medium and high scenarios the overshoot is significantly higher and the time it takes for CO_2 emissions to return to 2019 levels much longer. There are several reasons behind this:

- A new generation of aircraft is not expected to enter into service until 2030-35. As such, in the next decade, emissions reduction measures are limited to the uptake of SAF and any ATM and operational improvements that can be applied to existing aircraft. Similarly, hydrogen aircraft do not enter the market before 2035 and the fleet remains small until 2040, so they have a very limited impact on emissions reduction before this point.
- The ability of SAF to reduce emissions is initially limited. At the start of 2022, RefuelEU Aviation targeted a 5% blend for 2030, and owing to the expected high cost of SAF in the near-term, it is highly unlikely that levels of SAF penetration will exceed any mandated level.

- Current international initiatives, such as CORSIA, and policies at regional and national levels do not provide strong economic incentives to drive decarbonisation in the aviation sector:
- Although CORSIA (as specified at the start of 2022) is intended to limit international aviation CO_2 emissions to 2019 levels, CORSIA does not address emissions from domestic aviation or emissions from flights to or from non-participating countries. Several large countries, including China, India, Russia and Brazil, have not yet expressed an intention to participate and, without these countries, international flight coverage is also limited (ICF et al., 2020).
- Although the emissions trading schemes modelled cover domestic aviation and have cap levels set on a more stringent emissions-reduction basis than CORSIA, their ability to reduce global net aviation emissions is restricted by their limited geographic scope and the relatively weak price signal associated with an economy-wide ETS.

Figure 14 shows that even in a future with demand below historical trends (Low scenarios A and B), even the 50% 2050 emissions reduction target would only be met through very high up-take of SAF – 63% of global jet fuel supply. To meet these emission targets in a mid and high demand case, even higher early up-take of SAF (and hydrogen) would be required.

Emissions reductions are also strongly dependent on the availability of energy efficiency improvements and, to a lesser extent, on demand reductions associated with higher fuel prices driven by SAF use. Because different sources of emissions reduction interact with each other (for example, changes in demand change the composition and cost of the mix of alternative fuels needed to meet a given mandate), an exact breakdown of the level of emissions reduction from different sources is not possible. If comparing scenarios A-F against hypothetical alternatives with similar growth in demand drivers but no alternative fuels or energy efficiency improvements, year 2050 fuel lifecycle CO_2 emissions are reduced by between 76-96%. Of these reductions, around 31-47% is due to energy efficiency measures (more efficient aircraft and improvements in operations and load factors). Because aircraft efficiency improvements reduce airline fuel costs, they are typically cost-effective for airlines to adopt and would be expected to occur without additional policy support. Roughly a further 2-17% reduction of emissions reductions compared to these hypothetical scenarios occurs due to demand reduction from increased fuel costs in the mandate scenarios modelled, where the lower end of this range corresponds to scenarios with low demand growth where smaller amounts of high-cost alternative fuels are needed. The remaining 50-65% of fuel lifecycle CO_2 reductions arise from alternative fuel use.

5.4. FUEL PRODUCTION INVESTMENT COSTS

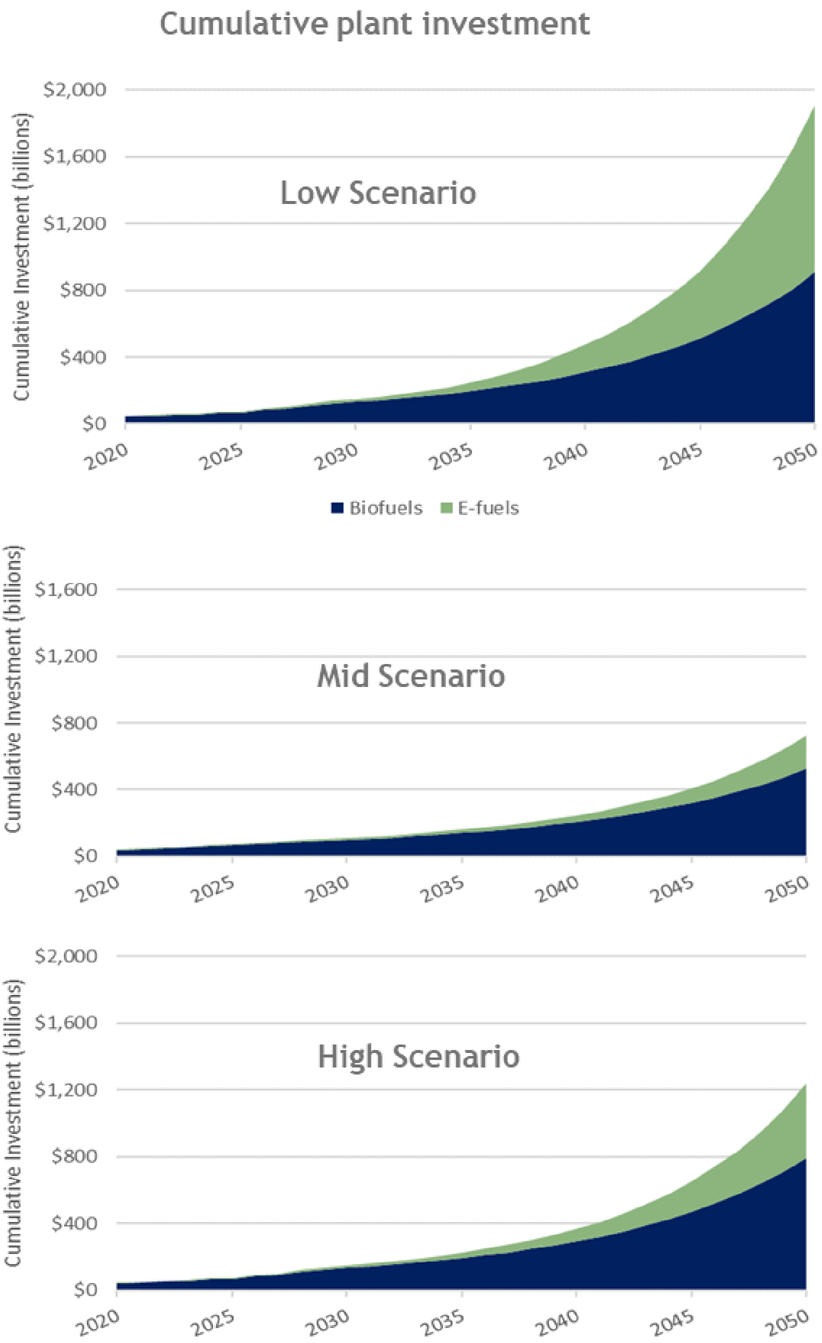

Figure 15 Cumulative plant investment for each scenario (low scenario (A, B), top; mid scenario (C, D), middle; high scenario (E, F), bottom)

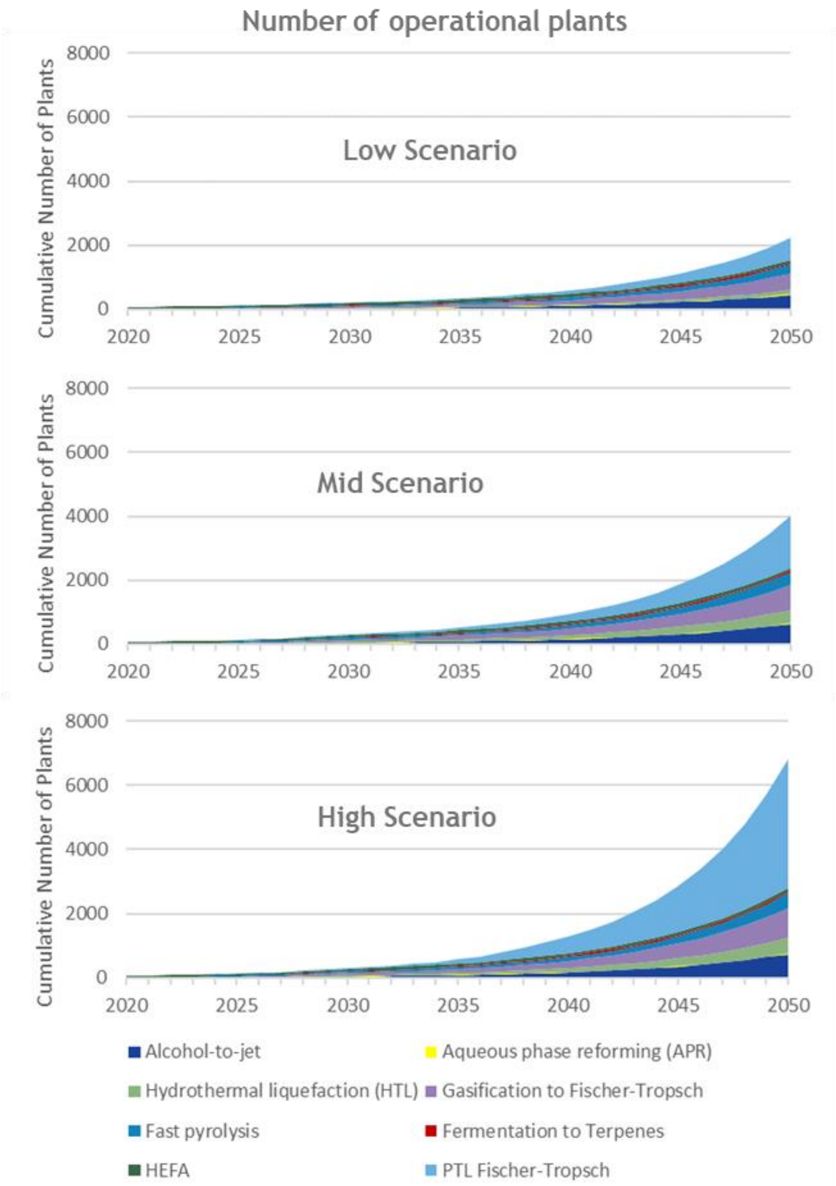

Figure 16 Number of operational plants in each scenario (low scenario (A, B), top; mid scenario (C, D), middle; high scenario (E, F), bottom)

Based on nameplate plant capacities and "nth additional plant"[7] specific capital investment costs taken from literature (**Appendix 5**), a high-level estimate of the required capital investment costs can be calculated.

Figure 15 shows the cumulative capital investment required over the period to 2050, with the low scenario requiring ~$700 billion and the high scenario reaching ~$1.9 trillion: equating to roughly 2,000 and 7,000 newly-built operational plants by 2050, respectively (see **Figure 16**). It should be noted that these estimates only account for the initial capital cost of the plant: total investment required is

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[7] Nth plant: once the technology is mature, i.e. after several commercial plants have been successfully deployed and full-scale capacity has been reached

likely to be significantly greater, due to the additional cost of setting up supply chains, operational costs, and the increased costs associated with early commercial plants. As shown in

Figure 17, in the low scenarios there is a greater proportion of spending on biofuel production, with expensive alcohol-to-jet and gasification-to-Fischer-Tropsch plants accounting for roughly a third of investment. In higher supply scenarios, the majority of investment goes towards the building of PTL Fischer-Tropsch facilities, due to the greater reliance on PTL in general.

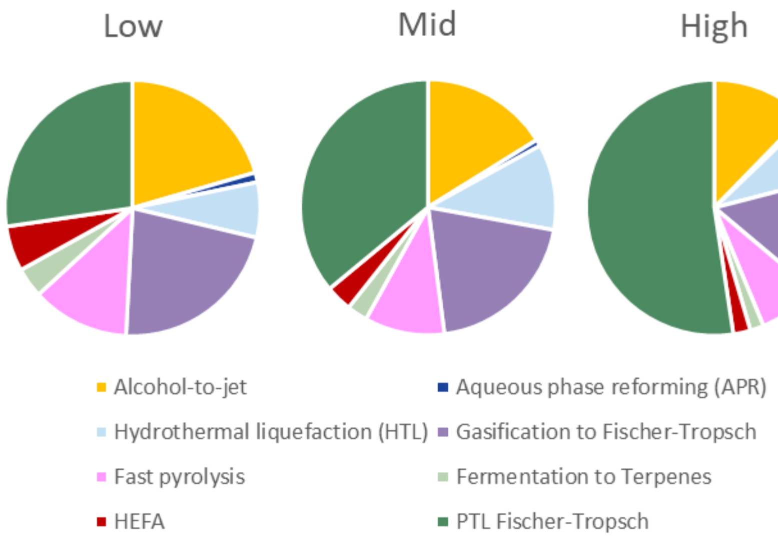

Figure 17 Share of cumulative plant investment, 2050

5.5. TICKET PRICE

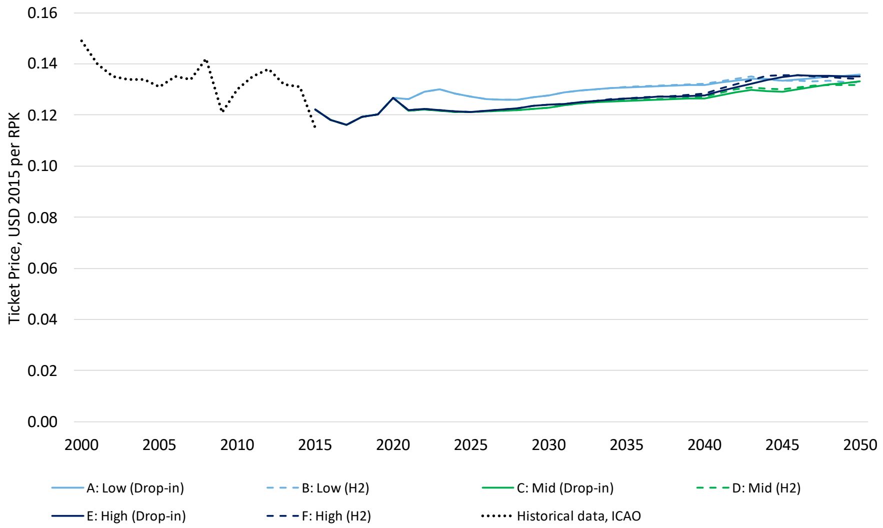

Figure 18 Ticket price 2000 - 2050 in 2015 USD per RPK

As shown in **Figure 18**, the model analysis suggests there will be minimal variation in ticket price across all scenarios between 2020 and 2050. The largest impact on ticket price arises from variation in oil prices assumed across the 2020-2040 period. Due to all scenarios imposing a significant mandate (minimum 63% SAF by 2050), the uptake of SAF is high in each scenario, with SAF prices assumed to be broadly similar in each ($4-6/gal). The uptake of SAF increases the airline operating cost. Historically, fuel costs have accounted for 10-30% of airline direct operating cost (ICAO, 2020). However, aircraft performance improvements are projected to drive down the proportion of operating costs attributable to fuel, while increases in effective fuel price from SAF uptake are projected to increase it. The net result, at typical rates of cost passthrough which are close to 100%, is a modest increase in ticket price. For comparison, ticket prices are projected to be between 3-14% lower in scenarios where only the technological and operational improvements are implemented, without the uptake of SAF, with the upper end of these differences seen in scenarios which have lower oil prices and hence a larger difference betwen SAF and fossil kerosene prices. Without mandates or carbon pricing, SAF would be unlikely to enter the market in any substantial way unless oil prices increase, given the increase in ticket price necessary to fund SAF use.

Despite the relatively modest change in ticket prices, some restructuring of the airline market is possible. This was seen during the high oil prices in 2014 – 2015, where a number of small airlines or those operating on very small margins were bankrupted as they were unable to pass the burden of the high oil price onto the consumer (GAO, 2014). If airlines cannot pass through the full extent of operating cost increases, the low profitability of the sector (**Section 2.4**) implies that airline bankruptcies and/or restructuring of the airline market may result. A comparable situation was observed during recent periods of high oil price, where a number of small airlines or those operating on very small margins were bankrupted as they were unable to pass the burden of the high oil price onto the consumer (GAO, 2014).

6. DISCUSSION

Technological improvements to aircraft alone will not be sufficient to reduce the aviation sector's CO_2 emissions, due to anticipated increases in demand.

Historically, aviation demand growth has been strongly correlated with global income growth, and without significant changes in attitudes towards flying, continued economic development is likely to lead to increased aviation demand. Although levels of future demand growth are uncertain, CO_2 reductions per tonne-km from technological and operational changes alone will almost certainly not be enough to offset the absolute emissions from the increased volume of aviation in tonne-km. Measures spanning the industry as a whole will be essential to mitigating emissions, with the most effective being those that reduce the industry's reliance on fossil fuels.

Bio-based kerosene can substantially contribute to aviation fuel, but supplying the aviation industry with 100% SAF would require vast quantities of biomass feedstock raising questions about availability and sustainability.

The biomass feedstock required to meet the demand scenarios in this study is significant, but studies are showing a potential supply which could be sufficient. An Energy Transitions Commission (ETC) study found that estimates of the potential availability of biomass range dramatically – as low as 10 EJ per year ranging up to 1,000 EJ per year (ETC, 2020) - depending on the assumptions and constraints imposed, particularly regarding sustainability criteria and land availability. **Figure 19** shows ETC estimates for total biomass feedstock potential, based on a prudent scenario and a maximum potential. The combined biomass feedstock supply in the high scenario exceeds the most conservative feedstock potential estimate, before considering demand from other industries. Under the maximum potential estimate, the feedstock supply scenarios range from 17% to 29% of total feedstock potential.

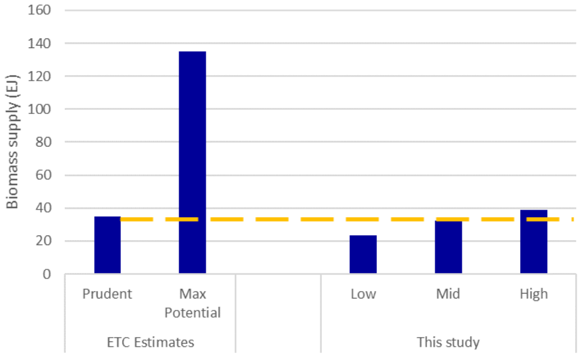

Figure 19 Comparison of modelled biomass supply scenarios against ETC estimates of feedstock potential (ETC, 2020)

The wide range of biomass availability in the literature stems from different definitions of sustainable biomass: in this case, the ETC defines sustainable biomass as material that is renewable, has a lifecycle carbon footprint equal or close to zero (including indirect land use change) and for which the cultivation and harvesting practices used consider biodiversity, land and soil health as well as socio-economic impacts. Biomass wastes and residues, such as forestry and agricultural residues and other organic wastes, could form a large part of the biomass potential.

In this study and the ETC study, the potential of feedstocks for HEFA production has been constrained based on estimates of the global availability of waste oils and fats as discussed in **Section 4.4.1**. Other studies consider the potential for energy oil crops, such as Jatropha or Camelina, which could significantly increase the feedstock availability for HEFA production, particularly if marginal land and the use of cover crops are considered. However, these are yet to be proven at large scale: establishing energy crops on such land requires a sustained effort over a period of years, and degraded sites often have alternative uses. Further, crop yields reported in literature from small-scale studies are often greater than those possible through sustainable large scale farming practices.

Algae has been discussed in the literature as a significant energy source in the future, and developers intending to use algae have been considered within this study. However, there is little activity currently, and microalgae production at demonstration scale has yet to be proven, with a notoriously low success rate. As such, the use of algae remains limited over the period to 2050.

Decarbonising the aviation sector strongly depends on the success of PTL technology and an abundance of low-cost renewable power

Due to the constraints on how quickly and to what extent biomass routes can be deployed, achieving 100% SAF supply by 2050 strongly relies on the success of PTL fuels. **Figure 13** showed that under the high scenario, PTL kerosene makes up between 54-63% of total fuel supply in 2050, in the hydrogen (F) and drop-in technology (E) cases respectively.

PTL does not face the same feedstock constraints as biofuel pathways, but costs are high and will need to be substantially reduced. The results of this study indicate that 5.4-32.4 EJ (1,500-9,000 TWh) of electricity is required, which in the high scenario is greater than the global renewable electricity generation in 2020 (~7,500 TWh from 2,700 GW installed capacity, of which ~730 GW wind and ~710 Solar PV (IEA, 2020a & IRENA, 2021). This would require substantial additional renewable electricity production above what is required to decarbonise other parts of the economy.

PTL is, to an extent, geographically constrained, in the sense that certain regions are more favourable for solar or wind power generation than others, which will enable the production of SAF at a lower cost. The IEA estimates that the global levelized production cost of hydrogen in 2050 will range between 10-27 USD/GJ (IEA, 2020). The production costs assumed in this study are based on lower-end estimates, as hydrogen production is likely to be prioritised in countries with abundant renewables potential. However, there is likely to be extreme competition for low-cost hydrogen, and hydrogen from less-than-optimal geographies may be required to satisfy demand, which may not be reflected in end fuel costs within the model.

Putting in place the required SAF supply requires a very substantial and rapid infrastructure roll-out

Meeting the estimated demand for aviation fuel in the modelled scenarios requires significant resources and investment in infrastructure. In the low scenario, based on typical nameplate capacities for fully commercial plants in each pathway, the equivalent of over 2,000 plants will need to be in operation by 2050. This increases to over 6,000 plants by 2050 in the high scenario. As a comparison, there are 700 fossil refineries in operation today.

The reason for the large quantities of plants required is that biofuel and PTL production facilities operate at smaller scales than fossil refineries; biofuel plant scale is limited by the feedstock sourcing radius and complex feedstock supply chains which can be costly. Most of these plants will need to be greenfield facilities, which will pose a significant logistic challenge not only in building the facilities but also in setting up the necessary feedstock, intermediate and end-fuel supply chains. The burden of supply chain development and costs will not fall on the aviation sector alone however as multiple industries will be competing for low carbon fuels and feedstocks. Although this will increase competition for resources, this may accelerate development of certain pathways and supply chains.

Hydrogen aviation scale-up is associated with a range of additional challenges. The introduction of hydrogen-based aircraft will place additional strain on airport infrastructure, due to the need for new on-site hydrogen storage or pipelines, and changes to existing infrastructure to cope with the extreme low temperatures of the liquid, very large volumes and other hazards. Additional uncertainties also exist regarding maintenance requirements and costs for novel hydrogen aircraft. The long lifetimes of aircraft and constraints on production line capacity limits the rate of production of new aircraft types. As a result, and assuming that the development of hydrogen aircraft makes sufficient progress to ensure that the first models enter the fleet beginning in 2035, the uptake of hydrogen aircraft would be limited to approximately a third of the global fleet by 2050. This occurs even if hydrogen aircraft are cost-competitive with new kerosene designs, as early retirement of existing aircraft would be required for greater hydrogen aircraft uptake. Early retirement is a particularly high-cost method of reducing aviation CO_2 compared to other interventions due to the increases in airline capital costs involved (e.g., Schäfer et al., 2016) and the need for investments in additional production line capacity.

Given these challenges, governments need to introduce ambitious policy measures in the near term to give industry the confidence to push forward with SAF development and hydrogen aircraft. The scenarios presented in this study introduce SAF (and hydrogen) supply through the use of ambitious mandates, which are enforced globally across all aviation travel. As noted in **Section 2.7**, although some regions are aiming to implement SAF mandates in the near term, there are many regions of the world with little to no policy currently targeting the aviation industry. In this analysis, the low supply scenarios (A and B) are based on the introduction of a global SAF mandate which mimics the proposed RefuelEU mandate as of the start of 2022. This equates to SAF comprising 63% of aviation fuel by 2050 compared to current levels, which are negligible (IEA, 2020d). Meeting this level of ambition would require a dramatic increase in uptake, and the contribution of multiple SAF production pathways, which in turn will require policy support in order to sufficiently accelerate development. For hydrogen aircraft to make any sizable impact on the aviation industry, clear and strong policy signals from governments are needed in the very near term for industry to commit and cycle through the development process for introduction of hydrogen aircraft in 2035.

Figure 14 illustrates that it will be very challenging for the aviation sector to reach net zero with the technology packages defined in this study. Whilst the combustion CO_2 emissions of SAF are considered to be zero, there are still emissions associated with the production of SAF. In 2050 the weighted average GHG intensity of SAF lies in the range 4-7 gCO_2e/MJ based on this analysis. The weighted average is lower in the high supply scenarios (E and F) due to the increased penetration of PTL kerosene which has emissions of only 1 gCO_2e/MJ when produced from renewable power. As a consequence, it is not possible to fully achieve net zero ambitions without relying on market-based-measures, e.g. offsets, or greenhouse gas removal (GGR) technologies, for example using carbon capture and storage on the SAF production plants.

7. CONCLUSIONS

This study illustrates the sheer scale of the challenge the aviation industry faces in its bid to decarbonise and ultimately achieve net-zero. The sector will not be able to rely on a single solution, and a range of measures, including aircraft developments, ATM and operational improvements, and SAF from multiple pathways will be required to meet global decarbonisation ambitions.

A significant quantity of low carbon fuels will be required, and a range of production pathways are necessary to reach the scales required to meet demand. The amount of biomass feedstock and dedicated renewable energy will be substantial compared to current usage. The necessary rate of development will also put appreciable strain on technology developers, infrastructure, and EPC resources, due to the number of production facilities that will be required and the complexity of their supply chains.

This analysis shows that, after the COVID-19 recovery period, the aviation sector can expect to see net CO_2 emissions which are higher than 2019 levels until 2030-2040, even under the most optimistic technology and policy scenarios, unless growth in demand deviates significantly from historical trends.

Nonetheless, this study shows that there is a pathway to achieving the CORSIA ambition of carbon-neutral growth, and that under the most extreme policy and technology roll-out, IATA’s previous long-term ambition of cutting emissions to half that of 2005 levels could be achievable even with continued demand growth. The modest changes in ticket prices seen in this analysis suggest such a pathway is economically attainable, but it requires aggressive technology roll-out and serious action from all stakeholders. Striving to achieve greater levels of decarbonisation, in line with the most recent ambitions set by ICAO and IATA, i.e. net-zero CO_2 by 2050, presents an even greater challenge.

Therefore, it is particularly important for policymakers to act soon if the 2050 decarbonisation objectives are to be realised. Both SAF and hydrogen aircraft can contribute significantly to reducing absolute sector emissions. But the study shows that both technology options require very aggressive development and roll-out for these aspirations to be within reach. It is therefore crucial to have firm and effective long-term policy in place soon, to give the industry proper direction and to signal that the necessary policy drivers and support will be in place.

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APPENDIX 1: INTRODUCTION

These Appendices aim to provide additional detail behind the analysis presented in the Aviation Deep Dive report. They should not be viewed as a standalone document; rather, they serve the purpose of supplementing the main report. In particular, the appendices cover details of:

- The reference aircraft used in the analysis.
- The aircraft technology assessment conducted in this study. All technologies considered are presented, with justification as to why some were not carried forwarded into the detailed modelling.
- The operational and Air Traffic Management (ATM) technologies considered.
- The alternative fuels considered in the analysis, including feedstock assumptions and the baseline GHG intensities and production costs for each route.
- How the scenarios, technology and fuel characteristics projected in this study were combined to produce projections of aviation system global-level outcomes to 2050.

In the main report, three scenarios are analyzed: low, mid and high. The appendices include additional sensitivity cases which pair low demand with high alternative fuel supply. The appendices also include additional figures and tables of outcomes from the modelling of all scenarios.

APPENDIX 2: TECHNOLOGIES

REFERENCE AIRCRAFT

This study builds upon four reference aircraft (**Figure 20**), jointly covering all major market segments. Aircraft with year 2000 technology form the basis of this classification and year 2015 technology aircraft represent improvements over the year 2000 generation.

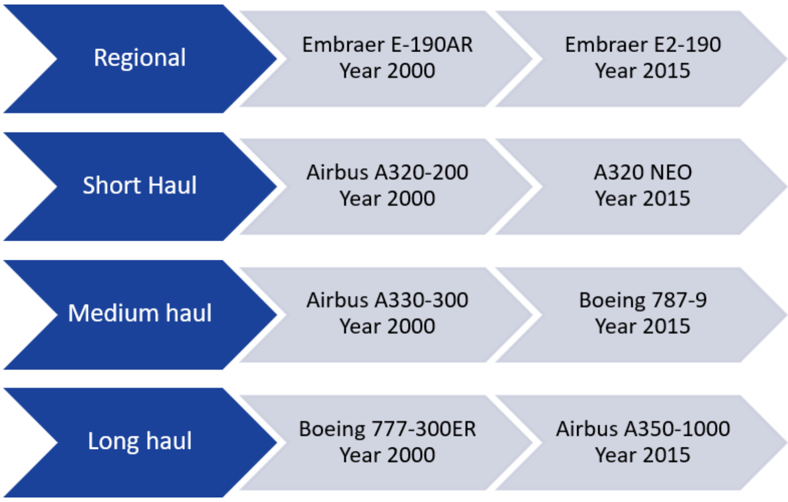

Figure 20 Aircraft types considered

For the Year 2000 aircraft **Table 5** shows the nominal seat counts and range capabilities with maximum passengers that have been assumed. In assessing the fuel burn, the aircraft weight and range factors (see subsequent section) have been taken from unpublished Ellondee analysis (Ellondee, 2020) and are also summarised in **Table 5** for the year 2000 aircraft, where MTOW is the maximum take-off weight and OWE is the operating weight empty.

Table 5 Year 2000 aircraft characteristics for fuel burn analysis

Aircraft	Seat Count	MTOW (kg)	OWE (kg)	Payload (nm)	Range with maximum passengers (nm)	Range factor (nm*lb/lbf/hr^2)
Embraer E-190AR	98	51,764	27.837	9,335	2,250	10,844
Airbus A320-200	150	78,000	43,472	15,241	2,750	13,101
Airbus A330-300	295	233,000	124,606	28,100	5,500	15,758
Boeing 777-300ER	368	351,535	168,555	35,054	7,750	16,741

In analogy to **Table 5**, **Table 6** shows the nominal seat counts and range capabilities with maximum passengers that have been assumed for the Year 2015 aircraft. To allow for a common fuel burn analysis, the seat count in each 2015 reference aircraft has been kept the same as its 2000 equivalent; this is a realistic proposition based on each aircraft's fuselage dimensions. It is noted, however, that all year 2015 aircraft have greater range capability than their 2000 counterparts as some technology benefit will have been used to achieve this at the expense of fuel burn improvement.

Table 6 Year 2015 aircraft characteristics for fuel burn analysis

Aircraft	Seat Count	MTOW (kg)	OWE (kg)	Payload (nm)	Range with maximum passengers (nm)	Range factor (nm*lb/lbf/hr^2)
Embraer E2-190	98	56,400	33,000	9,335	3,100	14,580
Airbus A320NEO	150	79,000	45,109	15,241	3,500	15,637
Boeing 787-9	295	254,012	122,924	28,100	8,250	18,304
Airbus A350-900	368	308,000	155,000	35,054	8,000	18,790

Methodology used in the assessment

To assess the potential of aircraft technologies to reduce aircraft fuel burn on the ground and in the air, an analysis based on published documents and other publicly declared information defining changes to key aircraft parameters for each technology has been used. The key parameters chosen are:

- L/D is the aircraft lift-to-drag ratio and signifies aircraft aerodynamic efficiency. Increases in this value reduce the aircraft drag for a given weight and require less fuel to be burnt during the mission.
- SFC is the engine specific fuel consumption and is the amount of fuel burnt per unit of thrust; it is an indication of the engine's efficiency. Decreases in this value reduce the amount of fuel burnt during the mission.
- Changes in empty weight change the amount of lift that is required to be generated by the aircraft. Reduction in weight reduces the amount of lift; for a constant L/D that reduces the aircraft drag and requires less fuel to be burnt during the mission.

The basis for assessing the fuel burn change using these parameters is the well-established Breguet range equation (shown below) with modifications to reflect the impact of mission reserves for diversion, hold and sufficient contingency fuel for unforeseen circumstances. This approach enables high-level technology changes to be assessed without the complexity of undertaking detailed and time-consuming aircraft conceptual designs for each technology.

The Breguet range equation in its modified form is shown below:

$$R = \frac{1}{a} * \left[ln\left(\frac{TOW}{ZFW}\right) * \left(\frac{VT * \frac{L}{D}}{SFC}\right) - b \right]$$

Where

a = 1.0435 and is the correction for specific reserve contingency used

b = 753 nm and is the correction for specific reserve diversion and hold used

TOW = mission take-off weight and is the weight of the aircraft at the point of take-off

ZFW = mission zero fuel weight and is the sum of the aircraft operating weight empty (OWE) and the payload

V_T = aircraft true speed in knots

L/D = aircraft lift to drag ratio

SFC = engine specific fuel consumption

The reserve and contingency assumptions above are defined for a specific set of conditions and have been chosen to represent the fuel requirements section of the ICAO requirements (ICAO, 2013). They are:

Diversion: 200 nm

Hold: 30 minutes at 1,500 feet above ground level

Contingency: 5% of trip fuel

And

$$\frac{V_T * \frac{L}{D}}{SFC} = RF\ or\ range\ factor$$

The block fuel burn is

$$FB = TOW - LW$$

Block fuel burn is the fuel burnt from start to shut down of main engines.

Where:

LW = landing weight (the weight of the aircraft at the point of touch down at the destination) and

$$LW = ZFW * e^{\left(\left(\frac{(A-1)*R+c}{RF}\right)\right)}$$

c = 561 nm and is the correction for hold only in the landing weight case

And take-off weight (TOW):

$$TOW = ZFW * e^{\left(\left(\frac{A*R+b}{RF}\right)\right)}$$

These equations show how changes in fuel burn can be linked to the individual technology attribute changes of L/D, SFC and weight (through a change in aircraft ZFW).

The modified Breguet range equation approach provides a fuel burn increment for a simple incremental change in attributes on an aircraft that does not change its physical size. This fixed increment can be used to represent simple part substitution on an existing aircraft such as replacing one engine type with another on an unchanged airframe. Improvements in OWE, aerodynamic efficiency (L/D) and engine efficiency (specific fuel consumption or SFC) also offer the potential for the aircraft to be redesigned to change the size of key components such as wing and engine to take advantage of the underlying attribute benefits. This is referred to as a snowballed or rubber increment and will be larger than the fixed increment. The ratio between snowballed and fixed depends on what is allowed to change and what is kept fixed.

To understand the corrections required to translate fixed results into snowballed results use has been made of an aircraft assessment tool developed by RAW Aviation Consulting Ltd. The RAWAvCon tool (RAWAvCon, 2020) is a conceptual aircraft modelling tool that estimates aircraft weight, drag and engine performance to understand mission and point performance capability including fuel burns. The results of this analysis are shown in **Table 7**.

Table 7 Snowball factors applied to the Breguet fuel burn results

Aircraft	L/D snowball factor (%)	SFC snowball factor (%)	OWE snowball factor (%)
Embraer E-190AR	+0.9	+3.5	+86.6
Airbus A320-200	+2.9	+3.1	+36.4
Airbus A330-300	+7.3	+7.6	+58.4
Boeing 777-300ER	+6.6	+6.5	+35.0

The snowball factors were derived by allowing the aircraft and engine size to change to meet a constant set of design requirements. In this case the design case for the wing was the maintenance of the aircraft's approach speed; take-off, climb and cruise performance and fuel volume were all non-limiting.

AIRCRAFT TECHNOLOGY ASSESSMENT RESULTS

The following strategies for reducing aircraft fuel burn or CO_2 emissions are described in detail below.

- Airframe related technologies
  - Reduced design cruise Mach number by 0.06
  - High aspect ratio wings
  - Ultra-high aspect ratio strutted wings
  - Natural and hybrid laminar flow
  - Flying wing or blended wing body
  - Composite materials
- Engine related technologies
  - Ultra-high bypass ratio (UHBR) turbofan
  - Open rotor
- Fuel related technologies
  - Hybrid electric propulsion
  - All electric propulsion
  - Sustainable drop in fuels
  - Hydrogen propulsion
  - Liquefied natural gas (LNG) propulsion
  - Fuel cells as APU replacement
- Air traffic management (ATM) technologies
  - Reduced taxi time
  - Cruise climb
  - Optimum track
  - Continuous Climb & Descent
  - Reduced contingency
  - Reduced diversion hold
- Operational technologies and techniques
  - Formation flying
  - Long range cruise to maximum range cruise speed/Mach number reduction
  - Engine inoperative taxi
  - E-tug
  - E-taxi

Design for reduced cruise Mach number

Aircraft fuel burn can be reduced by flying the existing aircraft slower and by designing a new aircraft to operate at a lower cruise Mach number.

Designing and operating the aircraft at a reduced cruise Mach number will not change the aircraft L/D but reduce the absolute aircraft drag and hence the thrust required; the engine will therefore be smaller and lighter, and the wing sweep can be reduced leading to reduced wing weight and improved low-speed maximum lift. The engine is also more fuel efficient (lower SFC) at lower speeds. All of these factors work together to significantly reduce aircraft size and weight and reduce fuel burn for the same mission.

The disadvantage of cruise Mach number reduction is the increase in flight time, which is getting larger with distance flown. In addition to challenges associated with passenger acceptance, airlines will see less revenue generating utilisation from each aircraft, which in turn may require more aircraft to meet the demand. At the slower Mach number, a redesigned B777-300ER would require an extra 45 minutes for a 5,000 nm trip. Conversely, the redesigned aircraft could only fly a route that is nearly 350 nm shorter if it is to be back at the home base within 24 hours of departing.

The E-190AR and A320 aircraft are designed to operate at around 0.78 Mach in cruise, whereas the A330-300 is designed for around 0.82 Mach and the B777-300ER for around 0.84 Mach. A nominal reduction of 0.06 in cruise Mach number has been used in this analysis based on a number of public reports for all of these classes and cruise Mach numbers.

The impact of slower cruise Mach number on fuel burn has been estimated by Greitzer (2010), MIT (2010), Bradley (2011). In each case, however, the reduction in cruise Mach number came with other technology changes, which had to be removed through specific corrections. The outcome in terms of expected improvements in L/D, SFC and weight, along with the snowballed fuel burn results are shown in **Table 8**.

Table 8 Changes due to 0.06 slower cruise Mach number

Aircraft	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	0	-3.4	-1,200	500	-11.3	-290
Airbus A320-200	0	-3.4	-3,180	1,000	-11.2	-660
Airbus A330-300	0	-3.4	-7,850	3,500	-12.4	-5,230
Boeing 777-300ER	0	-3.4	-12,470	4,500	-12.6	-8,660

High aspect ratio wings

Aspect ratio (AR) is a measure of the thinness of the wing from a bird's eye view. Longer, thinner wings have lower lift-induced drag than shorter stubbier ones and are thus favoured aerodynamically. Structurally, such wings will be heavier as they need to manage the resulting higher bending moments and reduce any adverse aeroelastic responses. The minimum fuel burn will then result from a balance between drag and weight. Current commercial aircraft wing aspect ratios are between 8 and 11; we define a high aspect ratio to be up to 15.

The data provided by Bradley (2011, 2012) allows comparing four different designs of the A320 size class, with aspect ratios between 9.8 and 23.1. Whereas the cruise Mach number and sweep vary with the change in AR, it will not affect the overall aircraft L/D. The Bradley (2011, 2012) assessments include some unspecified refinements in highspeed aerodynamics, interference drag and parasitic drag which cannot be corrected for. The Bradley (2011, 2012) data also includes the use of hybrid laminar flow on wings and vertical tail, which were corrected for based on information outlined in the laminar flow section.

Similarly, the aerodynamic improvement quoted in the above documents was at a higher cruise lift coefficient (C_L) than used by the reference aircraft and a correction has been applied to bring it back into the normal range (C_L ~ 0.5). The wing weight data from Bradley (2011, 2012) was verified with weight methods from Torenbeek (1986) and Al-Shamma (2013) when assessing the wing weight implications of higher aspect ratio. There is no implication on engine efficiency.

Large increases in aspect ratio move the aircraft aerodynamic centre aft, unbalancing the aircraft on the ground. Furthermore, there is an increased tendency for high incidence pitch instability as sweep and aspect ratio increase (Ellondee, 2020). The two wide-body reference aircraft thus require reductions in the sweep angle and cruise Mach number. The outcome in terms of expected improvements in L/D, SFC and weight, along with the percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 9**.

Table 9 Changes due to 15 aspect ratio wing

Aircraft	Original AR	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	8.9	+14.0	0	+1,130	500	-7.6	-200
Airbus A320-200	9.5	+12.0	0	+1,540	1,000	-8.3	-490
Airbus A330-300	10.1	+12.0	0	+5,940	3,500	-7.0	-2,970
Boeing 777-300ER	9.8	+15.0	0	+9,710	4,500	-9.8	-6,720

Ultra-high aspect ratio wings

An ultra-high aspect ratio wing, here defined as an aspect ratio of 20, requires support via a strut between a part span position on the wing lower surface and the lower fuselage. The wing will thus be mounted on the top of the fuselage. It will also have a wing mechanism to fold the outer portions of the wing upward and reduce the span to ease manoeuvring and parking when the aircraft is on the ground.

A 20 AR wing may well require a wing quarter chord sweep of 15 degrees or less. Hence, only the short haul aircraft will be able to slow their cruise Mach number down sufficiently to allow such a low sweep to be used. Nonetheless, the use of a 20 AR wing is unlikely to work with the current cruise Mach numbers for the E-190 and A320 aircraft and so the data provided below needs to be combined with a reduction in cruise Mach number of 0.06.

Greitzer (2020) considered aircraft variations relative to an A320-200 class aircraft with 17.3 and 25.9 aspect ratios, the latter being of a braced wing layout. Bradley (2011, 2012) provide data that allows a comparison to be made between four different designs (A320 size class), having aspect ratios between 9.8 and 23.1. As previously indicated, the aircraft also has some unspecified refinements in high-speed aerodynamics, interference drag and parasitic drag which cannot be corrected for. The data also includes the use of hybrid laminar flow on wings and vertical tail and corrections for this have been applied.

Bradley (2011, 2012) provides wing weights and the change in aspect ratio increase-induced weight of 6,200 lb plus 5,400 lb for the strut; the examined with also includes a wing fold mechanism. Other wing weight methods from Torenbeek (1986) and Al-Shamma (2013) result in an unstrutted weight increase of 4,100 lb for the E-190 and 6,000 lb for the A320, which are close to the Bradley (2011, 2012) results.

The outcome in terms of expected improvements in L/D, SFC and weight, along with the percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 10**.

Table 10 Changes in block fuel burn for 20 aspect ratio wings at average stage lengths

Aircraft	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	+24.0	0	+3,400	500	-3.8	-200
Airbus A320-200	+22.0	0	+5,170	1,000	-7.9	-460

Laminar flow

Laminar flow offers the potential to deliver large reductions in skin friction drag across an aircraft's wetted surfaces. The outside air when in contact with the aircraft skin forms a boundary layer that either flows in regular sheets (laminar flow) or these sheets can break down and form turbulent eddies (turbulent flow). These eddies dissipate a lot of energy which is seen as skin friction drag; the laminar sheets dissipate much less energy. On most surfaces the boundary starts off as laminar and then at some point (usually only a very short distance along the surface) it transitions (or trips) to become turbulent.

Controlling the boundary layer to be laminar for longer and reduce drag can take one of three forms which are characterised below:

- Natural laminar flow (NLF) – Managing the rate of change in air pressure through careful surface shaping to allow laminar flow to be retained for a greater distance along the surface.
- Hybrid laminar flow control (HLF) – Using suction on the front of the surface to remove the boundary layer locally and prevent turbulent flow from forming.
- Laminar flow control (LFC) – Using suction on the whole of the surface to remove the boundary layer locally and prevent turbulent flow from forming.

Of the three, LFC is least well developed and requires the most sophisticated surface finishes and mechanical suction systems and so will not be considered in this report. HLF has been developed with aerodynamic suction systems requiring no moving parts or weight; this has been designed and fitted to the Boeing 787-9 and 10 horizontal and vertical tailplanes and so will be assessed in this study. NLF is achieved through pure aerodynamic surface shaping and will also be considered in this report.

All laminar flow technologies require clean and smooth surfaces to prevent transition into turbulent flow. Both manufacturing and operational processes and technologies have to be further developed to ensure that this remains the case throughout the life of the product; this is the Achilles heel of laminar flow technology as it has yet to be consistently achieved in an operational environment. It is also noted that high wing sweeps consistent with high cruise Mach numbers are another impediment to the establishment of laminar flow.

Natural Laminar Flow

According to Braslow (1990), Bradley (2011, 2012), and Kharina (2016), a 5-6.5% improvement in aircraft L/D could be expected from natural laminar flow for the E-190 and A320 aircraft. In contrast, an only 1% aircraft drag improvement is expected for the A330-300 and B777-300ER aircraft with higher wing sweeps (Braslow, 1990; Bradley, 2011, 2012). In addition, Kharina (2016) anticipates a 1% drag reduction for aircraft size classes of the A330-300 and B777-300ER; however, this study does not include wing NLF for the A330-300 and B777-300ER size of aircraft.

Based upon these studies, this study uses a 5% overall drag reduction for both E-190 and A320 aircraft and a 1.5% for the A330-300 and B777-300ER aircraft. The percentage and absolute changes in block fuel at the average stage lengths are given in **Table 11**.

Table 11 Changes in block fuel burn for natural laminar flow at average stage lengths

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-5.2	-130
Airbus A320-200	1,000	-5.3	-310
Airbus A330-300	3,500	-1.8	-780
Boeing 777-300ER	4,500	-1.9	-1,290

Although NLF is well understood as a technology and many attempts have been made to turn it into a practical proposition, they have failed because of the manufacturing and operational challenges referred to earlier and there does not appear to be any breakthrough technology on the horizon that will change this situation. For this reason, this technology has not been considered in this study.

Hybrid laminar flow

According to Braslow (1990), HLF could result in an L/D improvement of 16-19% for E-190 and A320 type of aircraft and a 10-12% improvement for the A330-300 and 9-11% improvement for the B777-300ER aircraft. In addition, Joslin (1998) quotes a 1-1.5% drag reduction on the fin of an A320-sized aircraft and 1-1.5% reduction on the nacelles. Moreover, a FlightGlobal (2011) article quotes Boeing sources on the drag benefits of HLF on the empennage of the 787-9 of 1%. However, subsequent Boeing designs do not feature HLF, which implies that the technology is still not yet mature enough to be used operationally.

Kharina (2016) assesses HLF on the horizontal and vertical tails and concludes a total benefit of 10%. For the A330-300 and B777-300ER the benefit is 12% and would include both wings and empennage. The rationale behind the greater benefit for HLF in the larger classes in that study is not understood as these aircraft have higher sweeps to achieve higher cruise Mach number and this is not conducive for the establishment of laminar flow.

Taken collectively, and based on wing and tails, this study uses a 10 % drag reduction for all aircraft. It is further assumed that the HLF system is passive using local areas of low pressure to achieve the necessary suction. There is therefore no weight penalty for HLF. The percentage and absolute changes in block fuel at the average stage lengths are summarised in **Table 12**.

Table 12 Changes in block fuel burn for hybrid laminar flow at average stage lengths

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-9.9	-260
Airbus A320-200	1,000	-10.1	-590
Airbus A330-300	3,500	-11.2	-4,730
Boeing 777-300ER	4,500	-11.4	-7,830

The same position as postulated for NLF is taken on entry into service, namely that it is not possible to predict a date. The unwillingness of aircraft manufacturers to include this technology in new aircraft designs supports a recommendation not to consider this technology.

Flying wing or blended wing-body

The fuselage of conventional aircraft is aerodynamically inefficient as it produces drag but very little lift. The flying wing aims to remove this inefficiency by placing passengers and cargo within the deepest inboard sections of the wing and removing as much of the fuselage as possible. Further drag reductions will result from the removal of the parasitic wetted area of the fuselage.

At the same time, the removal of the fuselage and perhaps the horizontal tail will also lead to a reduction in weight, but the pressurised passenger cabin will no longer be cylindrical and is therefore likely to be heavier, as cylinders are an efficient way to manage loads associated with pressurised bodies. At this level there are no engine implications and so there will be no change in engine efficiency specially from the flying wing.

Liebeck (2004) analysed an 800 passenger, 7,000 nm aircraft and estimated an L/D improvement of 21% for comparable technologies. Plas (2007) examined similar aircraft and found an improvement in L/D of between 17.5 and 25%. Greitzer (2010) has developed a large transport flying wing concept with the same capacity as the A330-300 and a range of over 9,000 nm. It has a 16% improvement in L/D over the A330 class of aircraft. Because it also employs boundary layer ingestion, it is difficult to attribute the improvement to the flying wing concept alone without understanding the drag accounting being used.

Flying wing designs have also been considered for smaller aircraft. Bradley (2012) examined an A320 sized aircraft and projected an L/D improvement of 44%, of which around 35% could be attributed to the flying wing shape alone. Drawings in the report show an outside cabin height of ~11 ft, which in the absence of any underfloor cargo space would be sufficient for a stand-up cabin. It is less likely, however that an E-190 sized aircraft could be designed with a usable cabin height as the wing inner section height would be too small and so this aircraft class has not been considered suitable for this technology. A drag improvement of 17.5% is taken to be the same for the A320, A330-300 and B777-300ER.

For large aircraft, Greitzer (2010) projects a snowballed weight saving of 34% OWE compared to 12-19% following Plas (2007). Liebeck (2004) projects an 11% reduction in unsnowballed aircraft empty weight. The higher weight reduction has been discounted and combining the other data on an unsnowballed basis, a 10% reduction in OWE has been assumed. In contrast, Bradley (2012) points to a weight increase of 15,300 lb for the snowballed design of an A320 sized flying wing. This is contrary to the weight savings for the larger aircraft sizes and may be due to the trades involved in fitting the passenger cabin inside the wing. Even though it is a fundamentally different value to the large aircraft it has been taken on face value and used in unsnowballed form.

The outcome in terms of expected improvements in L/D, SFC and weight are shown in **Table 13**.

Table 13 Changes due to Flying Wing or Blended Wing Body architecture

Aircraft	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Airbus A320-200	+17.5	0	+5,080	1,000	-4.7	-280
Airbus A330-300	+17.5	0	-12,500	3,500	-31.2	-13,140
Boeing 777-300ER	+17.5	0	-16,870	4,500	--29.6	-20,410

The above-cited studies, which were produced between 2004 and 2011, point to a suitably designed passenger cabin being at TRL4 by 2025. However, since then, little further research work has been done on the architecture. If research restarted now, it would be unlikely that the aircraft could be in service before 2040. There are also significant airport infrastructure implications (such as jetway access and taxiway design) that will also need to be funded and built, before the aircraft can be commercially operated. The reported weight increase for the small flying wing aircraft leads to a very modest fuel burn improvement in conjunction with the difficulties associated with designing a useful cabin in a relatively small wing cross-section. This suggests that the technology may only be suited to widebody aircraft.

Composite materials

Over the past five decades, composite materials, such as carbon fibre reinforced polymers (CFRP), have been replacing metals, initially in aircraft secondary and then primary structures. The degree of composite use on aircraft has continuously increased from essentially zero in the 1970s to around 50% of structural weight today (Smith, 2013). In addition, gas turbine engines are progressively introducing CFRP materials to engine structures and rotating components, where the temperatures are cool enough not to affect the material's strength. Ceramic matrix composites (CMC) are also under consideration in the hottest parts of the gas turbine engine to replace exotic metal alloys.

In all cases, the technology aims to reduce the weight of the materials for a given level of strength and may also introduce other beneficial properties such as better fatigue resistance. The added advantage of CMCs is that they allow even hotter engine cycles with the potential to improve engine efficiency. There may also be some small improvements in aerodynamic efficiency by the tailoring of the material properties to manage changes in wing shape with changes in aerodynamic loads. This benefit has not been considered in this study.

The A320 and E-190 aircraft have about 15% of composite use by weight, the A330-300 about 13% and B777-300ER around 11% (Smith, 2013; Arakaki, 2007). Whereas the most recent aircraft designs have around 50% composite use, it seems likely that the full weight saving benefit of composite material has yet to be achieved due to relative inexperience with the material in the design phase and conservatism in the certification rulemaking. Ashcroft (2011) suggests that a further 15% weight saving can be achieved through the use of composites in place of traditional aerospace metals. Bradley (2012) provides further definition on weight saving potential for different component types, ranging between 15-25%. A similar structural weight reduction potential of 17% is projected by Kharina (2016) for 2034 aircraft. Based on these studies, a weight reduction of 17.5% will be taken for composites relative to current aluminium alloys and it can be applied to 50% of the components by weight.

It is necessary to understand the likely change in empty weight as a consequence of the component level change. Major structure level aircraft weight breakdowns are found in Obert (2009) and Torenbeek (1986) and are summarised in **Table 14**.

Table 14 Component group weight as a function of maximum take-off weight

Aircraft	Wing & Controls (%)	Fuselage (%)	Empennage (%)	Landing Gear (%)	Nacelle (%)	Total (%)
Embraer E-190AR	13	12	3	4	1	32
Airbus A320-200	14	12	2	3	1	32
Airbus A330-300	17	12	2	4	2	36
Boeing 777-300ER	17	11	2	4	2	36

The engine will also benefit from low temperature composites in some of the structural frames and fan. Lolis (2014) estimates the percentage weight breakdown for major components of gas turbine engines, which can be used as a rough approximation to any weight savings targeted against these components for the 2-shaft gas turbine engines in the E-190, A320 and B777-300ER aircraft and the 3-shaft gas turbine engine in A330-300 aircraft in **Table 15**.

Table 15 Gas turbine weight breakdown relative to dry engine weight

Component	2 shaft engine weight (%)	3 shaft engine weight (%)
Fan	30.8	33.7
Booster or Intermediate pressure compressor	7.5	10.0
High pressure compressor	9.8	3.8
Combustor	2.4	1.3
High pressure turbine	4.6	3.2
Intermediate pressure turbine	n/a	2.9
Low pressure turbine	11.3	17.8
Ducts	0.9	0.6
Shafts	2.4	3.0
Frames	20.2	13.6
Controls & accessories	10.0	10.0

The weight benefit from CMCs in engines is a third of the weight of the metal equivalents (Bradley, 2012). Grady (2013) quotes a 4.85% dry weight reduction for an unspecified engine.

Consistent with the airframe, a 17.5% weight reduction has been applied to 50% of the components in the fan and frames. A 4% saving to high pressure turbine weight from CMCs is also applied to the values in **Table 15**. The resulting weight reduction for airframe and engine for each aircraft type is shown in **Table 16.**

Table 16 Airframe and engine weight reductions through the use of composites

Aircraft	Airframe weight reduction (kg)	Single engine weight reduction (kg)	Total weight reduction (kg)
Embraer E-190AR	-1,500	-170	-1,840
Airbus A320-200	-2,180	-200	-2,580
Airbus A330-300	-7,580	-410	-8,400
Boeing 777-300ER	-11,070	-690	-12,450

Bradley (2012) quotes a potential thermal efficiency improvement of 2.5-5% due to higher temperature cycles enabled by the CMCs; the upper end being achieved if it becomes possible to eliminate the high-pressure turbine cooling air. Grady (2013) quotes a 3% improvement level. Based on these studies, a value of 3% improvement is used in this study.

The outcome in terms of expected improvements in L/D, SFC and weight, along with the percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 17**.

Table 17 Changes in block fuel burn for the use of composite materials at the average stage length

Aircraft	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	0%	-3	-1,840	500	-12.6	-330
Airbus A320-200	0%	-3	-2,580	1,000	-9.4	-550
Airbus A330-300	0%	-3	-8,400	3,500	-12.5	-5,260
Boeing 777-300ER	0%	-3	-12,450	4,500	-12.0	-8,300

The airframe and engine have both already adopted some structural composites although, as noted above the industry has some way to go to get down the learning curve to fully exploit the potential. It is suggested that the full exploitation could be achieved by 2035.

Small CMC components are now being introduced into the current engine designs but not yet enough to achieve the technology impact identified here. In the absence of any information, it is proposed to link the timescale of the maturity of CMCs, sufficient to meet the improvement attributes, to that of low temperature composites. This may prove to be optimistic.

Ultra-high bypass ratio (UHBR) turbofan

The greater the ratio of bypass air to core air, the greater the propulsive efficiency and the lower the SFC. On the negative side it increases engine physical size, weight and drag for a given thrust. For it to reduce fuel burn, the contribution to fuel burn from SFC reduction has to be greater than the combined fuel burn increase from the weight and drag plus any other aircraft related weight and drag changes due to installing a much bigger engine on the airframe.

Greitzer (2010) and an MIT (2010) study compare the UHBR performance on an aircraft to replace an A320-200 class aircraft. An engine of 20 bypass ratio (BPR) will reduce fuel burn by 4.2% relative to the baseline (Greitzer, 2010), whereas the MIT (2010) study suggests a cruise SFC of 0.37 lb/lbf/hr at 0.74 Mach number in a Boundary Layer Ingestion (BLI) installation with a BPR 20 engine. This report also shows how SFC varies with Mach number for the same engine, suggesting that SFC reduces by 0.01 lb/lbf/hr when the Mach number declines from 0.76 to 0.72. This implies a 19% SFC reduction relative to the baseline CFM56 engine at the same Mach number for a 14 BPR engine.

Bradley (2011) quotes a cruise SFC of 0.442 lb/lbf/hr for a similar engine (with a fan diameter of 71 inches) and a dry weight of 6,400 lb but a sea level static thrust of only 22,000 lbf (cf. 33,000 lbf for the reference A320 CFM56 engine). Collier (2009) quotes fuel burn savings of 13-15% relative to the CFM56-7 (the engine on the Boeing 737-800), whilst Bradley (2012) suggests a 28% SFC reduction to a CFM56 (subtype not specified) and a dry weight increase of 1,500 lb for an engine with a 77-inch diameter fan and 13 BPR.

According to ENOVAL (2014), UHBR technology will provide a 26% fuel burn improvement for a long-range engine relative to year 2000 technology (ENOVAL, 2014). Rolls-Royce (2016) predict a 25% improvement relative to Trent 700. Daggett (2003) found that higher-bypass ratio engines will offer an up to 9% lower SFC than the GE90-94B (SFC datum 0.528 lb/lbf/hr giving improved SFC of 0.480 for a BPR of 13.1) and 14.5% lower than the PW4000 (SFC datum 0.554 lb/lbf/hr giving improved SFC of 0.474 lb/lbf/hr for a BPR of 21.5).

Giesecke (2018) suggests a top of climb SFC of around 0.47 lb/lbf/hr, probably at 0.78 Mach number for an A320-200 sized aircraft. This is a 27,000 lbf take-off thrust class engine and so is some 22% lower than year 2000 engines in this class. This is consistent with other references.

Building upon data from Jenkinson (2001) and Rolls-Royce (2006) contain the data describing the baseline engines fitted to the reference aircraft. These are shown in **Table 18**.

Table 18 Engine characteristics for reference aircraft

Aircraft	Engine	BPR	Fan diameter (m)	Dry weight (kg)	Cruise SFC (lb/lbf/hr)	Reference thrust (lbf)
Embraer E-190AR	CF34-10E	5.3	1.35	2,080	0.629	18,500
Airbus A320-200	CFM56-5B	5.5	1.74	2,380	0.528	30,000
Airbus A330-300	CF6-80E	5.3	2.44	5,090	0.567	72,000
Boeing 777-300ER	GE90-115B	8.9	3.25	8,280	0.539	115,000

For engines in the 14 to 15 BPR class on small aircraft it seems likely that the SFC reduction is of the order of 20% and this will be used for the E-190 and A320 aircraft as the potential improvement. Based on the datapoints describing relationship between change in SFC and change in BPR discussed above, it is assumed that the A330-300 will improve SFC by around 15% for engines of around 15 BPR and the B777-300ER by 12%.

Two weight data points have been found for engines to be fitted on the A320 size of aircraft. An increment of 1,200 lb can be discerned when comparing the baseline engine with that dry weight quoted in Bradley (2011) and an increment of 1,500 lb in Bradley (2012). Kharina (2016) points to weight reductions rather than increases and other reports suggest no weight change; this is in contrast to industry trends of increased BPR. The latest technology CFM56 sized engines such as the CFM Leap and the Pratt & Whitney Pure PW1000 series engines are some 1,000 lb heavier than the CFM56 even with the application of the latest weight saving technologies (EASA Type Certification Data Sheets, EASA 2016, 2017, 2019). A nominal weight increase of 1,500 lb/engine is to be used for A320 and the same percentage weight delta applied for the E-190 (i.e., 1,300 lb per engine). The A330-300 engine has the roughly the same BPR increase and will take the same percentage engine weight increase to give an absolute increase of 3,200 lb per engine. The B777-300ER already has a higher BPR and so the increase in weight will be less. Linearly scaled by the BPR change, there is predicted to be a weight increase of 4,000 lb/engine.

There has been no discussion on drag in any of the references found on this topic. Thus, a simple analytical assessment approach has been used to assess the change in nacelle drag for the increase in fan diameter required to increase the BPR of the engine; this assumes that nacelle drag change is proportional to diameter squared. Any interference drag effects between the nacelle and the rest of the airframe have not been included as industry best practice will seek to remove these through careful aerodynamic tailoring of the local surfaces. A typical cruise drag breakdown by component is shown by Bradley (2012) and nacelles contribute ~10% to the skin friction drag and skin friction drag contributes ~60% to the total aircraft drag. The resultant drag is around 1.6% for the fan diameter changes required to meet the BPR for the E-190, A320 and A330-300. The B777-300ER engines have a higher BPR and so the fan diameter change required for the UHBR is much smaller and the drag increase is estimated at 0.2%.

The outcome in terms of expected improvements in L/D, SFC and weight, along with the percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 19**.

Table 19 Changes due to installation of UHBR engine

Aircraft	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	-1.6	-20	+1,180	500	-14.4	-380
Airbus A320-200	-1.6	-20	+1,120	1,000	-17.2	-1,010
Airbus A330-300	-1.6	-15	+2,900	3,500	-13.3	-5,630
Boeing 777-300ER	-0.2	-12	+3,630	4,500	-12.2	-8,440

Projected entry into service information for UHBR engines has been sparse. On the one hand, MIT (2010) refers to TRL4 in 2025 and Rolls-Royce (2016) anticipate the launch of a UHBR in 2025. Normally the time between TRL4 and entry into service (EIS) is at least 10 years and launch to EIS is 5 years so there is some difference in these two datasets. Furthermore, the impact on the aerospace industry of the ongoing COVID-19 pandemic (at the time of writing) has probably pushed plans for any new aircraft programme backwards by at least a few years. 2030 will be set as the earliest EIS for the E-190 and A320 and 2035 for A330-300 and B777-300ER (noting that UHBR requires a gear box on the low-pressure fan and turbine shaft and that higher thrust for these bigger engines will require much higher transmission of power and torque that in turn will require extra technology and capability development).

Open rotor

Open rotor engines are a way of using propellers rather than turbofans to increase the BPR even further than a UHBR without the weight increase of a larger fan structure and the weight and drag increase of a larger nacelle. Propellers lose efficiency as Mach number increases and this will offset any SFC gains; open rotors aim to reduce this efficiency loss by tailoring the shape and thickness of the rotor blades. Guynn (2011) comments that work has been undertaken on aircraft with cruise Mach numbers less than 0.8 and the only aircraft currently using them (Airbus A400M) are well below this value (Aviation Week, 2013). The Airbus A400M has a cruise Mach number of 0.68 and maximum operating Mach number (MMO) of 0.72 and the Antonov An-70 (Balabuyer, 2002) claims to be able to achieve an MMO of 0.8 and a cruise Mach number of 0.70.

Given that the normal cruise Mach numbers for open rotors in service and in research seem to be in the region of 0.70 to 0.73 with one outlier at 0.78, it is judged unlikely to be high enough for economic operation of the longer ranges utilised by the A330-300 and B777-300ER.

Work undertaken by GE to support a NASA study (Bradley, 2011) developed an A320 sized aircraft using a wing mounted 144-inch diameter open rotor weighing 7,700 lb and having an SFC of 0.394 lb/lbf/hr at 0.73 Mach number but being powered by liquefied natural gas (LNG). A correction for the energy density between LNG and kerosene gives an SFC of 0.404 lb/lbf/hr for a kerosene powered open rotor (-32.4% relative to baseline). Further work in the NASA report (Hendricks, 2012) looked at a 27,000 lb open rotor (again the same thrust capability required by A320). A cruise SFC of 0.428 lb/lbf/hr (-28.4% relative to baseline) was quoted at a Mach number of 0.78 with a total powerplant system (PPS) weight of 9,220 lb. Correcting this to 0.73 Mach number would result in an SFC around 0.41 lb/lbf/hr, which is consistent with the value above. In addition, Larsson (2012) presented a short haul aircraft open rotor with a 14% better SFC and 11% higher weight than a 2020 direct drive turbofan at its design Mach number of 0.73. This is roughly equivalent to a CFMLeap or PW1000 engine. Data from the EASA TCDS (EASA 2016, 2017, 2019) point to a 1,000 lb heavier engine than the reference CFM56 engine and so this reference would suggest an engine weight of 7,000 lb, which is in the same ballpark as the NASA study (Bradley, 2011) data. According to Fehrm (2015), cruise SFC for the CFMLeap and PW1000 is reputed to be 15% better than the CFM56 and so a 14% improvement on that would suggest a cruise SFC of 0.437 lb/lbf/hr (-27% relative to baseline). This is slightly higher than noted in the other sources. Aggregating this data, it has been decided to set the SFC reduction for an open rotor at 30% for both the E-190 and A320.

The only source on aircraft drag due to open rotors was found in a COMAC paper (Chao, 2016) and looked at both fuselage and wing mounted open rotors. Based on computational fluid dynamic (CFD) assessments, the wing mounted installation increased drag by 3% whereas the fuselage mounted installation reduced drag by about 0.5%. For both the E-190 and A320 the 3% increase in drag will be used. Where the weight is declared as a dry engine weight for the A320 class engine, the increment is around 1,500 lb giving a total increment of around 2,500 lb when corrected for the year 2000 technology baseline point, rather than 2015. The higher weight of 9,220 lb is a PPS weight and will include accessories and other installation fitments so is not directly comparable with the dry engine weight. Kim (2010) suggests that these items contribute about 18% to a PPS and so this allows a simple correction to be made to get a rough dry engine weight estimate of ~7,600 lb. The nominal weight increase per engine has thus been set at 2,500 lb per engine for the A320. The E-190 weight has been scaled by the current engine weights to achieve the same percentage weight change; the resulting weight increase in 2,200 lb per engine.

The outcome in terms of expected improvements in L/D, SFC and weight, along with the percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 20**.

Table 20 Changes due to installation of open rotor engine

Aircraft	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	-3.0	-30	+2,000	500	-19.5	-500
Airbus A320-200	-3.0	-30	+2,270	1,000	-24.1	-1,410

The EIS is only referenced in one document and points to between 2040 and 2050. It is known that Safran have been running an open rotor demonstration programme as part of EU research programme CleanSky2 and that there are no active programmes in the US. Whilst the original intent was to fly the engine on the CleanSky2 project, the engine only completed a ground test programme and there are now no publicly declared plans to continue development of the technology. Comparison of the fuel burn benefits with the UHBR show that the Open Rotor has the potential to provide around 5% lower fuel burn than the UHBR. The challenges that face the industry in adopting this technology consist of noise (where the Open Rotor can act like a siren), increased mechanical complexity and the economic aspects of lower cruise Mach number. Given these challenges and the relatively small improvement relative to a UHBR, open rotor engines are not considered any further.

Electric propulsion

Electric propulsion for aircraft is divided into two categories, hybrid-electric and all-electric and both categories are discussed in this report. The use of electricity to supplement or completely replace hydrocarbon fuels offers the potential to reduce the CO_2 emitted by the aircraft.

All-electric

All-electric uses electrical storage devices (such as batteries or super capacitors) to power electric motors and generate thrust through propellers or fans. As such, no hydrocarbon fuel is burnt by the aircraft and there are no CO_2 emissions during the flight. There is therefore no relevance of aircraft weight or aerodynamic or engine efficiency to emissions. The power and energy required to fly the aircraft will be strongly governed by weight, aerodynamics and electric storage, motor and distribution efficiencies.

Energy storage and motor capabilities will govern the entry into service for this class of aircraft. Weight will be key to managing the power required to fly the aircraft and volume will be key to fitting the batteries into the aircraft and to managing weight as extra volume requires more mounting structure and external skin to enclose it. Kerosene is ~80 times more energy dense in weight terms than lithium-ion batteries and ~35 times more energy dense in volume terms. A simple analysis has been undertaken on a E-190 sized aircraft with a 20% allowance on maximum take-off weight fitted with batteries to drive propellers and flying at 0.73 Mach number. The datum battery densities are 0.5 MJ/kg and 0.8 MJ/litre with technology-based weight allowances made for the motors and distribution systems. Two-, three- and four-fold improvements have been made to these technologies and the impact of range assessed based on the same mission reserve assumptions applied in this document. The aircraft requires around 1.5 MW of power just to get airborne.

The E-190AR is capable of carrying 98 passengers around 2,400 nm using the same reserve assumptions; the fourfold increase in current electrical technology will only be able to fly the same payload 310 nm which is of limited real interest to the market. It is recognised that much work is being done around the world to improve densities for all the electric components but there is a very long way to go to achieve sensible complete substitution of kerosene by electricity noting that a fourfold increase above the current state of the art is nowhere near enough to create a viable aircraft at the bottom end of this report's analysis scope.

A number of all electric demonstration flights have been undertaken using small general aviation and commuter aircraft, the largest at the time of writing being the Cessna Caravan which is advertised as being able to carry 4 to 5 passengers 100 miles plus reserves. This is a far cry from the requirements of the commercial aircraft being studied in this report. It is clear that powering any of the commercial aircraft being evaluated in this report by electric power alone by 2050 will not be a viable proposition.

Hybrid electric

Given the difficulties in using all-electric power for aircraft being considered in this report, as laid out above, a solution that uses both hydrocarbon and electrical power sources needs to be considered. There are a number of different ways in which hydrocarbon and electrical power can be combined from batteries supporting fuel burning engines via motors or fuel burning engines charging batteries and driving electric motors. Bradley (2011, 2015) explores one particular arrangement, the parallel hybrid-electric, where an electric motor is embedded in a gas turbine engine to provide supplementary power to the gas turbine shafts and is powered by batteries. The motor may also be a generator and re-charge the battery when excess power is available from the gas turbine.

Bradley (2015) quotes an equivalent SFC reduction of 28% for a battery powered embedded motor on an aircraft of E-190 or A320 size; the motor in this case is sized to supplement the engine thrust rather than replace it in certain flight segments. In the absence of any other information, the same SFC improvement will also be employed for the A330-300 and B777-300ER.

The engine powerplant system (PPS) weight is quoted at 9,300 lb for a 72.1-inch diameter fan. This is bigger than the reference CFM56-5B (see **Table 21**) and a correction to the dry weight of an engine in the same class is required. Scaling to the power of 1.5 is used based on fan diameters and suggests that this engine should weigh around 5,700 lb; hence, there is 3,600 lb of extra equipment fitted to it to support the hybridisation. Using the same factor, the nacelle will be 9% heavier or around 500 lb/engine. Thus, the PPS weight increase for hybridisation is around 4,100 lb/engine. The battery densities in these studies are 750 Wh/kg and 1,200 Wh/litre and the motor is 1,000 W/kg. These are roughly 2-3 times higher than the current capability and the nominal values used in the all-electric study above. The same reference also quotes the installed battery weight as 15,700 lb and the power systems weights as 4,000 lb. The total aircraft weight increase is thus 27,900 lb.

To apply this to other engines, a simple thrust ratio law will be employed on the assumption that weight scales with thrust or power for the engine and the systems. Batteries will be scaled by thrust and design range to allow sufficient power for the full flight. So, the weight delta for hybrid electrification from the CFM56 can be used to estimate weights for the engines on the E-190, A330-300 and B777-300ER.

These weight increases will be extremely large; even given the large reduction in SFC the outcome will not give any meaningful fuel burn reductions. To understand the scope for improvement, a scenario with a further two-fold improvement in power and energy density for batteries (1,500 Wh/l) and motors (2,000 W/kg) (as looked at in all electric power but accounting for the different datum energy density) has also been examined. The resulting total nominal aircraft engine and system weight increments for this improved scenario are shown in **Table 21**.

Table 21 Unsnowballed hybrid electric aircraft weight build-up for improved energy density

Aircraft	Delta engine weight (kg)	Number of engines	Delta battery weight (kg)	Delta system weight (kg)
Embraer E-190AR	560	2	1,820	560
Airbus A320-200	820	2	3,560	900
Airbus A330-300	2,220	2	17,100	2,180
Boeing 777-300ER	3,560	2	37,240	3,460

Aerodynamically, the battery surfaces add an additional 1% drag, according to Bradley (2011). As the engine has a larger fan diameter, the nacelle will be bigger and contribute additional drag. This equates to a 12% increase in area (if the nacelle length to diameter ratio is maintained). Nacelle drag is 3% of aircraft drag for each twin-engine aircraft so it will increase aircraft skin friction drag by 0.4%. The overall aircraft drag is 1.2% for twin engine assuming that zero lift drag is 60% of overall aircraft drag.

The outcome in terms of expected improvements in L/D, SFC and weight, along with the percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 22**.

Table 22 Changes due to parallel hybrid electric engine and batteries

Aircraft	Delta L/D (%)	Delta SFC (%)	Delta OWE (kg)	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	-1.2	-28	+3,500	500	-11.5	-310
Airbus A320-200	-1.2	-28	+6,100	1,000	-15.2	-890
Airbus A330-300	-1.2	-28	+23,720	3,500	-7.5	-3,180
Boeing 777-300ER	-1.2	-28	+47,820	4,500	-0.6	-400

Per annum battery energy density improvement is currently between 5-8% but there is no opinion expressed on whether this can be sustained on a compound basis. Based on current values, battery energy densities will not reach the assessment value before 2050 at a 5% compound improvement rate. Bradley (2012) suggests 2040 to 2050 for this technology's EIS; the later date is consistent with the continuous improvement value. It is also noted that the technology works better on smaller aircraft given the lower weight penalty of the batteries and may also be more practical given the motor power required for the larger aircraft will be very high. It is recommended, therefore that this technology is not considered for assessment up to 2050 but may be applicable to smaller regional aircraft at some point between now and 2050.

A report prepared by NLR and SEO (2021) has concluded that hybrid electric offers potential to reduce fuel burn. It has looked at the same concept studies as this report to draw this conclusion. It has not however, assessed each technology individually and so the claim for fuel burn improvement for hybrid electric is being confused with a fuel burn improvement for a whole series of aircraft technologies including hybrid electric. As this report has attempted to look at each technology in isolation, it is believed that the conclusion that hybrid electric does not offer any meaningful benefit in the aircraft sizes assessed until significant system weight reduction technologies are matured is valid. Even then it will most likely be applied to the smaller aircraft classes and this is consistent with the views in the NLR/SEO report.

Sustainable aviation fuels

Sustainable aviation fuels (SAF) are synthetically created from renewable or waste feedstocks to create a kerosene-style liquid that can be blended with kerosene and burnt in current gas turbine engines. Feedstocks can include waste oils from other processes, solid waste from homes and businesses, wood, residues and other energy crops.

The net reduction in CO_2 emissions comes from the reabsorption of CO_2 through recreation of the biomass or from the avoidance of other CO_2 emissions, rather than reducing the jet pipe emissions at the aircraft level. The intent with SAF is that the fuel can be used without any change to the gas turbine engine or associated fuel systems on the aircraft and as such is characterised as a drop-in fuel. The amount of SAF that can be blended with kerosene is currently limited to 10-50% depending on the type of SAF, although SAF types that can be used without blending with fossil kerosene are being developed. Technical details and reference values such as indicative emission factors for various types of SAF are given in the fuel production section of the appendices, below.

The impact on the aircraft weight and drag of using SAF is zero. However, if there is a deviation in fuel density and/or calorific value relative to the datum values of fossil kerosene used during the aircraft design processes, it must be accounted for to understand the aircraft jet-pipe impact. A change in calorific value will be equivalent to a change in SFC. This could result in either an increase or decrease in fuel weight which will be equivalent to changing zero fuel weight at each stage length to account for the different weight of fuel being burnt and carried. In addition, the aircraft payload/range capability may be impacted through limitations in the aircraft’s maximum take-off weight or fuel tank capacity. If the payload/range is negatively impacted and must be restored this would require a significant degree of aircraft re-design that, in the worst case, will affect wings, engines, undercarriage and empennage.

Assessment of the impact of operating aircraft on 100% Sustainable Aviation Fuels

The amount of SAF that can be used in conjunction with kerosene is currently limited by certification to up to 50% by volume for certain SAF types and 10% by volume for others. However, certain SAF types may at some point be certified to operate without blending with fossil kerosene. In light of the slightly different thermo-physical characteristics than fossil kerosene, this section evaluates the aircraft level performance impact of a 100% SAF use. Guidance from CONCAWE has provided SAF properties, which are shown in **Table 23**. Note that these characteristics were used exclusively for the assessment of the impact of operating on 100% SAF and that they differ slightly from the baseline kerosene and SAF values used in the rest of the study.

Table 23 Fuel properties used for the 100% SAF analysis

	Kerosene	SAF	Percentage Delta wrt. Kerosene
Fuel density	807 kg/m^3	755 kg/m^3	-6.4%
Fuel calorific value	43.10 MJ/kg	44.11 MJ/kg	+2.3%
CO_2 to fuel burn ratio	3.15	3.10	-1.6%

The change in fuel density affects the mass of fuel that can be loaded into an aircraft tank, which in turn affects the maximum amount of energy that can be stored. The change in fuel calorific value changes the amount of energy carried per unit of weight which changes the aircraft's weight for a given mission and hence its payload. Both impact the aircraft's payload range and only the fuel calorific value affects mission block fuel burn.

A typical aircraft payload range is shown in **Figure 21**, where the effects are exaggerated for clarity. Three limits exist that cannot be legally exceeded when determining the maximum aircraft payload for a given range.

- Maximum zero fuel weight: this is not relevant for the SAF fuel properties
- Maximum take-off weight: this requires that the sum of the aircraft empty weight and fuel weight must not exceed the maximum take-off weight.
- Maximum fuel volume: providing that the payload is low enough, the volume of fuel that can be loaded is constrained by the tank size.

Thus, depending on the amount of payload, the maximum range that the aircraft can fly can be limited by either the tank volume or the maximum take-off weight (MTOW) limit.

The reference case for fossil kerosene is show in blue in **Figure 21**. If the fuel density is decreased (grey line):

- At low payloads, maximum range is reduced as the amount of fuel that can be loaded is limited by the tank volume. With lower density fuel, this means less weight of fuel and therefore also less total energy for the given tank size.
- Once the MTOW limit is reached the weight of fuel that can be loaded - and therefore the total amount of energy - is the same as for the datum.

If the fuel calorific value is increased (orange line in **Figure 21**):

- At low payloads where maximum fuel uplift is limited by tank volume, maximum range is increased as the fixed tank volume can hold more total energy. Note that the slope of the boundary is increased due to the higher calorific value.

- Where maximum fuel weight is limited by the MTOW, the increased calorific value still means that maximum range is increased as the given weight of fuel translates into more total energy.

According to **Table 23**, 100% SAF is expected to have a higher calorific value and a reduced density relative to fossil kerosene. This is shown in the green line in **Figure 21**. The two sets of effects outlined above both apply and partially balance each other out:

- At low payloads, and dependent upon the relative changes in fuel density the two effects may partially balance each other out
- Where maximum fuel weight is limited by the MTOW, the boundary is the same as for the orange line, yielding slightly increased range.

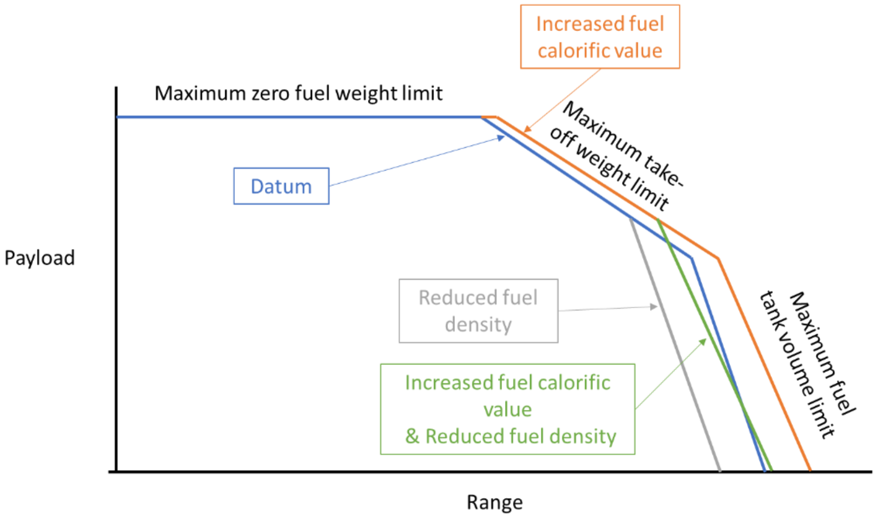

Figure 21 Aircraft payload range diagram with different fuel properties

Different aircraft types can be either maximum take-off weight or maximum tank limited on their design payload and design range case as shown in **Figure 22**.

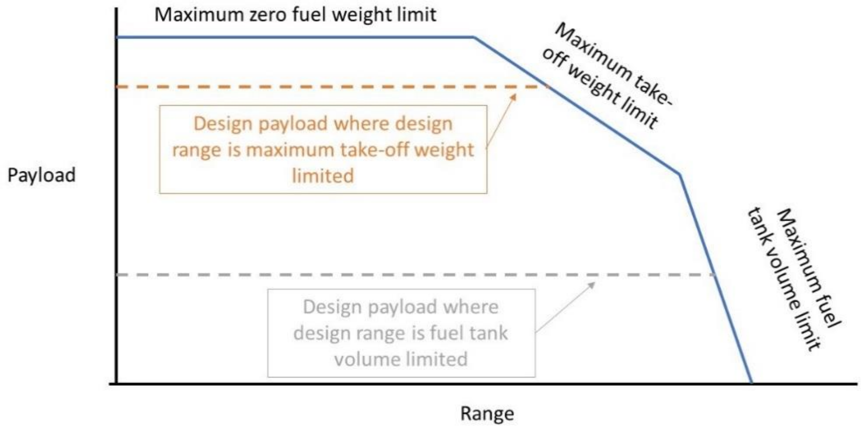

Figure 22 Aircraft payload range diagram for different aircraft types

The specifics for the chosen aircraft and their design payload are as follows:

- Embraer E-190AR is tank volume limited and the reduction in design range for the change in SAF properties is 120 nm from the datum value of 2,370nm (5% reduction)
- A320NEO is maximum take-off weight limited and there is an increase in design range for the change in SAF properties of 80 miles from the datum value of 2,850nm (2.8% increase)
- A330-300 is tank volume limited and the reduction in design range for the change in SAF properties is 220 nm from the datum value of 5,520nm (4% reduction)
- Boeing 777-300ER is maximum take-off weight limited and there is an increase in design range for the change in SAF properties of 180 miles from the datum value of 7,900nm (2.3% increase)

These calculations have been estimated using the Breguet range equation method outlined at the beginning of the Appendices.

In practice, commercial aircraft rarely operate at their maximum payload range point, especially at lower tank volume limited payloads. This is less true of business jets where low payloads and long distances are the norm. It is possible that new commercial aircraft designs will include a requirement for tank sizing to take account of SAF and this may increase aircraft wing area and weight by a small amount. For the purposes of this study, it is sufficient to recognise the potential for small aircraft changes to maintain headline payload range capability and to accept that it will not be an impediment to the introduction of the use of 100% SAF.

The percentage and absolute changes in fuel burn and jet-pipe CO_2 for aircraft operating with 100% SAF have been assessed using the Breguet range equation method outlined at the beginning of the Appendices, applying a change in SFC equivalent to the change in fuel calorific value from **Table 23**. The results are shown in **Table 24** and suggest that aircraft level impacts will result in additional reductions in both fuel burn and jet-pipe CO_2 emissions beyond those accounted for in the conventional life-cycle emission for various SAF pathways when operating on 100% SAF.

Table 24 Fuel properties used for the 100% SAF analysis

Aircraft	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)	Jet pipe CO_2 change (%)	Jet pipe CO_2 change (kg)
Embraer E-190AR	500	-2.5	-20	-4.0	-330
Airbus A320-200	1,000	-2.5	-70	-4.1	-750
Airbus A330-300	3,500	-2.7	-510	-4.2	-5,610
Boeing 777-300ER	4,500	-2.7	-850	-4.3	-9,280

Other considerations on the impact of SAF on the design and durability of the engine gas path and its fuel delivery systems have not been considered, nor has the impact on the wing tank corrosion resistance properties.

Liquid hydrogen fuel

Compared with kerosene, liquid hydrogen (LH2) has a much higher weight-based energy density (120 MJ/kg vs 43.1 MJ kg) but a much lower volume-based energy density (8.5 MJ/litre vs 32 MJ/litre). To remain a liquid, it needs to be stored at around +20 K and this is a requirement of aircraft use as gaseous hydrogen volume density is much too low to allow it to be sensibly stored onboard. LH2 will be pumped into aircraft tanks that will be designed to store the liquid at an overpressure and to minimise the temperature rise of the liquid to minimise any boil off into gas.

The key advantage of burning hydrogen, rather than kerosene is that it does not generate CO or CO_2 and so will remove aircraft's emission contributions to both of these gases if adopted. It does generate 2.6 times as much water vapour that may have implications for global warming through the creation of cirrus clouds from contrails. Whereas it will also create NO_x from the natural nitrogen in the atmosphere, it is not clear whether more or less NO_x will be created given the different engine combustor volumes, flame temperatures and flame speeds that exist between hydrogen and kerosene.

Other considerations for liquid hydrogen are:

- Possible CO_2 generation associated with the creation of hydrogen (usually through electrolysis of water) and the subsequent cooling of the gas to form and maintain it as a liquid.
- Airport infrastructure will need to change to safely handle and distribute liquid hydrogen to the aircraft, noting the extreme cold temperatures of the liquid and the very large volumes that need to be moved. Maintenance of short aircraft turnaround times whilst delivering four times the fuel volume during refuelling will need careful consideration during both airport and aircraft design phases.
- Storage on board the aircraft:
  - Given the need to store the liquid at a constant overpressure and at very cold temperatures, it is most likely that it will be stored in spheres or cylinders to minimise surface to volume ratio, thus reducing heat transfer into the liquid causing it to boil into a gas, and to keep the

  storage system weight down. This means that kerosene style wing tanks will not be possible, and the tanks will either be positioned internally in the fuselage or externally above the fuselage or pylon mounted on the wings.

  - The position of the tanks will have to maintain the required ease of entry and exit for crew, passengers and cargo and not compromise the aircraft centre of gravity.
  - In the event of a tank rupture, the resulting gas leakage must not get into the crew or passenger compartment as it will quickly replace the air and is highly flammable.

- Both kerosene and hydrogen are flammable in air. Hydrogen rises and evaporates very quickly implying that any hydrogen stored at the top of the aircraft is unlikely to cause a fire in the cockpit or passenger cabin. It also has low thermal radiation properties. Any spill will also evaporate very quickly. Hydrogen, however, does burn with an invisible flame unlike kerosene, making it difficult to see during an evacuation.
- Hydrogen will not be a drop-in fuel as far as gas turbines are concerned and there will need to be significant research on fuel atomisation systems, ignition systems and combustors.
- The cooling properties of hydrogen, however, can be used to cool gas turbines, fuel cells or the charge air for air conditioning systems.
- Material choice for storage and distribution of liquid hydrogen needs to consider the possibility of embrittlement and its impact on tank and distribution system material properties.
- Ways have to be found to avoid moist air touching either the tank or distribution system to prevent the build-up of ice.
- An inerting system will be required around the LH2 tank and distribution system to avoid the potential formation of explosive hydrogen air mixtures.

At an aircraft level, the high weight energy density of LH2 means that the aircraft has to carry less fuel weight than kerosene to fly a given mission. A way must be found to store a much greater volume of very low temperature liquid and then distribute it safely to the energy conversion medium. In simple terms, the practicality of an aircraft from a performance perspective can be judged by the difference between the fuel weight and the additional storage tanks and distribution system weight; remembering that kerosene storage on commercial transports is usually in the wings and at worst is weight neutral and may even be weight beneficial through reducing wing bending moment due to lift.

Not surprisingly, research focus has been on minimising tank volumes and weights and aircraft configurations for suitable tank positioning for a range of aircraft types consistent with minimum heat transfer and boil off. The metrics used to understand tank contribution are either the ratio of tank weight to fuel weight or fuel weight relative to fuel and tank weight. It is very unclear in any of the research found whether the tank weight also includes the weight to distribute and condition the fuel and any additional mounting structure required for the tank and its systems.

Gravimetric indices (fuel weight relative to fuel and tank weight) between 0.25 and 0.80 are quoted or can be inferred in different reports (CleanSky2, 2020; Brewer, 1980; Silberhorn, 2019; Faaß, 2001; Sefain, 2005) and such a wide variation supports the view that different researchers may have accounted for tank weight in different ways. In this report the denominator in the gravimetric index contains tank weight, LH2 distribution system weight and any other weight attributable to the installation of the LH2 tank. A 10% change in gravimetric index yields a 13% change in range on long haul aircraft and 17% to 18% change on short haul aircraft for a fixed take-off weight. It is assumed that the aircraft L/D is 10% worse to allow for an enlarged fuselage to accommodate the LH2 tank and that the engine specific fuel consumption is 2.8 times smaller than shown in **Table 25**.

A trade-off analysis between MTOW and range suggests that the smaller the aircraft, the more powerful the take-off weight change will be in terms of changing range. A 10% change will change range by ~ 10% for the E-190 and A320, ~ 5% for the A330-300 and ~ 4% for the B777-300ER. The power of MTOW variation is almost twice as large for smaller aircraft than for larger ones, but gravimetric index change is almost twice as powerful as MTOW. The lack of clarity on what is within gravimetric index and the wide spread of estimated index values within many research papers undermines their conclusions on the viability of such aircraft.

A simple analysis has been undertaken to understand the required gravimetric index to achieve the same aircraft payload range whilst allowing a 20% increase in MTOW. It should be noted that MTOW increase will require other aircraft compensations such as bigger wings and or engines to manage the weight increases and the 20% value has been picked as a reasonable maximum allowable increase. The required gravimetric index to achieve the same aircraft payload range whilst allowing a 20% increase in MTOW is shown in **Table 25**.

Table 25 Impact of liquid hydrogen on empty weight and design mission energy consumed

Aircraft	Modelled gravimetric index	Delta OWE (%)	Delta design mission energy (%)
Embraer E-190AR	0.384	+65	+49
Airbus A320-200	0.405	+57	+46
Airbus A330-300	0.448	+67	+51
Boeing 777-300ER	0.465	+90	+53

Given the challenges posed by public research on the achievable gravimetric index of aircraft tanks and their systems, it is not possible to definitively conclude whether LH2 powered aircraft are viable or not although subjectively it does appear achievable. More high technology readiness level research into storage tank design for minimum LH2 heat gain, maximum storage efficiency and minimum weight will be required to confirm the probable range of gravimetric index. Siting of the tanks on the airframe and the implications on aerodynamics, aircraft handling, system safety, ground handling and crashworthiness will also need to be explored in greater detail before a certifiable design can be achieved.

The design and certification of the aircraft to manage the safety implications of LH2 are also challenging but should be manageable. There are separate challenges to deliver the LH2 to the airport and then to the aircraft that are out of scope of this section.

Research into aircraft powered by LH2 has been very patchy with work undertaken in the 1970s, 1990s and in the last few years. None of these activities have moved the technology on significantly and so the industry will be starting technology development from scratch, although experience from other industries that already use or transport LH2 will be helpful. Airbus (2022) discusses recent Airbus Press release talks about LH2 aircraft being available by 2035; this is probably the earliest opportunity given the quantity of technology research and development that is required.

Liquefied natural gas

Liquefied natural gas (LNG) is a mixture of hydrocarbons, dominated by methane. Its energy density is 24% higher than kerosene (53.6 MJ/kg vs 43.1 MJ/kg) but it has a 31% lower volume-based energy density (22 MJ/litre vs 32 MJ/litre). To remain a liquid, it needs to be stored at below 110 K and this will be a requirement as gaseous natural gas density is much too low to allow it to be sensibly stored onboard.

Burning LNG does emit CO_2 and it generates 56.1 kg/GJ of energy expended; this compares with kerosene at 71.5 kg/GJ (a 22% reduction per unit of energy). It will create NOx but about half the amount generated by kerosene for a given energy consumption.

Other considerations for LNG are:

- Airport infrastructure will need to change to safely handle and distribute it to the aircraft, noting the cold temperatures of the liquid.
- Storage on board the aircraft
    - Given the need to store the liquid at a constant overpressure and at very cold temperatures, it is most likely that it will be stored in spheres or cylinders to minimise surface to volume ratio to reduce heat transfer into the liquid and to keep the storage system weight down. This means that kerosene style wing tanks will not be possible, and the tanks will either be sited internally in the fuselage or externally above the fuselage or on pylons on the wings.
    - The position of the tanks will have to maintain the required ease of entry and exit for crew, passengers and cargo and not compromise the aircraft centre of gravity.
    - In the event of a tank rupture, the resulting gas leakage must not get into the crew or passenger compartment as it will replace air and is highly flammable.
- Both kerosene and LNG are flammable in air. Natural gas rises and evaporates very quickly implying that any LNG stored at the top of the aircraft is unlikely to cause a fire in the cockpit or passenger cabin. Its thermal radiation properties are more akin to kerosene and higher than LH2, making a fire more dangerous. LNG does burn with a visible flame making it easy to see and avoid in an evacuation.
- LNG will not be a drop-in fuel as far as gas turbines are concerned and there will need to be significant research on fuel atomisation systems, ignition system and combustors, given the higher flame temperature and greater fuel volume flow requirements.

- The cooling properties of LNG can be used to cool gas turbines, fuel cells or charge air for air conditioning systems.
- Ways have to be found to avoid moist air touching either the LNG tank or distribution system to prevent the build-up of ice.
- An inerting system will be required around the LNG tank and distribution system to avoid the potential of explosive LNG air mixtures.

At an aircraft level, there will have to be a balance between the benefits of the higher weight-based energy density of LNG and the tank weight required to contain the cryogenic lower weight-based density liquid.

There has been very limited research on LNG in aircraft (Terpitz, 2019; Rompokos, 2020) and the focus has been on tank design and positioning. From this research it seems that gravimetric indices between 0.65 and 0.75 have been achieved, although the comments on LH2 gravimetric index uncertainties are equally applicable here. A 10% change in gravimetric index gives a 11% change in range on long haul aircraft and 13% change on short haul aircraft for a fixed take-off weight.

A trade-off analysis suggests that the smaller the aircraft the more powerful the take-off weight change in terms of changing range. A 10% change in MTOW will change the range by ~11% for the E-190 and A320, ~4% for the A330-300 and ~3% for the B777-300ER. The power of MTOW variation is almost twice as large for smaller aircraft than for larger ones, but gravimetric index change is almost twice as powerful as MTOW. This is the same trend as seen for LH2 and opens up the same challenges in achieving a performance viable aircraft.

The required gravimetric index to achieve the same aircraft payload range whilst allowing a 20% increase in MTOW is shown in **Table 26**. It should be noted that MTOW increase will require other aircraft compensations such as bigger wings and or engines to manage the weight increases and the 20% has been picked as a reasonable maximum allowable increase.

Table 26 Impact of liquefied natural gas on empty weight, design mission energy consumed, and CO_2 emitted at the jet-pipe

Aircraft	Modelled gravimetric index	Delta OWE (%)	Delta design mission energy (%)	Delta jet-pipe CO_2 emissions (%)
Embraer E-190AR	0.73	+46	+23	-4
Airbus A320-200	0.81	+31	+38	+8
Airbus A330-300	0.85	+34	+33	+4
Boeing 777-300ER	0.86	+20	+34	+5

The target gravimetric indices are, like LH2, higher than currently published and sets the challenge to make this fuel type a viable proposition; a challenge that appears feasible to achieve. It is noted that, for most designs there is a small increase in jet pipe CO_2 emissions that will have to be managed through a lifecycle CO_2 reduction initiative.

The design and certification of the aircraft to manage the safety implications of LNG are also challenging but should be manageable.

Research into aircraft powered by LNG is a fairly recent phenomenon with no comments from any researcher on likely dates for a practical implementation. The aircraft and engine technologies and airport infrastructure will be the pacing items and given the lack of substantive research it seems unlikely that, even starting now, entry into service will be before 2040.

Replacement of auxiliary power unit (APU) by a fuel cell

Aircraft APUs provide electrical and pneumatic power to the aircraft when power from either the main engines or ground sources are not available. At the airport gate, power sources are required to run essential electrical services such as lights, cleaning equipment, galleys and pneumatic or electrical power for cabin air conditioning. On push back from the gate, power is required to start the first main engine (which in turn enables the second engine to be started).

In the past, ground use of APU has been common to avoid operators paying the airport for power and in some cases because ground power is not available. However, airports are now requiring significant reductions in ground-based APU use and may mandate the shut-down of the APU shortly after arrival and only allowing it to restart shortly before main engine start. Airports are providing the required electrical and pneumatic supply to enable this to happen.

(2021), Pratt & Whitney (2021) and Zurich Airport (Fleuti, 2005). The fuel cell weight is estimated using an energy density of 0.3 kW/kg weight. For simplicity it is assumed that the control and distribution weights of the APU and fuel cell are the same.

Table 27 APU and fuel cell characteristics

Aircraft	APU	APU weight (kg)	APU fuel flow under nominal load (kg/hr)	APU electrical rating (kVA)	Fuel cell weight (kg)	Overall aircraft weight change (kg)
Embraer E-190AR	APS2300	100	130	40	130	+30
Airbus A320-200	APS3200	150	140	90	300	+150
Airbus A330-300	GTCP331-350C	250	190	115	390	+140
Boeing 777-300ER	GTCP331-500	310	240	120	400	+90

Using a fuel cell instead of an APU at the airport will remove the on-ground fuel burn; the value being dependent upon how long the unit is running. Such fuel burn is not included in the mission block fuel as the mission does not traditionally start until the main engines have started. There is also an additional fuel burn on the mission for the carriage of the fuel cell. The percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 28**.

Table 28 Changes in block fuel burn for replacement of the APU by a fuel cell

Aircraft	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)	Ground based fuel burnt (kg)	Difference between ground and mission fuel (kg)
Embraer E-190AR	500	+0.1	+5	+20	-15
Airbus A320-200	1,000	+0.4	+30	+20	+10
Airbus A330-300	3,500	+0.1	+60	+30	+30
Boeing 777-300ER	4,500	+0.1	+40	+40	0

The environmental balance is determined by the difference between the time that operators will now be allowed to run the APU on the ground relative to the extra fuel burnt in the flight. Based on an allowance to run the APU for 5 minutes before and after flight, it can be seen in that it is finely balanced.

The adoption of this technology may well come down to economic rather than environmental considerations and may happen if installing and running a fuel cell is less costly than buying energy from the airport. Given this uncertainty and the relatively low values estimated, this technology is not being considered.

APPENDIX 3: TECHNOLOGY OPTIONS: AIR TRAFFIC MANAGEMENT (ATM) TECHNOLOGIES

The potential to improve air traffic management in terms of fuel burn and CO_2 hinges mainly on the use of flight management procedural changes, supported by new technologies, introduced by the air navigation service providers (ANSP) and aircraft OEMs. These changes apply both in the air and on the ground. As such it is about improving management of aircraft movements within airspace and at the airport to reduce operational inefficiencies that contribute to the overall flight fuel burn and emissions creation.

Bradley (2011) outlines some changes to aircraft flight profiles that might be expected by 2030, consisting of

- Reduced taxi time
- Cruise climb
- Reduced hold time in main mission – Continuous Climb Operations (CCO) & Continuous Descent Operations (CDO)
- Optimum track
- Reduced reserves – contingency and diversion

These strategies focus on changes to flight profiles and therefore ignore aircraft technical attributes of L/D, SFC and weight; the modified Breguet range equation techniques are therefore not usable to assess fuel burn change. Instead RAWAvCon has been used to identify block fuel burn improvements for each flight profile change and each aircraft type as a function of range.

In aircraft performance modelling, a reference flight mission is used that precisely defines each part of the flight and also lays out a reserve policy in terms of extra fuel to be carried to manage a diversion, hold and still provide some contingency fuel.

REDUCED TAXI TIME

Taxi times are driven by airport congestion and the bottlenecks caused by the time required to complete a take-off or the need to release a parking space for an incoming aircraft. Taxi-in is often quicker than taxi-out but can still be slow if the gate earmarked for the arrival has not yet been cleared by the outbound flight. The challenge in both cases is one of real time current and future traffic position awareness. The solution will be provided by improved traffic system data management and analysis to link aircraft position and movement information to define a minimum wait sequence of events.

EuroControl (2020), FAA reports (2021a-d) and ICAO (2016b) all discuss the work that is underway to meet this challenge. EuroControl is aiming for a reduction in departure delays by between 1 and 3 minutes with an interim programme in place by 2027 and a final solution by 2035. FAA suggests that elements of solutions may be ready between 2025 and 2028.

Bradley (2011) does offer some target improvements for a 2030 flight profile, citing reductions in taxi-out time of 12 minutes (from 16 to 4 minutes) and taxi-in time of 6 minutes (from 10 minutes to 4). EuroControl data (EuroControl, 2021) shows that between 2015 and 2019 there has been no real change in taxi times, even though there have been projects that have focused on use of data to better manage ground movements. It may be that the benefits of these projects have been offset by the continued increase in ground movements over the same period. Separate assessments for European and American airports show the same trends, although the actual values are different (Europe has slightly lower times and USA has much higher times).

It may therefore be optimistic to assume that the Bradley (2011) assumptions can be met by 2030 although it may be possible by 2040.

For the purposes of this analysis,

- By 2030, taxi-out times are set to 10 minutes and taxi-in times set to 8 minutes to be broadly consistent with the EuroControl position.
- By 2040, taxi-out times are set to 4 minutes and taxi-in times set to 4 minutes.

For each aircraft type, RAWAvCon has defined block fuels as a function of stage length with baseline and reduced taxi times as defined above. The results are shown in **Table 29** and

Table 30, along with the percentage and absolute changes in block fuel at the average stage lengths.

Table 29 Changes in block fuel burn for 10 mins taxi-out and 8 mins taxi-in; 2030 scenario

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-2.4	-80
Airbus A320-200	1,000	-1.4	-90
Airbus A330-300	3,500	-0.4	-190
Boeing 777-300ER	4,500	-0.4	-270

Table 30 Changes in block fuel burn for 4 mins taxi-out and 4 mins taxi-in; 2040 scenario

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-5.3	-170
Airbus A320-200	1,000	-3.2	-220
Airbus A330-300	3,500	-1.0	-430
Boeing 777-300ER	4,500	-0.8	-610

CRUISE CLIMB

In an ideal aircraft performance world, the lowest fuel burn will come from an aircraft that maintains the optimum aircraft lift to drag ratio during cruise. This can be achieved by allowing the aircraft to slowly increase altitude as its weight decreases through fuel burn off. In the current air traffic environment this is not possible as aircraft fly in closely controlled altitude specific lanes to help manage air traffic control (ATC) regulated vertical separations; stepping from one lane to another can only be achieved through ATC approval. Current altitude specific lanes have a 2,000 ft separation for aircraft travelling in the same direction and 1,000 ft when travelling opposite directions. This was introduced under the revised vertical separation minima (RVSM) initiative.

EuroControl (2020), FAA (2021) and ICAO (2016b) make reference to the technology challenges of cruise climb. The references note that the implementation of Automatic Dependent Surveillance – Broadcast (ADS-B) capability (see FAA, 2021b) is a key element of cruise climb, and it will be mandated in FAA controlled airspace by 2020. EuroControl will bring this in using various programmes linked to ADS-B and GPS capabilities between 2026 and 2035. Other aircraft to aircraft capability developments and on-aircraft decision making will also be required. ICAO (2016b) also indicates the existence of programmes to reduce separations in the 2019 to 2030 timescales.

RAWAvCon has been used to compare mission fuel burn performance with and without cruise climb; the baseline uses RVSM separations and is compared against cruise climb. The results are summarised in **Table 31**.

Table 31 Changes in block fuel burn for the use of cruise climb

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-0.4%	-10 kg
Airbus A320-200	1,000	-0.4%	-20 kg
Airbus A330-300	3,500	-0.4%	-180 kg
Boeing 777-300ER	4,500	-0.4%	-320 kg

In this case the degree of improvement is very small. It may come along as part of other ATM enabling technology developments but is not considered as a standalone technology for this project.

OPTIMUM TRACK

The lateral control of aircraft separation is achieved through a series of prescribed paths in airspace, called “airways”. Because of the need to manage airspace it is not possible to fly directly from origin to destination rather aircraft are routed through a series of straight paths started and terminated at virtual waypoints; this is equally true of both the airspace around airports and that between airports. If separation can be managed dynamically by each aircraft, it might be possible to make more direct routings and reduce the overall distance flown.

It is clear that this capability requires similar technology development to cruise climb noted above and the same EuroControl, FAA and ICAO references and comments on timeliness information apply. In addition, FAA (2021d) covers the time-based en-route flow management aspects of this capability. FAA expects that this capability to be in place by 2030.

According to Bradley (2011), the 2030 flight profile will represent a perfect great circle distance reducing the overall distance flown by 5% in today’s flight profile model. In practice a track of minimum fuel burn will be designed, via an assessment of distance travelled and the impact of actual local winds. The success of this activity will also need a much greater understanding of actual winds along the flight and the ability to react in real time to change the aircraft's lateral flight path.

RAWAvCon analysis has defined block fuel reductions as a function of aircraft type and stage length for the 5% reduction in distance flown for each seat class and the results for the average stage length are shown in **Table 32**.

Table 32 Changes in block fuel burn for the achievement of optimum track

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-3.2	-100
Airbus A320-200	1,000	-4.0	-260
Airbus A330-300	3,500	-4.9	-2,160
Boeing 777-300ER	4,500	-5.2	-3,850

This technology is significant and is considered to be implemented by 2030 in line with the FAA's expectation.

CONTINUOUS CLIMB AND DESCENT

Because of congested airspace in and around the world's airports, both climb out and descent into airports can often include a circular holding pattern at a given altitude. In each case the aircraft's mission fuel burn is increased relative to a continuous climb or descent as the aircraft is not making progress to its destination.

Reducing the need for holds can be achieved by determining the correct time to depart the airport or start the descent to allow an unimpeded flight path. This in turn, demands real time flexible management of the preceding flight phases to manage ground speed to ensure the aircraft is in the right place at the right time (noting any potential fuel burn penalty for not flying at a fuel burn optimised speed). It is an aircraft position data management challenge allied to the airport's real time arrival activity.

Both EuroControl and FAA are exploring 4D flight management (i.e., 3 distance dimensions plus time). EuroControl (2020) and FAA (2021) both cover different aspects of this from 4D management to reduced longitudinal separation. In the UK, NATS has been working on a programme called XMAN to help with cross ANSP data flow (SESAR, 2014) which is essential if the technique is to be made to work. Timing for key elements of this work is between 2022 and 2025 but other essential pieces identified have no declared completion date.

The ICAO report (2016b) notes that an 'optimisation' of climb and descent procedures could save up to 340,000 tonnes of fuel in Europe in a year. This report also notes, from collected EuroControl data, that the amount of time flying level in the descent is ten times higher than that in the climb and so the focus of the ANSP's has been on descent rather than climb.

Bradley (2011) postulates that the 2030 flight profile will have no hold in descent. For comparison, the current flight profile would have included a 12-minute low altitude hold. It is noted that the 2030 flight profile includes a climb hold. Given the much higher propensity for hold in descent than climb, the analysis in this report has only defined the benefits of removing the descent hold to achieve a continuous descent.

Following RAWAvCon-based modelling, the resulting percentage and absolute changes in block fuel at the average stage lengths are shown in **Table 33**.

Table 33 Changes in block fuel burn for the achievement of a continuous descent

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-12.0	-390
Airbus A320-200	1,000	-7.0	-460
Airbus A330-300	3,500	-2.4	-1,050
Boeing 777-300ER	4,500	-2.0	-1,490

This technology is also significant and ANSPs have already made major inroads into achieving this. For the purposes of this study, the capability is available now.

REDUCED CONTINGENCY

There are formal requirements that aircraft carry sufficient extra fuel, that is, contingency, to account for unforeseen circumstances en-route (ICAO, 2013). These can include stronger than forecast winds, longer than planned flight tracks and lower than planned cruise altitudes, all of which increase the amount of fuel burnt. The practice of carrying extra fuel causes more fuel to be burnt to carry it. Any reduction in the extra fuel carried will help reduce fuel burn.

Greater robustness in forecasting and flight planning in terms of winds, routes and altitudes is the key to reducing the contingency carried. FAA and ICAO (2016b) identify data management systems and improved weather prediction capabilities as areas being worked on. ICAO’s list of projects suggests that activities in this area will run from 2019 to 2030.

Bradley (2011) suggests that today’s assumption of a 5% contingency may be reduced to 3% by 2030. In practice, a number of operators are already running on the equivalent of 3% by using techniques that provide sufficient reserve to fly to an interim point and check that sufficient contingency is onboard to fly on to its final destination; the risk being that if sufficient fuel is not onboard then the aircraft must divert. Three percent contingency has been used in the RAWAvCon model and **Table 34** summarises the resulting percentage and absolute changes in block fuel at the average stage lengths.

Table 34 Changes in block fuel burn for the use of reduced contingency

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-0.1	-5
Airbus A320-200	1,000	-0.2	-10
Airbus A330-300	3,500	-0.5	-200
Boeing 777-300ER	4,500	-0.6	-460

Many operators have found ways to achieve this contingency reduction. It is proposed that as such techniques are now widespread, the improvement can be applied from 2020.

REDUCED DIVERSION HOLD

Another key part of the reserve fuel philosophy is the diversion, where an aircraft carries sufficient fuel to fly to an alternative pre-specified destination in the event that the original destination is closed (through, for example, unexpected weather or a runway incident or accident). Given the wide range of possible reasons for an airport closure and the speed with which this can happen, it is unlikely that this part of the reserve will ever be removed.

What is open to improvement though, is the extra hold in preparation for landing at the alternative destination. It is included because the destination airport is not expecting all of the extra flights and gets congested so that it has to put aircraft on hold prior to landing (in the same way as covered for continuous descent). As noted above, the practice of carrying extra fuel causes more fuel to be burnt to carry it and so any reduction in the extra fuel carried will help reduce fuel burn. Solutions for reduced diversion hold are very similar to those for continuous descent although they would have to be more flexible to manage the sudden emergence of a stream of diversions. Thus, the research comments from the continuous descent section are equally valid in this case.

The difference is in the degree of change that can be anticipated. Bradley (2011) points to reducing diversion hold time from 30 minutes to 10 minutes and this has been modelled in RAWAvCon; the percentage and absolute changes in block fuel at the average stage lengths are summarised in **Table 35**.

Table 35 Changes in block fuel burn for the use of reduced diversion hold

Aircraft	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	500	-1.1	-40
Airbus A320-200	1,000	-0.9	-60
Airbus A330-300	3,500	-0.7	-320
Boeing 777-300ER	4,500	-0.8	-560

The ability to reduce diversion hold and to include it in the reserves is linked to the confidence the industry has in its ability to remove main mission holds. This is now common practice and should allow regulators to permit the reduction in fuel carried for diversion holds. Given that the regulatory approval is not yet in place it is postulated that a timeframe of 2025 can be set for its introduction.

APPENDIX 4: TECHNOLOGY OPTIONS: OPERATIONAL TECHNOLOGIES AND TECHNIQUES

Operational fuel burn improvement potential is derived from those technologies and procedural changes that the airlines themselves can apply when operating the aircraft in the air and on the ground. There is inevitably an interaction between these technologies and those described in both the Aircraft and Air Traffic Management technologies sections.

The technologies and procedures covered in this section are as follows and have been derived from a subject literature search and previous knowledge of areas being researched:

- Formation flying
- Long range cruise to maximum range cruise speed/Mach number reduction
- Engine inoperative taxi
- E-tug
- E-taxi

In the cases of formation flying and long-range cruise to maximum range cruise speed/Mach number reduction the modified Breguet range equation method has been employed as they both affect the key attributes. The three taxi analysis methods employ simple taxi fuel flow data to establish the fuel burn change.

FORMATION FLYING

The idea of formation flying has been taken from migrating bird formations, which use a V formation as a way of easing the flying workload for the majority of the flock during long flights. In simple terms, correct positioning of one wing tip on the leading aircraft relative to the wing tip on the trailing aircraft will reduce the drag of the trailing aircraft, whilst having no impact on the leading aircraft. There is no weight or engine efficiency impact of this approach. The change will be implemented through aircraft and ATM systems revisions. Note that re-designing the aircraft to take advantage of the aerodynamic efficiency will negatively impact the aircraft’s capability when formation flying is not possible and is therefore unlikely to happen.

The technique will be at its most useful well away from congested airspace and where long periods of straight and level flight are anticipated; cruise conditions on long haul flights are consequently where this is most likely to happen. ICAO (2016b) include projects to reduce aircraft separation and increase the level of cockpit management of such separation and these will be prerequisites for such capability to be employed.

Ning (2011) claims a 12% fuel burn improvement for a 2 aircraft formation based upon a 30% reduction in induced drag and a 40% induced drag contribution to total aircraft drag. This increases to a 40% induced drag change for a 3 aircraft formation. Verhagen (2015) suggests a 5-10% fuel burn improvement when applying aerodynamic improvements to real airline flight networks. However, there is insufficient detail in the report to understand how these numbers were derived. Ray (2002) looks at the change in drag reduction with relative wing tip position and estimates a 20% induced drag reduction on a formation of two F-18 fighter aircraft. As these are combat aircraft, it has to be assumed that their drag characteristics are sufficiently similar to a transport aircraft to make the information usable. Airbus, in a demonstrator project called Fello'fly (Airbus, 2020), plans to work with ANSPs to fly two aircraft only 1.5 km apart laterally and 1,000 ft vertically to understand both the potential benefits and the challenges. Demonstrations were expected in 2021 with an entry into service, if successful, by 2025. Airbus also quotes unspecified initial flight results as showing between 5 and 10% fuel burn improvement; this is consistent with Verhagen (2015).

Based upon these studies, it is assumed that formation flying results in a 12% improvement in aircraft L/D applied over 75% of the cruise portion and split equally between the two aircraft in the formation (i.e., a 6% improvement for each aircraft). This is equally applicable to all aircraft groups. Fuel burn improvement is then based on the Breguet method corrected for the amount of time that formation flying can be accomplished during the whole flight.

The resulting fuel burn change coming from application of the L/D change and percentage cruise time relative to the baselines for each aircraft type increases with range and is around 5% of block fuel for higher distances flown. These results, which are at the lower end of public pronouncements for the assumptions used in the analysis, are summarised for the average stage lengths in **Table 36**.

Table 36 Changes in block fuel burn for use of formation flying

Aircraft	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	500	-2.0	-50
Airbus A320-200	1,000	-3.0	-180
Airbus A330-300	3,500	-4.1	-1,750
Boeing 777-300ER	4,500	-4.4	-3,000

Formation flying is a possibility once the issues surrounding controlling aircraft in close proximity have been resolved and it is recommended that it be considered for introduction from 2025. In practice, it only really makes sense on the longer haul flights with the larger aircraft such as A330-300 and B777-300ER.

LONG RANGE CRUISE TO MAXIMUM RANGE CRUISE SPEED/MACH NUMBER REDUCTION

The option to reduce cruise Mach number during the design process was discussed previously. Existing aircraft designs also have the potential to reduce fuel burn through cruise Mach number or cruise speed reductions although it is much more limited in impact. Aircraft fuel mileage (weight of fuel required to fly a unit of distance) is called specific air range (SAR) and is a function of aerodynamic and engine efficiency and has an inverted U shape. Once the aircraft has been designed this characteristic is fixed and cannot be changed without aircraft modifications.

Because of its shape, each line of constant weight has a maximum SAR value, and this will be achieved at a unique Mach number. The maximum range cruise Mach number (MRC) can be quite slow, and operators look to define a slightly faster Mach number at which to operate to maintain the best aircraft utilisation. They generally choose one that has a 1% degradation in SAR, that is, the long-range cruise Mach number (LRC). By definition, slowing down from LRC to MRC will improve fuel mileage by 1%. Slowing down below MRC will make the fuel mileage worse and so the maximum SAR benefit that can be achieved is 1%.

The assessment has been based upon increases in L/D of 0.5% and reductions in SFC of 0.5% applied to all aircraft groups through the modified Breguet method. The resulting percentage and absolute changes in block fuel at the average stage lengths are detailed in **Table 37**.

Table 37 Changes in block fuel burn for reducing from LRC to MRC Mach number or speed

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-0.5	-10
Airbus A320-200	1,000	-0.8	-40
Airbus A330-300	3,500	-1.0	-440
Boeing 777-300ER	4,500	-1.1	-760

Operators are already using this technique today as there are no aircraft changes required and the ATM system is well able to cope with the small speed variations it creates. The implementation in the cockpit is via a dedicated function within the Flight Management System (FMS). Given the degree of use of this technique, the likely further reduction in fuel burn from the current operation will be very small; although it may be that other operators are flying at Mach numbers above the long-range cruise value, in which case the benefits may be more substantial. For these reasons this approach has not been included in the assessment.

TAXI

Fuel burn during the taxi phases can be reduced in the following ways:

- One engine inoperative taxi where one of the aircraft’s engines is shut down during the taxi phase.
- Electric tug taxi where an electric powered tug replaces the current diesel powered one for taxi. All main engines are shut down when the tug is attached. There are a number of providers of electric aircraft tugs and airports are now starting to use them in normal operations and for all sizes of aircraft (Design News, 2007; Avionics International, 2019).
- Electric motor taxi where an electric motor embedded in the aircraft wheels provides the motive power during taxi. All main engines are shut down when the motor is working. Work on the Safran project to deliver this was suspended in late 2019 (Reuters, 2019), although the Wheel Tug project continues, targeting retrofit into older A320 and 737 variants and may be in service by the end of 2021 (Wheeltug, 2021).

Taxi time is a variable and has been set nominally in this report at a combined 15 minutes for taxi out and taxi in. It results in a fixed value for each aircraft type as the model is incapable of changing taxi fuel flows with the different take-off weights for each mission. The APU fuel flows given in **Table 27** have been used in the analysis.

One engine inoperative taxi

Modelling one engine inoperative taxi fuel flow estimates the difference between "all engines running with APU inactive" and "one engine shut down and APU active" to cover the loss of electrical/hydraulic/pneumatic power from the shutdown engine. The fuel flow of the active engine in the latter case is increased by 10% to allow for additional manoeuvring thrust when starting from rest, moving on uphill gradients and/or turning. The resulting percentage and absolute changes in block fuel at the average stage lengths and 15-minute taxi time are shown in **Table 38**.

Table 38 Changes in block fuel burn for one engine inoperative taxi as a function of taxi time

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-1.3	-30
Airbus A320-200	1,000	-1.0	-60
Airbus A330-300	3,500	-0.4	-170
Boeing 777-300ER	4,500	-0.3	-210

This technique is currently being used by a large number of operators and so is likely to be easily implemented by all operators. As it has been introduced in more recent years, it can be credited as an improvement on a year 2000 datum.

Electric tug taxi

In this case, all main engines are switched off although the APU will still be running to provide the necessary aircraft electrical/hydraulic/pneumatic power. The unknown at this stage is whether the tugs will take the aircraft to and from the runway or somewhere in between; this is very dependent on the airport layout and infrastructure and their preparedness to provide new temporary parking areas to enable engine start up and tug engagement/disengagement. The shorter the distance, the lower the potential benefit. The resulting percentage and absolute changes in block fuel at the average stage lengths and 15-minute taxi time are summarised in **Table 39**.

Table 39 Changes in block fuel burn for electric tug taxi as a function of taxi time

Aircraft	Average stage length (nm)	block fuel burn change (%)	block fuel burn change (kg)
Embraer E-190AR	500	-4.3	-120
Airbus A320-200	1,000	-3.0	-180
Airbus A330-300	3,500	-1.0	-430
Boeing 777-300ER	4,500	-0.8	-550

Electric tugs are now starting to appear at major airports and are able to tow aircraft of all weights and sizes. This is clearly a useful technology for reducing airport emissions in the short term.

Electric wheel taxi

Electric motors embedded in the wheels of the aircraft provide the power and allow the aircraft to taxi with the main engines switched off and without a tug. As with the preceding case, the APU will still be running to provide the necessary electrical/hydraulic/pneumatic power to the aircraft. In this case though, the electric motor(s) will have to be carried throughout the flight and will negatively impact the mission fuel burn.

A project by Safran (2017) to develop main wheel motors for aircraft was stopped in 2019 (Reuters, 2019), following withdrawal by Airbus. The only current project is WheelTug (2021) which uses a nose wheel motor on A320/737 sized aircraft and is targeted at retrofit of current aircraft rather than installation on new build and may enter service in late 2021. From the foregoing, it can be inferred that aircraft manufacturers are currently not that interested in embedded motors in aircraft main wheels and are sceptical about the value of the technology at all on new aircraft projects.

It is believed that the limited nose wheel turning angle makes manoeuvring of larger aircraft in tight areas difficult. This may explain the lack of programmes to develop the technology for retrofit on larger aircraft. To reflect this, it is assumed that this technology will only apply to aircraft in the E-190 and A320 size classes. The weight of the motors and supporting systems has been taken from the above references and is 300 kg for both E-190AR and A320-300.

The analysis approach taken in this case is to combine the fuel burn reduction methods applied to the other two taxi fuel burn reduction techniques with the mission fuel burn increase due to the weight taken from the modified Breguet method. The resulting percentage and absolute changes in block fuel at the average stage lengths and 15-minute taxi time are shown in **Table 40**.

Table 40 Changes in block fuel burn for electric wheel taxi as a function of taxi time

Aircraft	Average stage length (nm)	Block fuel burn change (%)	Block fuel burn change (kg)
Embraer E-190AR	500	-4.0%	-110 kg
Airbus A320-200	1,000	-2.8%	-170 kg

There is some benefit to be had from this system, but it is less than that for an airport provided electric tug; the higher the weight of the system and the longer the mission stage length the greater the penalty for the wheel tug system will be. The decision to adopt this technology is more likely to be bound by the economics of airport tug charges relative to acquisition of the wheel motor and its maintenance and reliability costs; perceived departure time management benefit by being independent of the airport tug may also be a consideration. WheelTug claims 26 customers have ordered the equipment and time will tell whether this becomes an industry accepted technology. It is judged that this technology is unlikely to have much impact in the market given the retrofit approach taken by WheelTug and the abandonment of the project by Safran and is thus not being considered.

APPENDIX 5: ALTERNATIVE AVIATION FUELS

There are several alternative aviation fuels that could be adopted to reduce aviation emissions associated with fuel-use. These can be categorised as drop-in liquid fuels and non-drop-in fuels. Drop-in fuels have similar properties to fossil jet fuel, meaning that no significant modifications to existing infrastructure, aircraft and engines are required. On the other hand, uptake of non-drop-in fuels will require significant modifications and investment.

This study covered the following categories of fuels:

- Drop in fuels: Sustainable Aviation Fuel (SAF), produced from renewable feedstocks, including biomass and renewable hydrogen, as well as recycled waste fossil carbon (if it leads to a sufficient CO_2 emissions reduction). Lower Carbon Aviation Fuel (LCAF) was not included in the analysis.
- Non-drop-in : Liquid renewable hydrogen. Liquified (renewable) natural gas and electricity were included in the initial screening exercise but were not included in the technology roll-outs.

ALTERNATIVE DROP-IN FUELS: SAF

There are many different pathways to produce SAF, with many of the pathways capable of using a range of feedstocks. The pathways included in this study are summarized in **Figure 23**. Not all possible feedstock-pathway combinations were analyzed, but those which are most widely covered in literature and represent current and planned projects. It should be noted that, in order to simplify the analysis, co-processing pathways were not considered, although this could lead to several cost-effective production pathways. This section includes further details on the GHG intensity and levelized cost of production (LCOE) for each of the pathways, which are key parameters in the modelling.

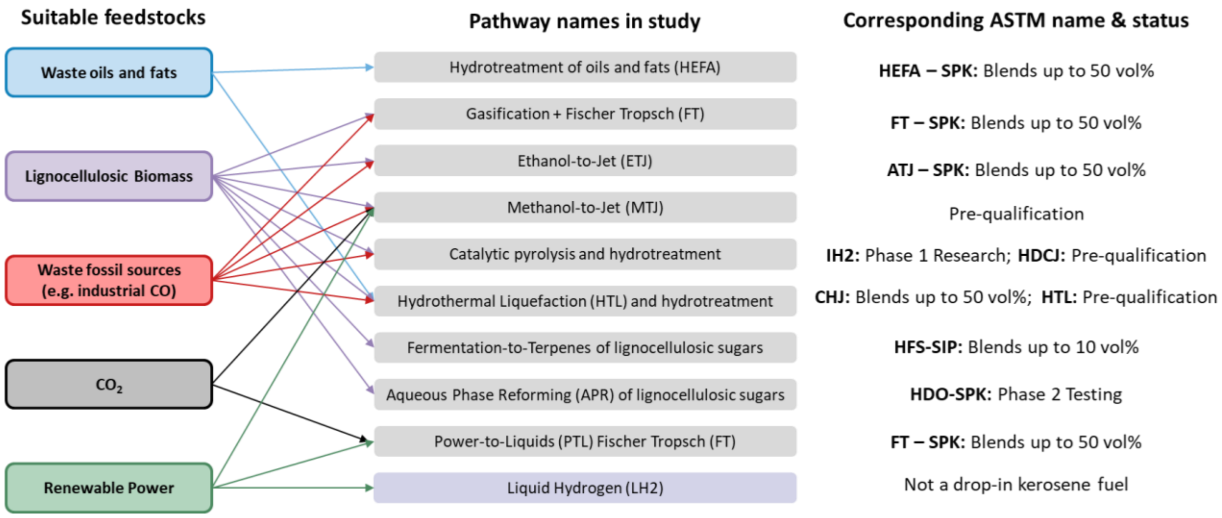

Figure 23 Alternative fuel pathways explored in this study

Feedstocks

The term SAF encompasses fuels produced from both biological and non-biological feedstocks.

Biofuel feedstocks

Generally, there are considered to be three main categories of biomass feedstocks: sugar and starch crops, lipid-based feedstocks, and lignocellulosic feedstocks. ASTM certification determines which feedstocks can be used to produce certified jet fuels However, there are additional feedstock considerations which must be acknowledged. Such considerations are often reflected in policies at State (e.g., LCFS), national (e.g., RED II) and international level (e.g., CORSIA).

Food and feed crop feedstocks, sometimes referred to as **conventional feedstocks**, include **oil-seed, sugar and starch crops** such as palm oil, sugarcane, corn and wheat. These feedstocks often have a high water and nutrient (fertiliser) demand, the latter of which contributes to high cultivation GHG emissions. Importantly, when crops are used for fuels, there is competition with food and feed production for land, water and energy inputs. Constraints can be seen in policy, to limit the extent of competition. For example, under EU RED II, biofuels from food and feed crops are capped at 7% of the Renewable Energy Share in Transport (RES-T) target of 14% of the final consumption of energy used in road and rail by 2030[8]. Furthermore, fuels derived from food and feed crop feedstocks can lead to deforestation and degradation of carbon-rich land due to the increased demand for land to grow crops, therefore "shifting" the land use: this concept is referred to as indirect land use change (iLUC). Sustainability criteria in policy mean that only feedstocks certified as low iLUC are likely to be supported in the future. For example:

- palm oil is not an approved feedstock in California's LCFS;

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[8] Under RED II, any type of renewable energy (biofuels, renewable electricity, renewable hydrogen etc.) supplied to any transport sector (road, rail, aviation, shipping) can be counted towards the RES-T target.

- under RED II, biofuels with high iLUC impacts are limited to EU Member State's 2019 levels until 2023 then phased out to 2032. Currently only palm oil falls under this category, but it could apply to soy in the future;
- under CORSIA, iLUC values are added to all food and feed feedstocks, not just palm oil, and are included in the 10% reduction target (ICAO, 2019b).
- Food and feed crops are excluded from this analysis as a result of the above.

Advanced feedstocks consist of **cellulosic (energy crops), wastes and residues**, therefore they avoid the issues surrounding food and feed competition that food-crop feedstocks are subject to. Nonetheless, advanced feedstocks still have competing uses such as in heat and power. There are policy mechanisms which promote the use of advanced feedstocks. For example, RED II sets an advanced biofuel sub-target, in which fuels produced from a defined list of cellulosic, waste and residue feedstocks (Annex IXa) "double count" towards the RES-T target of 14%, with a minimum contribution of 3.5% by 2030 (after double counting). Note, RED II also has a 1.2x multiplier if these feedstocks go into aviation fuel.

On the other hand, there are some advanced feedstocks which have limited availability, notably **waste lipids/oils and fats**, e.g., **used cooking oil (UCO), tall oil, waste vegetable oil and tallow**. Ecofys (2019) estimated that the global UCO supply will be 44 Mt/year. Nonetheless, using waste oils and fats for SAF production will still face significant competition and comes with high risk of fraudulent activity, if chain of custody measures is insufficient.

Algae are an advanced feedstock (sometimes termed 3G) which has sparked interest as it avoids use of agricultural lands and does not compete as a food source, but current research suggests cultivation yields are low and there is high energy consumption in the oil extraction stage. Consequently, algae-based fuel pathways remain at a nascent stage and are not currently economically viable (Doliente, SS. et al. 2020).

Recycled carbon feedstocks

Non-biological feedstocks are also available for SAF production, mostly through pathways that utilise thermochemical processes as an initial step. Recycled carbon fuels (RCFs) are defined in RED II as fuels produced from:

- Liquid or solid waste streams of non-renewable origin, which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or;
- The utilisation of waste processing gas and exhaust gas of non-renewable origin.

This enables the use of difficult-to-dispose of wastes, such as non-recyclable plastics and fossil portions of MSW, to produce fuels that benefit from both reduced GHG emissions when compared to the alternative use of the feedstock (for instance, if the waste would otherwise be incinerated), and the avoidance of waste disposal costs. Policy is still being developed in this area but is likely to reflect such considerations.

Renewable fuels of non-biological origin

Renewable fuels of non-biological origin (RFNBOs) are fuels in which the energy content is derived from renewable energy sources: for example, renewable hydrogen produced from electrolysis powered by offshore wind. This hydrogen can be used with other molecules, such as carbon or nitrogen-based molecules, to produce fuels: these pathways are termed Power-to-X (PtX), where the X stands for the characteristic of the end fuel (e.g., PtL – power to liquids, or PtM – power to methanol). To produce hydrocarbon PtL fuels with the necessary energy density and drop-in characteristics required for aviation, a source of carbon is required: this can be supplied either by collecting industrial flue gases (carbon capture utilisation and storage, CCUS), which could in turn be produced from processes using either fossil or biogenic feedstocks, or from the atmosphere using direct air capture (DAC).

Although PtL pathways can use any source of electricity for the electrolysis step, the sustainability of these pathways is entirely dependent upon the source of electricity being from renewable sources: hence the specific designation of RFNBOs.

GHG intensity of SAF

The GHG intensity of fuels and the corresponding savings may vary significantly depending on:

- The GHG methodology used: for example, CORSIA life-cycle emissions calculations include iLUC impact whereas other mechanisms, such as EU RED II do not. EU RED instead accounts for iLUC indirectly, through measures such as the crop cap
- The feedstocks used
- The conversion process used and assumptions on energy supply to the process (e.g, natural gas vs. recycled flue gases)
- The fossil fuel comparator used which will affect the relative savings

The quality and robustness of the reported GHG intensities are strongly dependent on the quality of data used. As many of the pathways included in this analysis are not at commercial scale yet, the GHG emissions are dependent on modelling, pilot and demonstration scale data[9].

In this study, the fossil fuel comparator aligns with CORSIA: a CORSIA-eligible fuel has GHG emissions savings of at least 10% compared to the benchmark of 89 gCO_2eq/MJ. Note, this varies from other policy schemes which fuel producers would need to comply with to benefit from. For example, to qualify under RED II the savings must be 50% and 60% compared to the fossil fuel comparator of 94 gCO_2eq/MJ for installations starting operations on or before 5 October 2015, 31 December 2020 respectively, and 65% for installations starting operations after 1 January 2021.

As far as possible, data was selected to align closely with the GHG methodology stipulated by CORSIA. All biomass feedstocks considered in this analysis have been constrained to those which are considered as “wastes and residues”. In this instance, CORSIA and REDII methodology are well aligned (with the exception of treatment of municipal solid waste), as wastes and residues do not have an iLUC factor. Importantly, the combustion emissions of biofuels and renewable fuels is considered to be zero.

Table 41 presents the GHG intensities of the pathway-feedstock combinations included in this study and outlines any key assumptions which may affect the interpretation of the results. The intensities presented are considered to be what the

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[9] Note, this is the same for cost data

pathway's emissions would be today, despite most routes not yet operating at a commercial status. As mentioned earlier, this introduces a degree of uncertainty. In this study, the GHG intensity of all pathways is assumed to be reduced by 30% by 2050, accounting for improved efficiencies and operations.

Table 41 Pathways considered in this analysis and their associated GHG emissions (current)

Pathway	Feedstock	GHG gCO_2e/MJ	Assumptions	Ref
Hydrotreatment of oils and fats (HEFA)	Waste oils & fats	13.9	Used cooking oil, CORSIA default value	ICAO, 2019c
Gasification + Fischer-Tropsch (FT)	Municipal Waste	5.8	Biogenic portion, CORSIA default value	ICAO, 2019c
	Lignocellulosic biomass	8.3	CORSIA default value	ICAO, 2019c
Ethanol-to-Jet (ETJ)	Lignocellulosic biomass	6.7 - 13	GHG emissions of this route strongly depend on the ethanol production. Hannon et al. estimates the emissions associated with the ethanol-to-jet conversion step to be between 3.2 - 6.7 gCO_2e/MJ jet.	EC, 2018; Hannon et al., 2019; Handler, 2015
	Waste Fossil CO	24.6		Hannon et al, 2019; Lanzatech 2017
Methanol-to-Jet	Lignocellulosic biomass	9.0	Based on Methanol-to-Gasoline process	Hannula, 2017
	Renewable electricity + CO_2	1.0	Assumes renewable electricity used for all energy demand	Internal Analysis
Catalytic Pyrolysis and hydrotreatment	Lignocellulosic biomass	22.0 - 24.8	Forestry residues - agricultural residues	De Jong, 2017; Kolosz,2020
Hydrothermal Liquefaction (HTL) and hydrotreatment	Lignocellulosic biomass	18.0	Forestry residues	De Jong, 2017
Fermentation-to-Terpenes of lignocellulosic sugars	Lignocellulosic sugars	25.0		Industrial Sources
Aqueous Phase Reforming (APR) of lignocellulosic sugars	Lignocellulosic sugars	21.9		IRENA, 2016b
PTL FT	Renewable electricity + CO_2	0.8	Assumes renewable electricity used for all energy demand	Internal Analysis
Liquid Hydrogen	Renewable electricity	~0	Assumes renewable electricity used for all energy demand, incl. liquefaction	Internal Analysis

Production cost of SAF

The production costs for the different alternative fuels' pathways were taken from literature, listed in **Table 42**. Where possible, the same literature source was used to ensure comparability between data points, though this was not possible for all pathways. Key assumptions in terms of feedstock type and cost, plant size and configuration (e.g., source of electricity) can strongly impact the overall cost of production. In **Table 42** the costs presented represent "Nth" plant costs, i.e., not first or early commercial plants. Unless otherwise stated, it's assumed that fossil sources are used to satisfy the energy demand for the processes.

Liquid hydrogen and PTL production costs were modelled using literature-based, harmonized assumptions with respect to the common process components. The cost of renewable electricity with storage is projected to decline from \$0.1/kWh in 2020 to \$0.05/kWh; those without storage decline from \$0.04/kWh to \$0.02/kWh and the capacity factor increases from 30% to 50% over the same period. Both processes rely also on PEM electrolysis under varying renewable power loads. Electrolyser capital costs are projected to decline from \$1,000/kW(H2) in 2020 to around \$170 in 2050 due to both manufacturing economies of scale and economies of scale due to plant size (which increases from 10 tonnes per day in 2020 to 1,000 tonnes per day in 2050). Another key assumption for producing liquid hydrogen (under constant loads) is the capital cost of the liquefaction plant, which is projected to decline from \$4,800 in 2020 to \$1,400 in 2050 (as the capacity increases). For PTL production, capital costs of the syngas and synthesis plant are projected to decline from around \$1,900/kW (PTL) in 2020 to \$400/kW (PTL) in 2050, as the capacity increases from nearly 7 tonnes PTL per day to around 1,140 tonnes PTL per day. Over the same period, the modelled costs of direct air capture decline from around \$250 to around \$50 per tonne of CO_2.

Table 42 Pathways considered in this analysis and their corresponding Nth of a kind levelized cost of production

Pathway	Feedstock	LCOE $/GJ	Assumptions	Ref
Hydrotreatment of oils and fats (HEFA)	Waste oils & fats	32	Cost of HEFA is feedstock driven.	ICCT, 2019a; IEA, 2020a
Gasification + Fischer-Tropsch (FT)	Municipal Waste	32	Assumes feedstock is secured at zero cost	De Jong 2015; IEA 2020
	Lignocellulosic biomass	51		De Jong 2015
Ethanol-to-Jet (ETJ)	Lignocellulosic biomass	65 - 100	Range depending on feedstock cost, with forestry residue cost approximately half that of wheat straw. Waste Fossil CO cost likely to be location specific.	De Jong 2015
	Waste Fossil CO			
Methanol-to-Jet	Lignocellulosic biomass	51		IEA, 2020a; IRENA, 2021; E4tech analysis
	Renewable electricity + CO_2	59	Waste CO_2 used as feedstock	E4tech analysis' CCC, 2020; Hannula, 2015
Catalytic Pyrolysis and hydrotreatment	Lignocellulosic biomass	38 - 52		De Jong 2015
Hydrothermal Liquefaction (HTL) and hydrotreatment	Lignocellulosic biomass	27 - 38		De Jong 2015
	Municipal Waste	20	Assumes feedstock is secured at zero cost	De Jong 2015; E4tech analysis
Fermentation-to-Terpenes of lignocellulosic sugars	Lignocellulosic sugars	179		De Jong 2015
Aqueous Phase Reforming (APR) of lignocellulosic sugars	Lignocellulosic sugars	60	Average of 2030 low and high scenario from IRENA.	IRENA, 2016b
PTL FT	Renewable electricity + CO_2 from DAC	60 - 20	Higher end: 2020, lower end: 2050	Internal Analysis
Liquid Hydrogen	Renewable electricity	80 - 26	Higher end: 2020, lower end: 2050	Internal Analysis

FUELS AND PATHWAYS EXCLUDED FROM THE ANALYSIS

Lower carbon aviation fuel

Annex 16 Volume IV of CORSIA also introduces Lower Carbon Aviation Fuels (LCAF) as an option to reduce aviation emissions. In this context, LCAF has been defined as “a fossil-based aviation fuel that meets the CORSIA Sustainability Criteria under this Volume” - i.e., a fuel that meets the 10% GHG emissions reduction compared to the benchmark of 89 gCO_2eq/MJ. LCAF can be produced by applying technologies and practices aimed at reducing upstream (e.g., flare reduction) and downstream (e.g., use of green hydrogen, renewable energy, carbon capture and storage, etc.) emissions of petroleum-based kerosene (Monfort, 2019). Measures applied to reduce the combustion emissions of jet fuel, such as through increasing the degree of hydrogenation to further saturate aromatics, are likely to have only a limited impact on WTW emissions and are not discussed in further detail. However, optimising the fuel composition can have other non-GHG benefits: for instance, reducing the aromatic content of the fuel has been shown to decrease the production of precursors that contribute to the formation of soot, which will in turn reduce PM emissions and improve combustion efficiency.

Different aviation emissions mitigation policies treat LCAFs differently. Alternative fuel use is exempt from the EU ETS provided that the fuel meets the REDII qualification threshold of a 65% reduction in fuel lifecycle emissions (European Parliament, 2020). As LCAFs do not meet this threshold, they are treated identically to other fossil-derived Jet A. Under CORSIA, an alternative fuel must deliver at least a 10% reduction in fuel lifecycle greenhouse gas emissions to be considered a CORSIA Eligible Fuel (ICAO, 2019a). CORSIA costs for these fuels are discounted by a factor equal to the reduction in the fuel's lifecycle greenhouse gas emissions compared to those of standard fossil-derived Jet A. It is possible for a LCAF to meet this standard, but the incentive to use LCAF under CORSIA is likely to be very small. This arises from a number of factors in combination:

- The CORSIA carbon price is small (around \$2/tCO_2 as of Summer 2021; OPIS, 2021) and is projected to remain low (e.g., Fearnehough et al., 2018). \$2/tCO_2 corresponds to around \$0.02 per US gallon of Jet A.
- CORSIA carbon prices apply only to emissions over the CORSIA baseline, which is currently set at a year-2019 level for the 2021-2023 pilot phase (ICAO, 2020) and has recently been reduced to 85% of year-2019 levels for subsequent phases (ICAO, 2022). Recovery from the COVID-19 pandemic means that demand is likely to remain suppressed for some time, implying potentially zero pilot phase CORSIA carbon costs. Over the longer term, this means that the effective CORSIA carbon price is likely to be well below \$0.02/gallon.
- CORSIA costs for alternative fuel use are reduced in proportion to the reduction in fuel lifecycle emissions associated with the alternative fuel. For a qualifying LCAF which reduces fuel lifecycle emissions by 10%, CORSIA carbon costs will be reduced by only 10% (i.e., well below \$0.002/gallon of fuel).

Unless CORSIA carbon prices are much greater than anticipated, the scheme is considerably strengthened, or LCAF production costs are very low, the above factors in combination mean that incentives under existing emissions mitigation schemes to use LCAFs are minimal and unlikely to stimulate uptake.

Liquefied natural gas

As discussed earlier and in the main report, liquefied natural gas was excluded from this study.

Electricity

As discussed earlier and in the main report, electric propulsion was excluded from this study.

Co-processing pathways

Several of the pathways selected for analysis are candidates for co-processing in fossil refineries, which could be a cost-effective way to introduce SAF into existing fossil kerosene streams by utilizing existing capital and infrastructure. This was not considered in the analysis due to the increased complexity necessary in the modelling, and uncertainties regarding cost and GHG projections. For completeness, pathways that could be eligible for co-processing, which are the subject of current research and testing, are listed in **Table 43**.

Table 43 Currently researched/developing co-processing pathways

Pathways and processes	Feedstock options	ASTM Certified?	Date of approval	Current blending limit
Co-processing of oils and fats in a refinery to produce kerosene	Vegetable and animal lipids	Yes	2018	5% (refinery input to jet production)
Co-processing of FT waxes from syngas to produce kerosene	MSW, forestry residues	Yes	2020	5% (refinery input to jet production)
Co-processing of pyrolysis oils in a refinery to produce kerosene	Lignocellulosic biomass residues, MSW	No	-	-
Co-processing of HTL crude in a refinery to produce kerosene	Lignocellulosic biomass residues, wet wastes	No	-	-

APPENDIX 6: TECHNOLOGY PACKAGES

ASSESSMENT OF THE BENEFITS OF BUNDLED TECHNOLOGIES

The single biggest challenge of the fuel burn assessment approach adopted is that each item has been assessed as a stand-alone and independent change and combining them into technology bundles will introduce interactions not modelled by these methods. In practice, there will be both positive and negative interactions between each change and the only way to fully understand this is to fully model each aircraft within the airline and ATM environments: this is beyond the scope of this project.

An approach to deal with this conundrum, favoured within the engineering community through custom and practice, is the use of root mean squares (RMS) to combine each technology benefit with an equation in the form of

$$\%age_{bundled} = \sqrt{({x_1}^2 + {x_2}^2 + {x_n}^2)}$$

Where

x = individual technology benefit

Unpublished work has shown that the RMS method predicts very similar fuel burn changes when combining independently assessed technologies to create an integrated aircraft design.

LH2 AIRCRAFT CHARACTERISTICS

Table 2 in the main report summarized the seat count, average stage length and the percent fuel burn change for kerosene aircraft over reference year 2000 technology. **Table 44** below reports the corresponding characteristics for liquid hydrogen (LH2) aircraft. The assessment has been based on a gravimetric index of 0.4 for the E-190AR and A320 and 0.45 for the A330-300 and B777-300ER. The improvements in L/D, SFC and weight (excluding LH2 tanks and systems) are the same RMS values as used for the drop-in fuel aircraft family. Neither the A330-200 nor B777-300ER with a second technology bundle iteration are quoted as they will not enter into service until after the completion of the study period.

Table 44 Scenario 2 aggregated energy improvements

Market Segment	Representative aircraft for the year 2000 (2015)	Seat count	Avg. stage length (nm)	% Fuel burn change over year 2000 technology, EIS	
				2035-40	2050
Regional	E-190AR (E2-190)	98	500	+9.6%	+9.8%
Short haul	A320-200 (A320 NEO)	150	1,000	+25.2%	+30.5%
Medium haul	A330-300 (B787-9)	295	3,500	+5.4%	
Long haul	B777-300ER (A350-1000)	368	4,500	+14.1%	

All the LH2 solutions burn more energy than their kerosene counterparts, implying that the other technological improvements are insufficient to offset the weight and drag impact of the LH2 tank. It is clear however that the removal of jet pipe CO_2 emissions will be instrumental in the development of this capability.

ATM AND OPERATIONS-RELATED IMPROVEMENTS

The ATM and operations scenario improvement per representative aircraft is shown in **Table 45** at the respective average aircraft stage length. The difference in magnitude of the ATM and operations fuel burns is in part driven by the average stage length. This is because a number of the technologies and processes give a fixed fuel burn improvement, which gives a reduced percentage change as the absolute fuel burn goes up with increasing range.

Table 45 ATM and operations scenario aggregated fuel burn improvements

Aircraft	Average stage length (nm)	Delta fuel burn 2020 (%)	Delta fuel burn 2025 (%)	Delta fuel burn 2030 (%)	Delta fuel burn 2040 (%)
Embraer E-190AR	500	-12.9	-13.1	-13.5	-14.3
Airbus A320-200	1,000	-7.6	-8.2	-9.1	-9.5
Airbus A330-300	3,500	-2.6	-4.9	-6.9	-7.0
Boeing 777-300ER	4,500	-2.2	-4.9	-7.1	-7.1

ESTIMATION OF DIRECT OPERATING COSTS

A new aircraft model is produced around every 15 years, when a critical number of fuel-saving technologies allow integration into an advanced vehicle with lower direct operating costs (DOC). The latter consist of crew, fuel, maintenance, ownership or depreciation, and other expenditures.

Ownership Costs

The capital costs of the projected aircraft were estimated with the Development and Procurement Cost of Aircraft (DAPCA) model, originally developed at RAND and further improved by Raymer (2012). DAPCA IV, which is the most recent model version, estimates the non-recurring (research and technology) costs and the recurring (production) costs of airframes using statistical relationships with engineering, tooling, manufacturing, and quality control, along with various material and component costs. The key determinants of airframe development and manufacturing costs are aircraft empty weight, maximum cruise speed, and the number of aircraft produced. An increase in any of the first two variables leads to an increase in aircraft capital costs. In contrast, an increase in the number of aircraft produced leads to lower unit costs due to technological learning and economies of scale. This analysis is based upon a typical production run of 500 aircraft.

Because engine research and technology costs are not included in the DAPCA model, an engine cost model was developed. That model estimates the engine list price as a function of maximum thrust, cruise engine specific fuel consumption, and certification year. A typical discount of 70%, which is based upon confidential discussions with industry experts, was applied to arrive at the engine research, technology and production costs. The model suggests that the engine list price correlates directly with the maximum thrust and the certification year, and indirectly with specific fuel consumption, as would be expected. All parameter estimates are significant and the R^2 resulted in 0.96.

Jointly, DAPCA IV and the engine cost model produce plausible cost estimates. For example, production costs of the A320-200 aircraft are estimated to be $54.8m for a production run of 500 aircraft and $31.8m for the 3,192 aircraft produced through 2012. These values compare to the average aircraft price of $46.6m in 2012 (Airliner Price Guide, 2018). DAPCA's weight dependence implies that heavier and thus larger aircraft experience higher capital costs, everything else being equal. However, without adjusting for the share of light-weight materials, the weight-based approach could be misleading as it would project lower capital costs for a more expensive carbon fiber composite-intensive aircraft compared to a comparable metal-intensive aircraft, all other factors equal. Thus, DAPCA IV allows for differences in material composition via an escalation factor. To account for the significantly larger amount of carbon fiber materials projected to be employed in future aircraft, an adjustment factor of 1.45 was used for the extra time dedicated to tooling, manufacturing, and quality control, which is the midpoint value of the range 1.1 to 1.8 given in Raymer (2012). Based upon a review of studies and news stories, $(2012) 1,750 per seat for narrow-body aircraft and twice that amount for the widebodies was added, due to the significantly more expensive business class seats, which is more prevalent in these vehicles. In addition, in line with FAA (2014) estimates, $670k per aircraft was added to be compliant with advanced air traffic management procedures. The capital costs were annualized using a residual value of 10% and an economic lifetime of 20 years following a linear depreciation. Interest on the investment was assumed to be 4%/yr and insurance to be 0.5%/yr (Jenkinson, 2001).

For hydrogen aircraft, extra capital costs will result from mainly the cryogenic fuel tanks. However, in the absence of robust cost estimates, these extra costs are neglected and thus the capital cost estimates represent an optimistic, lower-end estimate. However, given that ownership costs are a comparatively small share of total DOC and hydrogen fuel costs will increase strongly compared to jet fuel aircraft, the associated error is small.

Other direct operating cost elements

The other DOC components were estimated following Harris (2005), using Form 41 data (Schedules P-5.2, T-2, P-7) from the top-10 airlines operating in the US (Alaska, American, Delta, Hawaiian, Jet Blue, SkyWest, Southwest, United, US Air, Virgin), which jointly account for 85% of domestic RPK. Individual models for crew costs per flight hour (FH) were estimated as a function of the number of seats per aircraft and the number of flight hours per flight cycle; airframe maintenance costs as a function of the number of seats per aircraft, the first year of service, the passenger load factor, the number of flight hours per flight cycle, the share of inhouse to total repair, and a dummy variable for low-cost carriers; engine maintenance as a function of the engine thrust, the number of flight hours per flight cycle, a dummy variable indicating fleet commonality, a dummy variable for low-cost carriers, and the share of inhouse to total repair; and other expenditures with a dummy variables for Delta airlines. All coefficients have the expected sign and are highly significant, and the R^2 ranged from 0.83 to 0.98 (ATA and Ellondee, 2018). Airport and en-route charges are based on aircraft weight and passenger number-based relationships from Jenkinson (2001).

Direct operating costs of future aircraft

Using the above-described approach, **Figure 24** reports the resulting DOCs in US$(2020) per flight hour by category for the four aircraft size classes using fossil jet fuel for today's generation and liquid hydrogen for the Generations N+1 and N+2 in 2035/40 and 2050/55, respectively. Fuel costs are based upon a fuel price of $5 per gallon and the LH2 price corresponds to $4 per gallon of jet fuel equivalent for liquid hydrogen. Although capital costs of the 2035/40 aircraft are projected to increase above the current generation aircraft, the savings in all other expenditure items are anticipated to decline more strongly (particularly fuel costs), thus leading to a decline in total DOC. However, in practice, airlines will not accept an increase in capital costs compared to the previous-generation aircraft and manufacturers will thus have to absorb these extra production costs through a larger production run, as illustrated with the A320-200 example described above. Hence, the DOC reduction experienced by airlines would be larger than shown in **Figure 24**. The same figure also shows that the projected capital costs of the 2050/55 aircraft are below those of the next generation. This can be explained by the improved understanding of composites material behavior. As discussed above, composite materials are projected to account for 50% of the operating empty weight of all future aircraft, thus initially raising capital costs. At the same time, the associated weight reductions are projected to increase over the current generation aircraft due to improved understanding composite material behavior, thus leading to a lower material use and capital cost reduction between the two future aircraft generations.

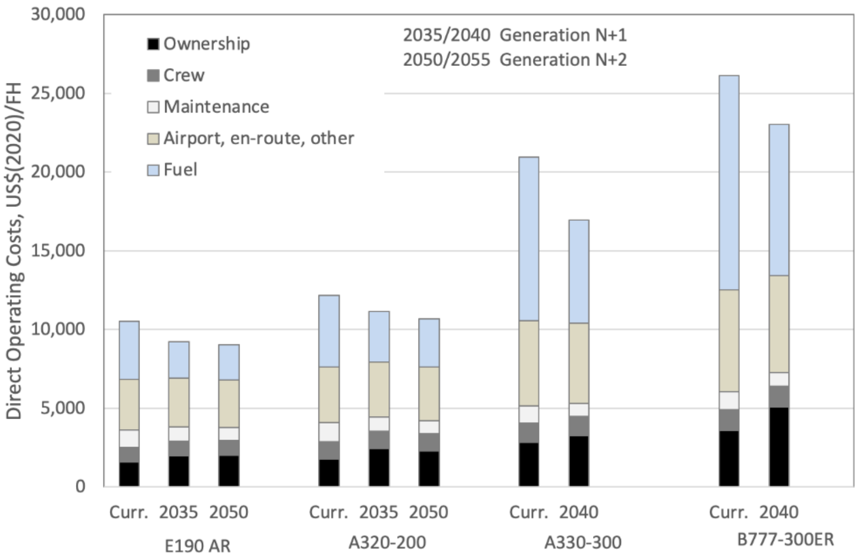

Figure 24 Estimated DOCs in US$(2020) per flight hour for the four aircraft size classes using synthetic liquid fuels for today's generation and LH2 for Generation N+1, and Generation N+2. The underlying jet fuel price is $5 per gallon and the liquid hydrogen price is $4 per gallon of jet fuel equivalent

APPENDIX 7: ASSESSING THE IMPACT OF THE TECHNOLOGY PACKAGES IN REAL-WORLD OPERATIONS

The potential of a new technology or fuel to reduce emissions on a single flight is not necessarily a good guide to how much that technology can practically reduce emissions on a global level. Typically, it is an upper limit. To achieve its full single-flight potential globally, a technology has to be adopted by airlines and aircraft leasing companies, put into use across all routes and aircraft size classes, and provide the same benefits across those different routes and aircraft sizes as it does on the example flight. For new aircraft designs, significant time lags are associated with fleet turnover and, if those designs are a large change from current ones, issues of public perception and airline risk-averseness may also delay uptake. In the case that the technology is widely successful, there may also be second-order effects that reduce its anticipated benefits. For example, airlines will not typically adopt a technology unless they anticipate cost savings or increased revenue from using that technology over current technology (unless the new technology is mandated on some or all of their routes). But a technology that significantly reduces operating costs allows airlines to reduce ticket prices, stimulating additional demand and leading to a rebound in emissions.

Aviation's ability to meet emissions targets and the potential of alternative fuels to help in this are also uncertain because future developments in aviation demand are uncertain. Current industry growth rate estimates in the wake of the COVID-19 pandemic are for 2019-2040 RPK growth rates of around 4% per year (Airbus 2021; Boeing 2021). Pre-pandemic growth rates were typically over 5%/year (e.g., ICAO, 2020a) and, if this level of growth returns, demand for aviation fuel in 2050 may be more than twice year-2019 levels. Under these circumstances, the potential for a supply-constrained amount of alternative fuels to fully substitute fossil kerosene is much smaller than in an alternative case where fuel demand does not grow much beyond year-2019 amounts. Similarly, emissions targets set at absolute levels (say, IATA's previous target of reducing aviation CO_2 to half its year-2005 value, which corresponds to around 325 Mt CO_2, or around a third of year-2019 direct aviation CO_2 emissions) are much easier to meet when demand growth is low.

To model the potential of the technologies assessed in this project in the real world, this study uses the global aviation systems model AIM, which simulates the interactions between airline, passenger, freight forwarder and regulator behavior which affect technology potential. The next sections give a longer description of how AIM works than the one included in the main report, and a more detailed discussion of how the technologies assessed above are introduced into the model. Because outcomes are strongly affected by the values of key uncertain input variables such as oil price and GDP/capita, a range of scenarios are used to assess technology potential. Each of the six quantified scenarios used here is based on assumptions for demand characteristics, policy characteristics, fuel supply characteristics, and available technology packages.

THE AVIATION INTEGRATED MODEL (AIM)

The Aviation Integrated Model (AIM) is a global aviation systems model which simulates interactions between passengers, airlines, airports and other system actors into the future, with the goal of providing insight into how policy levers and other projected system changes will affect aviation's externalities and economic impacts. The model was originally developed in 2006-2009 with UK research council funding (e.g., Reynolds et al., 2007; Dray et al. 2014), and was updated as part of the ACCLAIM project (2015-2018) between University College London, Imperial College and Southampton University (e.g., Dray et al., 2019), with additional input from MIT regarding electric aircraft (e.g., Schäfer et al., 2018). The model is open source, with code, documentation and a simplified version of model databases which omit confidential data available from the UCL Air Transportation Systems Group website (UCL ATS,2021). AIM has been used for aviation policy and technology assessment in a wide range of contexts, including for the UK Department for Transport (e.g., ATA & Clarity, 2018), EC DG CLIMA (e.g., ICF et al. 2020), and the International Energy Agency (IEA, 2020b).

AIM uses a modular, integrated approach to simulate the global aviation system and its response to policy. The basic model structure is shown in **Figure 25**. AIM consists of seven interconnected modules. The Demand and Fare Module projects true origin-ultimate destination demand between a set of cities representing approximately 95% of global scheduled RPK[10], using a gravity-type model based on origin and destination population and income, average journey generalized cost, and other factors, as detailed in Dray et al. (2019, 2014). For the pandemic period, several adjustments are made to this model to capture the impact of pandemic-related movement restrictions (Dray & Schäfer, 2021). Within each city-city passenger flow, airport choice and routing choice (including hub airport for multi-segment journeys) are handled using a multinomial logit model. Itinerary choice is modelled as a function of journey time, cost, number of flight segments, available flight frequency and characteristics of the origin and destination airports. This model is described further in Dray & Doyme (2019). Fares per individual itinerary are simulated using a fare model (Wang et al., 2017) based on airline costs by type per segment, demand, route-level competition, low-cost carrier presence and other factors. These models are estimated primarily on detailed disaggregate global passenger routing and fare data from Sabre (2017).

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[10] Note that non-scheduled flights and freight are also modelled for this report. Because less information is available on routing for these flights, they are dealt with using a segment-based scaling approach.

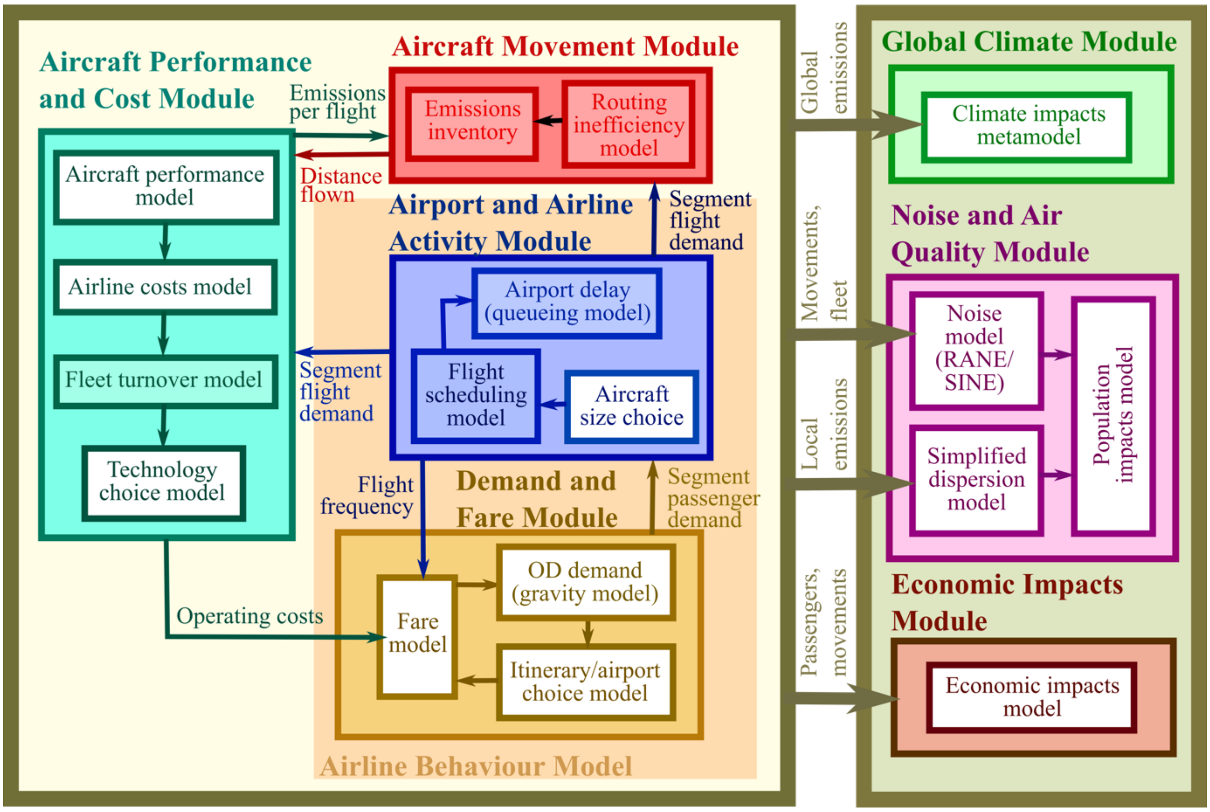

Figure 25 AIM model structure

The Airline and Airport Activity Module, given segment-level demand, assesses which aircraft will be used to fly these routes and at what frequency, using a multinomial logit model estimated from historical scheduling data (Sabre, 2017) and dividing the fleet into nine size categories. Given these aircraft movements per airport, a queuing model then estimates what the resulting airport-level delays would be (Evans, 2008). Given the lack of long-term airport capacity forecasts, in most cases this delay model is used to estimate the amount of (city-level) capacity that would be required to keep delays at current levels.

The aircraft movement module assesses the corresponding airborne routes and the consequent location of emissions. In particular, routing inefficiencies which increase ground track distance flown beyond great circle distance, and fuel use above optimal for the given flight distance, are modelled using distance-based regional inefficiency factors based on an analysis of radar track data, as discussed in Reynolds (2008).

Given typical aircraft utilization, the aircraft technology and cost module assesses the size, composition, age and technology use of the aircraft fleet, and the resulting costs for airlines and emissions implications. First, aircraft movements by size class including routing inefficiency from the Aircraft Movement Module are input to a simplified model of aircraft fuel use (estimated from outputs of the PIANO-X performance model (Lissys, 2017) with reference aircraft types and missions for CO_2 and NOx, the FOX methodology (Stettler et al. 2013) for PM2.5, and Wood et al. (2008) for NO_2). Second, the costs of operating this fleet for the given schedule are estimated based on historical cost data by category and aircraft type (Al Zayat et al, 2017). Third, emissions and costs are adjusted to account for the current age distribution and technology utilization of the fleet, including typical retirement and freighter conversion behavior (e.g., Dray, 2013). Finally, any shortfall in aircraft required to perform the given schedule is assumed made up by new purchases, and the uptake of technology and emissions mitigation measures by both new aircraft and existing ones is assessed on a net present value basis, as described in Dray et al. (2018), and the impact of this on costs and emissions is assessed. These four modules are run iteratively until a stable solution is reached. Data is then output which can be used in the impact modules, shown on the right of **Figure 25**.

The global climate module is a rapid, reduced-form climate model which calculates the resulting climate metrics (e.g., CO_2e in terms of global temperature potential (GTP) and global warming potential (GWP) at different time horizons; see Krammer et al., 2013). The air quality and noise module are similarly rapid, reduced-form models which provide metrics by airport for the noise and local/regional air quality impacts of the projected aviation system. In the case of air quality, dispersion modelling for primary pollutants uses a version of the RDC code (e.g., Yim et al., 2015). The type of noise modelling carried out depends on whether data on standard flight routes per airport is available, but for all airports noise modelling based on total noise energy is carried out (Torija et al. 2016, 2017). The regional economics module looks in more detail at the economic impacts, including benefits such as increased employment as well as costing of noise and air quality impacts.

The output data from the first four AIM modules can also be used more generally as input to external impacts models: for example, the model includes the option to produce detailed emissions inventories which can be input into climate models. Further information on the individual sub-models, on model validation, and on typical model inputs and outputs can be found in the papers cited above. This study concentrates on global and regional CO_2 emissions greenhouse gas emissions outcomes. Airport-level outcomes are used where necessary to constrain technology characteristics and choice (for example, in developing the technology specification, it was assumed that aircraft designs with significantly worse noise impacts or airport-level emissions than current technology would not be further developed).

FUEL RAMP-UP MODEL

The E4tech ramp-up model is a bottom-up model, separate from AIM, based on extensive information on companies currently developing SAF production technology, and the plants they operate or have planned. The model was developed to reflect the technical ability of the industry to scale-up from its current state, based on the current number of active technology developers, the scale of existing and planned plants, and plausible build-rates in this industry. The model has been used in previously published reports, including a 2018 JRC report on market development of advanced biofuels to 2030, and the Sustainable Aviation Fuels Roadmap (SAUK, 2020), and has been continually updated.

In contrast to past studies, the ramp-up model has not been used in this study to provide projections: the amount of SAF required is dependent on level of policy ambition and resulting demand, and supply would be expected to react according to future demand. SAF supply cases were instead developed jointly with the demand and policy cases produced by AIM, which allowed a wide range of levels for future SAF requirements to be explored. Therefore, the levels of SAF supply shown in this study are intended to be aspirational, reflecting the scale and rate of growth required to meet aviation emissions targets and satisfy future demand.

As the bottom-up analysis of the fuel supply is not integrated with the AIM system model, the fuel supply for each set of demand and policy cases was determined following an iterative process, assuming that low-carbon fuel supply would scale with and in response to demand to 2050. A baseline set of supply characteristics, based upon work previously conducted by E4tech for Sustainable Aviation UK (2020), was first used as an input into AIM. The difference in fuel supply and demand from the AIM model was observed, and the ramp-up model adjusted accordingly, to ensure an aviation fuel supply by 2050 of ~5-10% greater than projected aviation industry demand at a given level of policy ambition for each demand case. A slight oversupply of SAF was intended to ensure that some degree of cost competitiveness between pathways was factored into the modelling. Supply modelling variables were adjusted to enable greater SAF supply volumes. This process was repeated for each demand and policy case, resulting in three accompanying supply cases that are used as inputs to the AIM model.

Methodology

The ramp-up model is built upon the current and planned global deployment of plants using the selected pathway technologies. Importantly, the framework of the model does not consider competition between the individual developers or conversion routes, but instead considers how fast each developer and route could expand given demand to do so. The model operates with two distinct growth phases: a ramp-up phase and a growth phase.

The ramp-up phase, or introductory phase, acts as the foundation of the model, and determines near-term growth based on potential new facility build rates. Each known project is added to the model to provide a baseline of current and planned SAF production capacity over time, which is dependent on the starting date of each project, the reported scale of the plant and expected plant lifetime. Developers are assumed to build additional plants over time, corresponding to the stage of technology development (Demonstration, 1st commercial, 2nd commercial, nth commercial), with the rate of capacity growth determined by a range of factors, which are discussed in detail below.

Beyond 2030, the model introduces a growth phase, where the growth rate is determined by overall market expansion, rather than individual developer growth. The model is structured so that pathways with a greater number of developers and plants during the ramp-up phase will reach commercialisation more quickly: this is simulated by switching to the growth phase at an earlier date. This is necessary as the ramp-up phase methodology does not have a built-in method to model new market entrants, so pathway capacity would begin to level off. This would not be consistent with typical industry cycles where the introduction phase is followed by a period of accelerated growth.

This methodology is followed for all pathways, with the exception of HEFA. The rate at which HVO and FAME plants can be built is unlikely to be a limiting factor in the short-to-medium-term, since there are several technology and plant developers already operating at commercial scales, with further plans to expand in response to growing demand. Instead, the main limiting factor will be the availability of advanced feedstocks, such as waste oils and fats. Although novel energy crops such as Camelina and Carinata are being explored, their use at scale, particularly when cultivated on degraded land or as a cover crop, is yet to be proven and subject to high uncertainty. Establishing energy crops on degraded land requires a sustained effort over a period of years, and degraded sites often have alternative uses (IRENA, 2017).

Cover crops are traditionally tilled into the soil to provide additional nutrients and organic matter, and to protect the soil from erosion and crusting: the harvesting of cover crops could therefore produce unwanted side-effects, including reducing crop yields and soil quality. Hence, sustainability remains a major challenge, while crop yields in literature can be significantly reduced if sustainable farming practices are followed (Matteo, Roberto, et al., 2020).

As a result, only feedstocks from waste oils were considered in this study. The global potential for UCO has been estimated to be as high as 34 Mt/yr (Ecofys, 2019), including brown grease and gutter oil: however, this figure likely includes UCO used in other sectors and countries, and the gutter oil typically contains both virgin vegetable oil and UCO. The global potential for waste animal fats has been estimated at ~10 Mt/yr, although this figure also includes a range of categories of animal fats, of which some will have competing uses. These figures represent an absolute theoretical maximum, and practical collection potential is likely to be lower. However, the combined total of 44 Mt/yr is used as the maximum feedstock potential for HEFA in this study, to account for additional advanced feedstock sources becoming available in future, such as the novel crops noted previously. HEFA supply is projected using an S-curve, starting at the current capacity from operational and planned plants, and approaching the maximum feedstock potential in 2050, in all three scenarios. As HEFA is already commercially mature, and more cost-effective than other pathways, it is expected that developers will expand operations within the constraints of feedstock availability in all scenarios.

Ramp-up phase assumptions

The number of developers is an important factor in determining future deployment of a technology, as each developer is expected to progress their technology to commercial scale and begin initiating new commercial projects (accounting for failure rates) either under an owner-operator or a licensing model. Projects are only included that have reached pilot scale or beyond: lab-scale facilities, research institutes, and developers without proven technologies at this scale, are excluded. **Table 46** shows the number of developers actively operating, building, or planning fuel production projects within each fuel pathway, at the time of modelling.

Table 46 Number of active developers operating in each pathway with projects at pilot scale or beyond[1]

Pathway	Developer Count
Alcohol-to-jet (ATJ)	9
Aqueous phase reforming (APR) of lignocellulosic sugars	1
Hydrothermal liquefaction (HTL) and hydrotreatment	10
Gasification + Fischer-Tropsch (FT)	15
Catalytic pyrolysis and hydrotreatment	8
Fermentation-to-Terpenes of lignocellulosic sugars	4
Hydrotreatment of oils and fats (HEFA)	35
Power-to-Liquids (PTL) Fischer-Tropsch (FT)	8

1 Based on analysis in 2021

Once these developers and plants are added to the model, future deployment is then projected based on several key factors, which are summarised below:

Technology type

Each pathway was assigned a technology archetype, either **chemical**, **thermochemical**, or **biological**, based on the type of processes involved and equipment required. For each archetype, a different set of assumptions were used regarding project development timelines: pathways were grouped as shown in **Table 47**.

Table 47 Technology types assigned to each fuel pathway in the ramp-up model

Pathway	Technology type
Alcohol-to-jet (ATJ)	**Chemical**
Aqueous phase reforming (APR) of lignocellulosic sugars	**Thermochemical**
Hydrothermal liquefaction (HTL) and hydrotreatment	**Thermochemical**
Gasification + Fischer-Tropsch (FT)	**Thermochemical**
Catalytic pyrolysis and hydrotreatment	**Thermochemical**
Fermentation-to-Terpenes of lignocellulosic sugars	**Biological**
Power-to-Liquids (PTL) Fischer-Tropsch (FT)	**Chemical**

Project Timelines

The development timeline defines how long it would take from project inception to a fully operational plant. This includes **project development & financing (PD)**, **construction (CO)**, **commissioning & ramp-up (CM)** phases. For each technology type (biological, thermochemical and chemical) and for each stage of plant scale-up (pilot, demonstration, 1st commercial, 2nd commercial and Nth commercial) an average development timeline is applied, as illustrated in **Figure 26**.

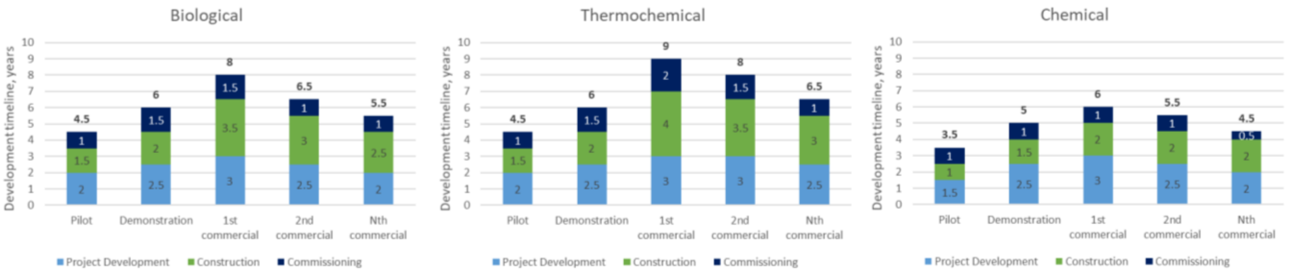

Figure 26 Project development timelines assumed in the ramp-up model

The project development timelines for each archetype were based on discussions with industrial partners and stakeholders. Pilot and demonstration plants are generally quick to design and build compared to 1st commercial facilities, where technologies are being rigorously tested at larger scales, proven over an extended period of time, and where there are additional supply chain complexities. 2nd and subsequent (Nth) commercial plants are assumed to have shorter development timelines, as a result of learning and replication.

Launch point

The launch points define when the next project is most likely to start, assuming that the next project represents the next stage of commercialisation for the technology. Launch points are not relevant for operational or planned projects: in these cases, the reported year of construction/operation is input into the model. The launch point for projected projects was assumed to be similar for each technology type, reflecting the fact that investors are likely to require a similar number of years of operational evidence before taking larger investment decisions, independent of the specific technology. However, the launch points vary depending upon the technology stage, and were varied between supply cases within this study, as described in **Table 48**. For the mid and high supply cases, an accelerated development schedule is assumed, which shortens the development time towards full commercialisation. There is no launch point for pilot plants, as developers at lab scale are excluded from the model.

Table 48 Summary of launch points assumed in the supply cases in this study

Technology stage	Low supply	Mid/high supply
Demonstration	**PD begins 0.5 years from the point at which pilot plant is fully operational**	**PD begins 0.5 years from the point at which pilot plant is fully operational**
1st Commercial	PD begins 2 years from the end of the comissioning period of the demonstration plant	PD begins 2 years from the beginning of the comissioning period of the demonstration plant
2nd Commercial	**PD begins 2 years from the end of the comissioning period of the 1st commercial plant**	**PD begins 2 years from the beginning of the comissioning period of the 1st commercial plant**
Nth Commercial	PD begins 1.5 years after the previous plant begins development	PD begins 1.5 years after the previous plant begins development

Plant lifetime

Table 49 shows the assumed plant lifetimes used in modelling. With this approach, pilot and demonstration-scale plants built during the early period do not contribute towards the total production capacities towards the end of the ramp-up period. The short lifetime of pilot and demonstration plants reflects the fact that they are often loss-making facilities, and generally developers choose to operate these plants for only long enough to gain valuable test data and experience, to finance future plants.

Table 49 Plant lifetime assumptions used in ramp-up model

Development stage	Plant lifetime (years)
Pilot	3
Demonstration	5
Commercial	28

Generic plant output

The assumed capacity of projected Nth commercial plants is shown for each pathway in **Table 50**, based on planned facilities. It was assumed that each technology pathway would converge towards an average fuel output capacity per year. These are not assumed to vary by scenario, given that economically viable plant scales are not particularly dependent on the wider industry development - rather they depend on capital costs, operating costs and efficiencies, trading off against feedstock prices and local availability near plants (or imports).

Table 50 Assumed nameplate capacities of projected projects

Pathway	Nameplate capacity (ML/yr)	Nameplate capacity (PJ/yr)
Alcohol-to-jet (ATJ)	**183**	**6.3**
Aqueous phase reforming (APR) of lignocellulosic sugars	132	4.5
Hydrothermal liquefaction (HTL) and hydrotreatment	**72**	**2.5**
Gasification + Fischer-Tropsch (FT)	102	3.5
Catalytic pyrolysis and hydrotreatment	**83**	**2.9**
Fermentation-to-Terpenes of lignocellulosic sugars	55	1.9
Power-to-Liquids (PTL) Fischer-Tropsch (FT)	**140**	**4.8**

Biofuel production facilities using lignocellulosic residues are limited in their scale by relatively low conversion efficiencies. An optimized collection distance, or “sourcing radius” is often a key consideration in bioenergy projects, which typically is a matter of optimising the trade-off between decreasing levelized capital costs of the conversion plant and increasing biomass feedstock costs as the required collection radius increases. This is highly dependent upon the feedstock: for instance, woodchips from logging residues have a significantly smaller economical collection radius than woodchips from energy crops. However, factors such as the availability of infrastructure (e.g., forest roads, railways, canals), capital expenditure limits, biomass price volatility and local regulations also play a role. There are also geographical constraints which must be considered.

For this reason, facilities receiving primary biomass residues, such as wood or agricultural residues, are assumed to be smaller in scale on average than plants receiving secondary products (e.g., ethanol or concentrated sugars). Similarly, PTL FT facilities are assumed to be less constrained in scale in comparison to the gasification + FT counterpart.

Availability of plants

All plants across all pathways were assumed to run at 90% utilisation once successfully constructed and commissioned. Therefore, actual annual fuel production is slightly below the nameplate capacities.

Product slate

The technology pathways considered in the model can produce several different fuel types: often, it is not possible for these fuel production pathways to produce 100% jet fuel. Therefore, a product slate is applied to the total plant capacity for each pathway, to determine the amount of jet fuel available. In this study a jet optimised scenario is assumed, where the percentage of jet fuel output is maximised. This product slate (**Table 51**) is applied post-process to the entire supply curve.

Table 51 Jet-optimised product slate assumed in the supply cases

Pathway	Gasoline	Diesel	Jet	LPG
Alcohol-to-jet (ATJ)		10%	90%	
Aqueous phase reforming (APR) of lignocellulosic sugars	**18%**	**8%**	**72%**	**2%**
Hydrothermal liquefaction (HTL) and hydrotreatment		40%	60%	
Gasification + Fischer-Tropsch (FT)	**13%**	**13%**	**75%**	
Catalytic pyrolysis and hydrotreatment		40%	60%	
Fermentation-to-Terpenes of lignocellulosic sugars			**100%**	
Power-to-Liquids (PTL) Fischer-Tropsch (FT)	13%	13%	75%	

Market growth phase assumptions

As discussed in earlier, the ramp-up model introduces a market growth phase after 2030. The growth rates assumed in the growth phase are shown in **Table 52**.

Table 52 Assumed market growth rates for each pathway

Supply case	Biofuel pathways	E-fuel pathways
Low supply	15% CAGR	21% CAGR
Mid supply	15% CAGR	23% CAGR
High supply	16% CAGR	36% CAGR (2031-2040) 23% CAGR (2041-2050)

The market for advanced biofuels and e-fuels are considered separately, as each face different constraints. The growth of the biofuels market is limited by feedstock availability, which is in turn constrained by the need to establish and maintain extensive supply chains, in addition to the costs associated with building and operating the plant itself. For biofuel production pathways, the historic growth rate of US corn ethanol production between 2000 and 2016 is used as a proxy for the growth rate in this period, resulting in a CAGR of 15%. This rate was chosen due to similarities in market behaviour, where slow growth due to the development of the conversion technology was followed by a rapid market expansion, and there was a similar need to establish new feedstock supply chains. This growth rate is slightly accelerated in the high supply scenario, above historic levels of growth.

For e-fuel pathways (PTL FT), the industry is expected to be capable of faster growth rates. Electrolyser manufacturing is considered to generally be demand driven, rather than supply-constrained. Manufacturing processes are easily scalable, requiring relatively low investment in terms of critical components. A study by NOW GmbH investigated future hydrogen demand scenarios to meet Germany's GHG reduction targets, including scenarios with installed electrolyser capacities of over 250 gWel by 2050 (NOW GmbH, 2018). Analysis showed that, for the manufacturing of many of the critical electrolyser components, only a single production line was required to meet the necessary demand, with relatively limited investment required. Although the study did not consider the further investment requirements for non-critical peripheral components or hydrogen infrastructure, which are necessary, it was concluded that the water electrolysis industry is capable of up-scaling production within a few years with no critical bottlenecks. This matches E4tech's findings from interviews with electrolyser manufacturers who stated that there were no constraints on mid to long term uptake, with any degree of scale up being possible within a five-year lead time.

Similarly, IRENA note that electrolyser learning rates are similar to those for solar PV, where economies of scale can readily be reached with large scale deployment, and significant growth rates have been achieved since 2000 (IRENA, 2020). As such, the renewable energy industry is used as a proxy for e-fuels industry growth: combined solar and wind installations have grown at a CAGR of ~21% in recent decades (IEA, 2020a), while solar PV has operated at a CAGR of ~40% since 1990 (European Commission, 2019). The latter is considered to be unrealistic for e-fuels, due to additional challenges regarding plant complexity and infrastructure: therefore, accelerated growth for e-fuels in the high scenario is not sustained over the entire period.

IMPLEMENTING THE TECHNOLOGY PACKAGES IN AIM

New technologies and fuels affect aircraft fuel use, operating cost, and potentially other per-flight characteristics such as turnaround time or the typical number of seats on an aircraft. There are two potential future cases for technology adoption. In the first case, using the technology reduces airline costs (where costs are potentially affected by policy, for example carbon pricing), and airlines freely decide to use it. In the second case, airline choices about which technologies to use, or manufacturer decisions about which designs to offer, are constrained by policy (for example carbon standards or fuel mandates). In the first case, when deciding whether to invest in a technology, an airline or leasing company will assess the costs associated with using that technology, including fuel and carbon costs, and compare them to the costs of alternatives. In AIM, the choice of whether or not to adopt operational and retrofit measures is treated separately to the choice of whether or not to purchase new aircraft designs. For new aircraft models, the cost-effectiveness of an aircraft of technology x is assessed using net present value (NPV), i.e.

$$NPV_x = \sum_{t=0}^{T_N} R_{t,x}/(1 + i^t) \ ,$$

where T_N is the time horizon over which the technology is evaluated, i is the discount rate, and $R_{t,x}$ is the cash flow associated with technology x in year t. The discount rate and time horizon are user input values in AIM. By default they are set at ten percent and seven years. The net present values for each available technology in a given year for a given world region are assessed, and airlines are assumed to choose the technology with the greatest net present value across typical route networks for that aircraft size in that region. However, airlines may choose more than one technology option in a given year, world region and size class: for example, if the model associated with the lowest costs has other usage restrictions that mean it cannot be used on all flight segments, the second-best option may be adopted on other routes.

For operational measures, a simple payback period model is used, in which a retrofit is cost-effective if

$$\sum_{t=0}^{T_P} R_{t,x} - R_{t,base} > 0,$$

i.e., the measure is adopted if over a period of T_P years overall cost savings relative to the base technology in use in that aircraft cohort can be made, provided that that measure is not incompatible with any other measures already in operation. The payback period is a user input but is three years by default.

In the case that mandates or standards are applied, the choice of a particular technology or fuel blend can be made mandatory (subject to supply constraints). This in turn will have an impact on airline operating costs and ticket prices. In this case, the extent of this impact is determined by the different costs associated with the technology as well as by its operating characteristics. A mandated technology or fuel blend may also change other airline technology-related decisions; for example, airlines which are required to use more expensive fuels have a greater incentive to use strategies which increase operational efficiency.

To assess technology adoption, information on how the costs, benefits and operating constraints of using that technology differ from current technologies is therefore needed. Non-fuel operating costs for new aircraft designs were assessed above, while operating constraints formed part of the decision on which technology options to take forward in the initial analysis and filtering of individual mitigation options. Fuel-related costs, and in-practice fuel use, are a function of several factors that may vary over time (oil prices, carbon prices, typical payload, the availability of other technologies and operational measures) and so are calculated within AIM based on this analysis of aircraft operating characteristics.

Characteristics of kerosene aircraft technologies

Aircraft fuel use is modelled per aircraft size class at a flight segment level in AIM. The calculation of fuel use is a three-step process:

- First, typical ground track inefficiency factors and passenger and freight payloads for the aircraft type on that segment are calculated, to provide estimates of payload and actual distance flown.
- Second, these factors are used as input into a simple aircraft performance modelling routine for the reference aircraft for that size class, to estimate reference aircraft fuel use, NOx and flight time (at anticipated levels of delay) at the given payload and distance. This step also includes consideration of non-lateral fuel use inefficiency factors (i.e., increases in fuel use over performance modelling values from flying at non-ideal speeds or altitudes).
- Third, the aircraft age distribution and technology composition of the fleet in that size class in the region of operation are used to calculate adjustment factors to this fuel use and to associated costs.

For kerosene aircraft, performance modelling by flight phase for climb out, cruise and descent is based on a model fit to fuel use as a function of distance and payload estimated from the output of the PIANO-X aircraft performance model (Lissys, 2017). This modelling is carried out for each of nine aircraft size classes, shown in **Table 53**, along with the associated reference aircraft and engine.

Table 53 Reference aircraft by size class used in AIM

	Size Category	Approx. seat range	Reference aircraft	Reference engine
1.	**Small regional jet**	30-69	CRJ 700	GE CF34 8C5B1
2.	**Large regional jet**	70-109	Embraer 190	GE CF34 10E6
3.	**Small narrowbody**	110-129	Airbus A319	V.2522
4.	**Medium narrowbody**	130-159	Airbus A320	CFM56-5B4
5.	**Large narrowbody**	160-199	Boeing 737-800	CFM56-7B27
6.	**Small twin aisle**	200-249	Boeing 787-800	gEnx-1B67
7.	**Medium twin aisle**	259-299	Airbus A330-300	Trent 772B
8.	**Large twin aisle**	300-399	Boeing 777-300ER	PW4090
9.	**Very large aircraft**	400+	Airbus A380-800	EA GP7270

For the gate, taxi and holding phases similarly-derived fuel use and emissions rates are used (i.e., kg fuel/s) by size class to estimate fuel use at a given level of airport-related delay, as emissions from these flight phases are typically sensitive to the amount of system congestion. For take-off and landing standard fuel use and emissions totals by type are used. 100 kg is assumed for a passenger with luggage and hold freight average load is calibrated against available capacity, global totals and typical passenger-to-freight payload ratios by region-pair (ICAO, 2009; ICAO, 2014; ICCT, 2019b). It is assumed that the ratio between maximum available passenger payload and freight payloads per route group will remain similar into the future, with fluctuations in freight demand growth compared to passenger demand growth resulting primarily in changes to the number of freighter aircraft flights flown. This results in an effective short-term (post-COVID-19) switch towards freighter flights, which may lead into a longer-term trend away from freighter aircraft over time, as discussed by Boeing (2020).

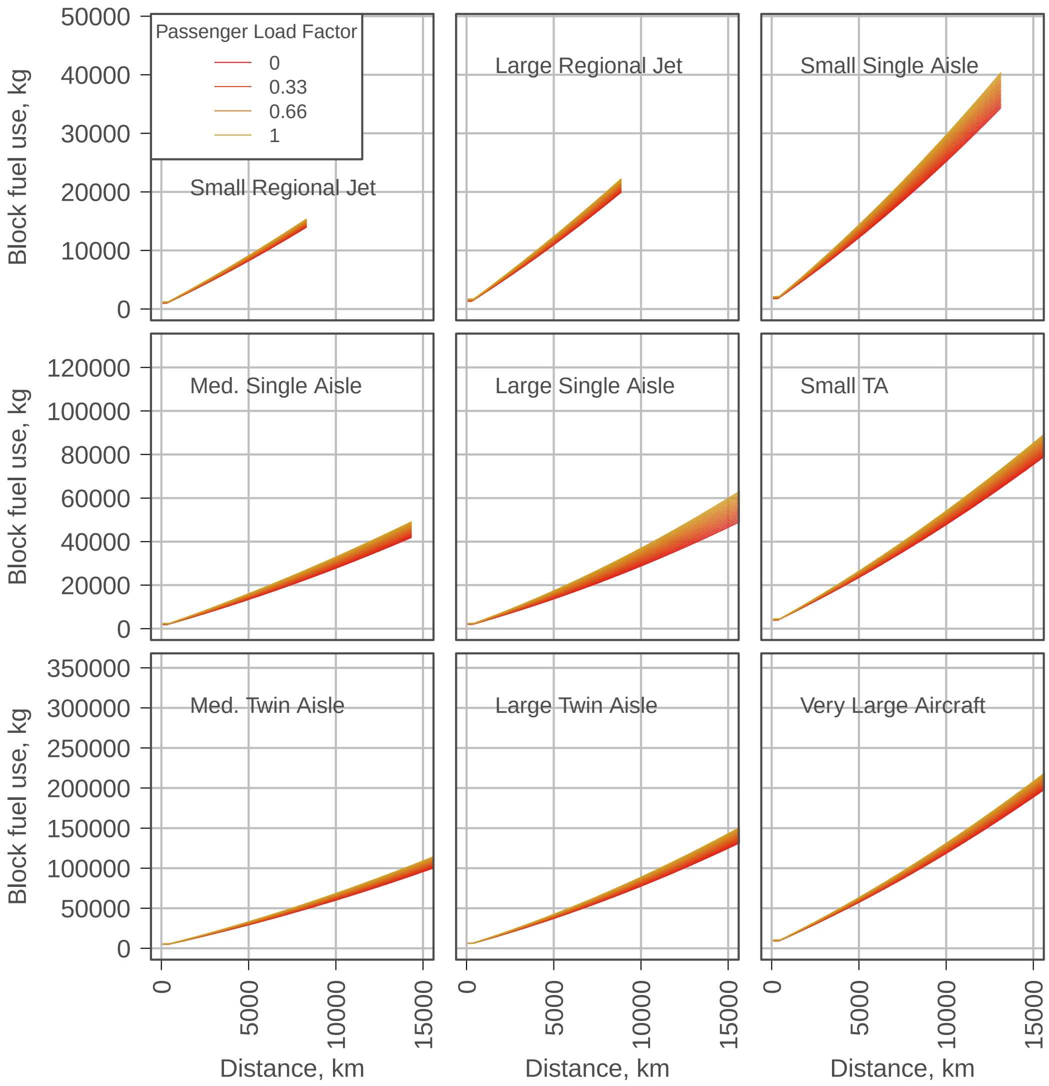

Figure 27 Baseline kerosene aircraft performance model

This performance modelling estimates fuel use by the reference aircraft in each size category for a given flight at a given payload and distance. To estimate the fuel use and operating costs of the alternative aircraft models assessed in this study, their fuel use and operating costs relative to those of the reference aircraft is required. This analysis was carried out in the initial phase of technology assessment for this study for four aircraft size classes chosen to be intermediate between the nine AIM size classes. To adapt those results to the AIM size classes, outcomes are scaled using the relative properties of the reference aircraft in each size class[11].

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[11] For example, for size classes which do not match exactly to the aircraft sizes assessed in this study, typical purchase price is scaled by the ratio of the typical purchase price in that aircraft size class to the purchase price in the nearest size class represented in this study. Note that these are purchase prices rather than list prices (airlines typically receive a substantial discount, which can be of order 50%, on advertised list prices).

Table 54 shows the assumed relative characteristics of the technologies chosen for further investigation in the first phase of this study to the reference aircraft in each size class, for technologies which are evolutionary developments of the baseline kerosene aircraft. Note that changes in other yearly costs exclude fuel and capital costs, which are calculated from the block fuel use and typical purchase price, respectively. For the current generation of aircraft (e.g., the A320neo compared to the A320ceo), aircraft characteristics are taken from values published by manufacturers and other literature sources (see, e.g., Dray et al. 2018).

The adoption of the next generation of kerosene aircraft is likely to be similar to the adoption dynamics of previous generations of kerosene aircraft. Under typical circumstances, the next generation of kerosene aircraft are expected to offer operating cost savings compared to their predecessors and to be widely chosen for new purchases from the time that they become available, with a limited overlap period in which both old and new aircraft models are available for purchase. Uptake is likely to be limited mainly by fleet turnover, i.e., the rate at which airlines have a need for new aircraft over time, either because they have retired existing aircraft or because they are growing their operations.

Table 54 Techno-economic characteristics of current and future kerosene aircraft generations used in AIM for this study: summary

Technology	Size class	Available from	Price inc. typical discount, million US$(2015)	Change in other yearly cost, million US$ (2015)	Change in block fuel use, %	References
NEO/MAX generation	Small RJ	2020 (2018-2025) a	32.6 (28.5-36.8)	-0.35 (- 0.3 -- -0.47) b	16 (15-21)	ACI, 2018; Embraer, 2016; Al Zayat & Schäfer, 2017
	Large RJ	2020 (2018-2025)	41.5 (36.3-46.8)	-0.4 (-0.35 -- -0.55)	16 (15-21)	ACI, 2018; Embraer, 2016; Al Zayat & Schäfer, 2017
	Small SA	2019 (2018-2020)	54.0 (50.1-57.9)	-c	20 (15 - 22)	ACI, 2018; Airbus, 2017; Schäfer et al. 2016; Vera-Morales et al. 2011
	Med SA	2016	55.3 (51.3-59.2)	-	20 (15 - 22	Same as for small SA
	Large SA	2018 (2017-2019)	55.4 (51.4-59.4)	-	20 (15 - 22)	Same as for small SA
	Small TA	No aircraft modelled; reference aircraft is already based on the 787-800				
	Med TA	2020 (2018-2022)	172 (154 - 190)	-0.026	12 (10 - 14)	ACI, 2018; Leahy, 2013; Airbus, 2017.

	Large TA	2020 (2018-2022)	214 (199-229)	-0.35 (0 -- 0.07)	21 (17.5 - 23.7)	ACI, 2018; Reuters, 2013; Airbus, 2017.
	VLA	No aircraft planned in this generation and size class				
Next generation Kerosene	Small RJ	2032 (2030-2035)	46.1	-0.42	29 (28 - 31)c	Characteristics assessed in this study; see earlier sections of appendix.
	Large RJ	2032 (2030-2035)	48.3	-0.42	29 (28 - 31)	
	Small SA	2032 (2030-2035)	64.4	-0.79	30 (29 - 32)	
	Med SA	2032 (2030-2035)	66.2	-0.79	30 (29 - 32)	
	Large SA	2032 (2030-2035)	66.5	-0.79	30 (29 - 32)	
	Small TA	2037 (2035-2040)	117.1	-0.93	26 (23 - 28)	
	Med TA	2037 (2035-2040)	147.6	-0.93	26 (23 - 28)	
	Large TA	2037 (2035-2040)	192.9	-0.86	26 (22 - 28)	
	VLA	No aircraft planned in this generation and size class				
Subsequent Generation kerosene	Small RJ	2047 (2045-2050)	46.0	-0.67	36 (35 -- 38)	Characteristics assessed in this study; see earlier sections of appendix.
	Large RJ	2047 (2045-2050)	48.2	-0.67	36 (35 -- 38)	
	Small SA	2047 (2045-2050)	63.9	-1.02	38 (37 -- 40)	
	Med SA	2047 (2045-2050)	65.8	-1.02	38 (37 -- 40)	
	Large SA	2047 (2045-2050)	66.1	-1.02	38 (37 -- 40)	
	Small TA	2052 (2050-2055)	100.3	-1.59	57 (54 -- 59)	
	Med TA	2052 (2050-2055)	126.5	-1.59	57 (54 -- 59)	
	Large TA	2052 (2050-2055)	159.8	-1.60	53 (49 -- 55)	
	VLA	No aircraft planned in this generation and size class				

a Values in brackets indicate the estimated range of potential values for each variable, where applicable.

b Compared to the reference aircraft in each size class, excluding fuel and capital costs.

c A dash in cost data indicates no cost change relative to reference aircraft; a dash in the reference's column indicates that all calculations are undertaken within this project.

d For next and subsequent generation aircraft the range given in these values is the range across different mission types with the same aircraft, rather than a range across different aircraft designs.

Characteristics of hydrogen aircraft technologies

For more radically different aircraft technologies (e.g., electric, hydrogen or LNG aircraft), a separate performance model is required to assess outcomes in AIM. Because detailed performance modelling was not undertaken in this project, an adapted version of the kerosene aircraft performance model is used to estimate hydrogen use by flight phase, payload, distance and aircraft size class, given estimates of hydrogen aircraft block fuel use by distance at a reference payload. Whole-flight estimates using this adapted model are shown in **Figure 28**. These values are calculated for the first generation of hydrogen aircraft; for subsequent generations, fuel use is calculated relative to the first generation, similarly to calculations for kerosene aircraft.

Typically, the hydrogen aircraft modelled here use more per-flight fuel energy than the equivalent kerosene aircraft[12]. This is because hydrogen aircraft are heavier than the equivalent kerosene aircraft due to the additional weight of the hydrogen tanks and supporting infrastructure. However, because hydrogen has a much higher energy density than kerosene, the amount of fuel used in kilograms is much smaller.

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[12] Note that the equivalent kerosene aircraft in this case is the generation of kerosene aircraft entering service in 2030-2035, rather than current aircraft.

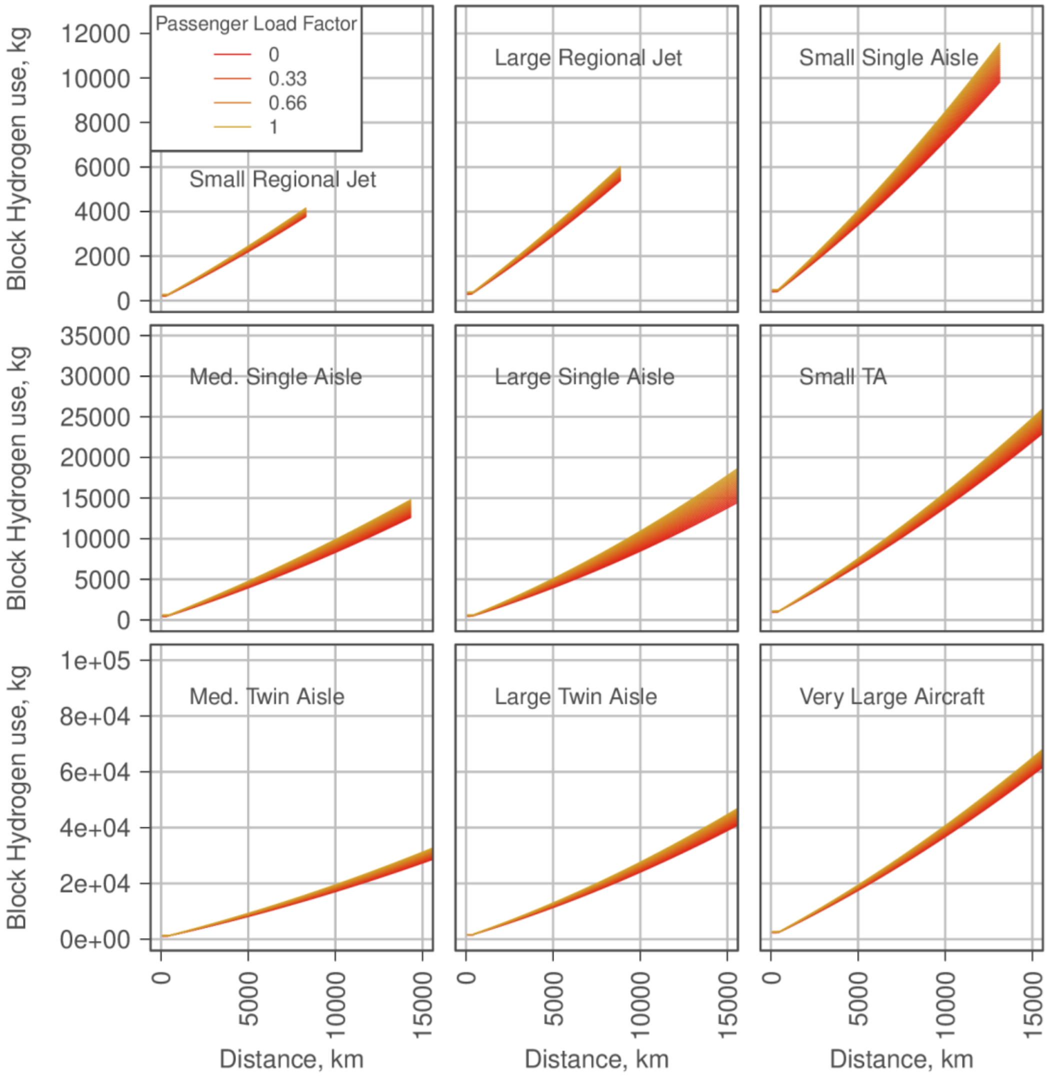

Figure 28 Adapted hydrogen aircraft performance model

The characteristics of the first and subsequent generation of hydrogen aircraft relative to the hydrogen aircraft performance model are shown in **Table 55**. Because the performance model is based directly on the first generation of hydrogen aircraft, the change in fuel use from the performance model for these aircraft is zero. In practice, the second generation of hydrogen aircraft will not make an impact on modelling year-2050 outcomes, as they only become available in 2050 at the earliest.

Because hydrogen aircraft are substantially different to kerosene aircraft, in the absence of additional policy the adoption of the first generation of hydrogen aircraft is likely to be slower than the adoption of an equivalent kerosene aircraft would be. This is both because new infrastructure is required at airports to operate hydrogen aircraft, and because airlines are risk-averse and may look to see how early adopters fare with the new technology before considering purchases themselves. To capture this effect, literature estimates of adoption levels of cost-effective new technologies over time can be used (Kar et al. 2010) where airlines have a free choice of technologies. For this study, because mandatory adoption of hydrogen aircraft is simulated, a shorter phase-in time period (5 years) from entry into service date to the time that all new aircraft must use the technology is used, based on historical transition periods between different technology generations.

Table 55 Techno-economic characteristics of future hydrogen aircraft generations used in AIM for this study: summary

Technology	Size class	Available from	Price inc. typical discount, million US$(2015)	Change in other yearly cost, million US$ (2015)	Change in block fuel use, %	References
Next generation hydrogen	Small RJ	2037 (2035-2040)	50.6	-0.54a	0b	Characteristics assessed in this study (See earlier sections of appendix)
	Large RJ	2037 (2035-2040)	53.0	-0.54	0	
	Small SA	2037 (2035-2040)	75.8	-0.86	0	
	Med SA	2037 (2035-2040)	77.9	-0.86	0	
	Large SA	2037 (2035-2040)	78.3	-0.86	0	
	Small TA	2042 (2040-2045)	120.6	-1.10	0	
	Med TA	2042 (2040-2045)	152.2	-1.10	0	
	Large TA	2042 (2040-2045)	245.2	-0.92	0	
	VLA	No aircraft planned in this generation and size class				
Subsequent Generation hydrogen	Small RJ	2052 (2050-2055)	51.8	-0.82	1.3	Characteristics assessed in this study (See earlier sections of appendix)
	Large RJ	2052 (2050-2055)	54.3	-0.82	1.3	
	Small SA	2052 (2050-2055)	71.1	-1.17	1.1	
	Med SA	2052 (2050-2055)	73.1	-1.17	1.1	
	Large SA	2052 (2050-2055)	73.4	-1.17	1.1	
	Small TA -- VLA	No pre-2055 aircraft planned in this generation and size class				

[a] Compared to operating costs for baseline kerosene aircraft, excluding fuel and capital costs.

[b] Compared to baseline hydrogen aircraft performance model (**Figure 28**).

Characteristics of operational measures

As well as purchasing new aircraft, airlines have the option, now and in the future, of changing their operations to reduce fuel use. This could include, for example, more efficient routing, changing the fuel source used for taxiing, or improvements in the way that delays are dealt with. These measures typically also have some associated costs, which may be spread between airlines, airports and air traffic control depending on the type of system changes needed to implement them. Similar to other new technology measures, the implementation of most operational measures is not immediate but depends on timeframes associated with infrastructure construction, pilot and ATC training, regulatory approval, aircraft maintenance, and early/late adopter dynamics. Individual measures typically target individual flight phases, with some additional impact across the whole flight from the second-order impact of carrying less fuel weight.

The techno-economic characteristics of the operational measures assessed in the first phase of this study are shown in **Table 56**. Where not specified in this study, costs estimated from the literature are used (e.g., Marais et al. 2013; Schäfer et al. 2016). For adoption dynamics, estimates of time to cost-effective measure adoption for similar measures from Kar et al. (2010) are used.

Table 56 Techno-economic characteristics of current and future operational and ATM-related measures used in AIM for this study: summary

Measure	Size class	Available from	Cost, million US$(2015)	Change in fuel use, %	References
Reduced taxi time (level 1)	Small RJ - VLA	Phased in 2025-2030	0.015 - 0.06	13 - 44a	Marais et al. 2013 ; Schäfer et al. 2016
Reduced taxi time (level 2)	Small RJ - VLA	Phased in 2035-2040	0 - 0.06	56 - 78a	As above
Optimum track	Small RJ - VLA	2030	0.07 - 0.13	3.2 - 5.2b	As above
Continuous climb and descent	Small RJ - VLA	2020	0.2 - 0.6	100c	As above
Reduced contingency fuel	Small RJ - VLA	2020	0 - 0.5	0.1-0.6	As above
Reduced diversion hold	Small RJ - VLA	2025	0 - 0.5	0.7 - 1.1	As above
Formation flying	Small TA - VLA	2025	0	2.0 - 4.4	As above
e-Tug	Small RJ - VLA	2020	0.001 - 0.002	1d	As above

[a] Taxi phases only. Upper end of range for taxi out, lower end for taxi in. [b] The higher end of the range applies to longer-range aircraft [c] Holding only [d] Taxi only

Changing load factors can also be considered as an operational measure. Historically, global average load factors have increased over time (e.g., ICAO, 2020a; average year-2019 scheduled passenger load factors were 0.82, up from 0.78 in 2010). This arises from increasing sophistication in ticketing and flight scheduling. Although there are practical limits to achievable load factor given fluctuating demand over time, the general trend upwards is likely to continue in the post-pandemic period[13]. To include this effect, an increase in load factors as an extra mitigation measure is also simulated, at similar growth rates to historical increases in load factor.

IMPLEMENTING THE FUEL MODELLING IN AIM

The adoption of alternative fuels in AIM is modelled as a function of cost and available supply at that cost, plus any applicable fuel mandates. The cost and supply characteristics of the fuels modelled in this study are discussed in the earlier sections of these appendices. The alternative fuel cost modelling applied here depends on the type of fuel. The production of hydrogen via electrolysis uses significant amounts of electricity and so is strongly dependent on electricity price assumptions. Similarly, hydrogen is a major input to PTL kerosene production, so PTL kerosene prices are strongly dependent on electricity prices. These fuels are modelled separately with an input electricity price trend.

For biokerosene, costs vary significantly by fuel production pathway and feedstock, but have a much weaker dependence on electricity prices. Biokerosene is modelled using a cost curve derived from the analysis carried out in the earlier sections of these appendices. The following two sections discuss how the cost and supply assumptions are incorporated into AIM in each case.

Biokerosene

A range of feedstock/pathway combinations were identified, along with associated supply, cost, and emissions characteristics, and how these are likely to vary over time. These are used to construct cost curves for typical blended biofuel costs for a given global amount required. A sample cost curve for the central supply scenario used in this study is shown in **Figure 29**. Note that PTL is not included in totals as it is modelled separately. A global market for biofuel is assumed. For simplicity, a set amount of feedstock per pathway for a given year is assumed based on an exogenous judgement of likely feedstock-pathway combinations, rather than allowing a choice of pathway per available amount of feedstock.

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[13] During the pandemic, load factors have reduced significantly, but this is likely to be a temporary condition.

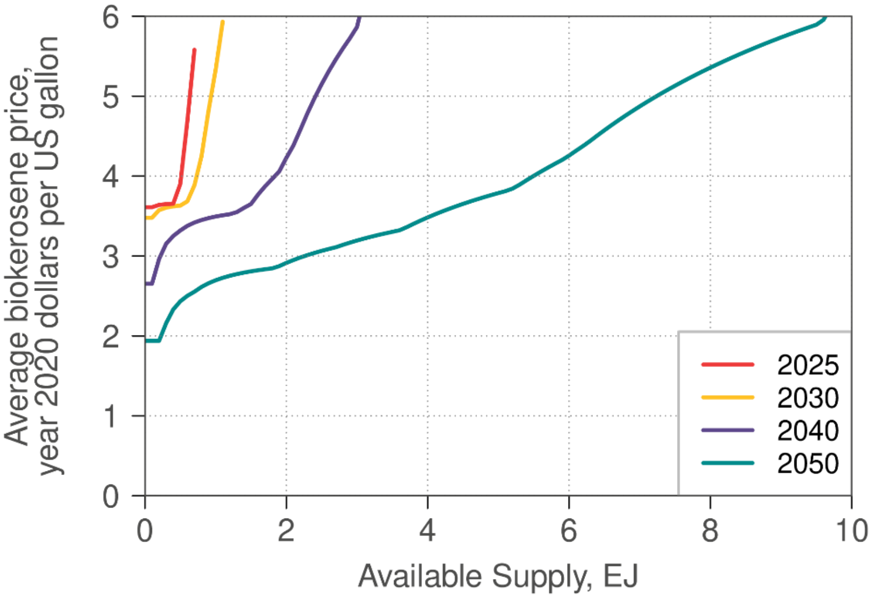

Figure 29 An example biokerosene cost curve (central supply scenario) used in this study

For reference, year-2015 fossil jet fuel prices excluding carbon costs were $1.1-1.9 per US gallon (EIA, 2021). If fuel prices remain at around this level and are not supplemented by carbon prices, and there are no uptake mandates, minimal uptake of biokerosene would be expected in 2050. At around $2-2.5 per gallon (fuel + carbon) in 2050 a small amount of low-cost biokerosene is projected to be available, primarily via MSW feedstocks. However, effective fossil kerosene prices in excess of $3/gallon are likely needed to promote significant use of biokerosene under these assumptions.

One additional impact of using high biokerosene and/or PTL blends is that these fuels have slightly different density and energy content to fossil kerosene. This in turn slightly changes the amount of fuel that aircraft have to carry (because fuel weight is a significant amount of an aircraft's take-off weight, a higher energy density fuel means less take-off weight and thus a smaller requirement for fuel in energy terms beyond the reduction in weight terms). As discussed above, this results in an overall reduction in fuel use by around 2.5%, depending on range, and this is implemented in the modelling.

Hydrogen and PTL

Green hydrogen produced from renewable electricity via electrolysis is assumed in calculating hydrogen prices. Two separate hydrogen-related pathways are assumed. For hydrogen used in hydrogen aircraft, scale-up timeframes are likely dependent on the timeframe for hydrogen aircraft development. Because widespread use of hydrogen aircraft is more likely to occur in a world where hydrogen is used in other sectors as well, scale-up of plants can occur before the point that hydrogen aircraft enter the system. This hydrogen must be liquefied before it is used, with additional liquefaction and transport-related costs. PTL kerosene can be used in existing aircraft, so timescales for uptake are more dependent on the rate that production capacity can be ramped up. It is assumed that hydrogen for PTL production is produced locally with no need for liquefaction. In both cases, production is assumed to be at locations with high renewable energy potential; direct electricity costs appropriate for large industrial users of \$0.04/kWh in 2020, falling to \$0.02 in 2050, are assumed, with electricity costs with storage of \$0.10/kWh and \$0.05/kWh in 2020 and 2050 respectively.

For hydrogen production via electrolysis, other costs and scale-up assumptions are taken from literature sources (e.g., IRENA, 2020; Noack et al. 2015). Liquefaction assumptions are also derived from literature sources (e.g., Ohlig & Decker, 2015; Stolzenburg & Mubbala, 2013). There are several potential constraints on increasing hydrogen use in aviation which may act as bottlenecks. These include increasing hydrogen production; providing refuelling and storage infrastructure at airports; certification and safety requirements; and the rate at which hydrogen aircraft can enter the fleet. It is assumed in this study that the bottleneck on hydrogen uptake in aviation is fleet turnover. The resulting hydrogen production costs are shown in **Figure 30**. These are used as hydrogen price estimates, i.e., neglecting profits.

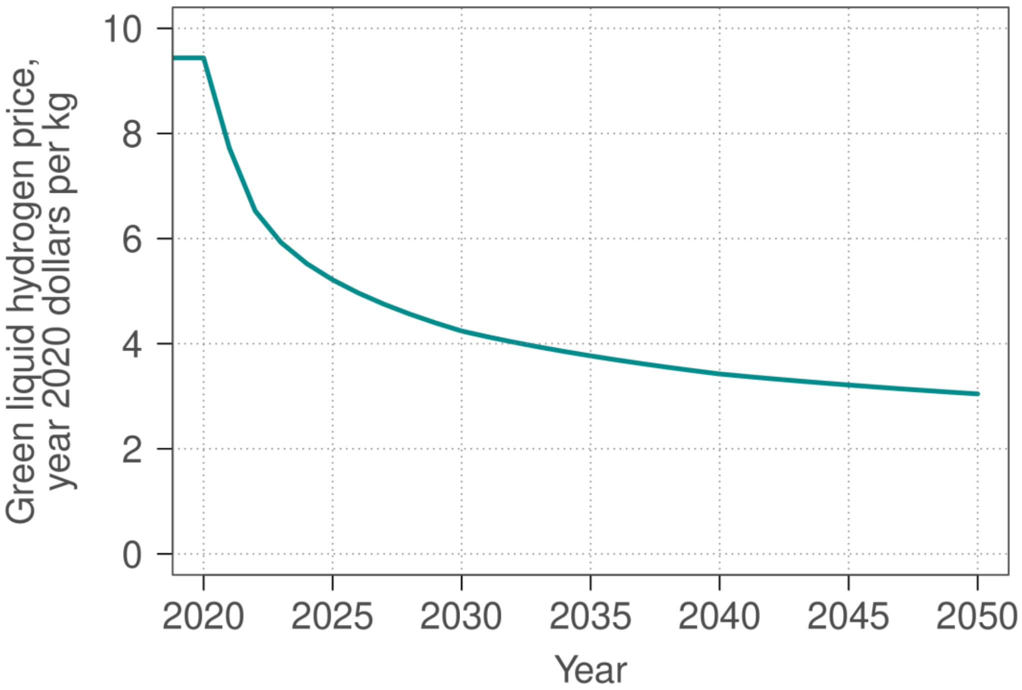

Figure 30 Liquid hydrogen prices used in these model runs

For hydrogen used in PTL kerosene production, the same sources are used in cost estimation. Direct air capture costs of \$250/tCO_2 in 2020, falling to \$60/tCO_2 in 2050, are assumed (e.g., Fasihi et al. 2019). Other cost and plant scale assumptions are taken from a range of literature sources (e.g., Smejkal et al., 2014; Bajirao, 2012; Fasihi et al., 2019). The resulting PTL kerosene production cost trends are shown in **Figure 31**. As with hydrogen, these are assumed to be similar to prices.

The supply of PTL kerosene is uncertain, with limited current development due to high costs but the potential for large decreases in cost over time. Although there is no significant constraint on CO_2 or water availability, scale-up may be constrained by the large amount of renewable electricity needed and by the initially lower costs associated with biokerosene production. Conversely, scale-up may be accelerated by the potential requirement under RefuelEU to use small amounts of PTL fuel by 2030. For this study, supply estimates are made as part of the supply calculations to meet specific mandate policy requirements as defined by the different scenarios modelled (discussed further in the next section). PTL scale-up is strongly dependent on the fuel supply scenario modelled, with maximum PTL availability ranging from 3.5 – 19.2 EJ in 2050.

As discussed above, year-2015 fossil jet fuel prices excluding carbon costs were $1.1-1.9 per US gallon (EIA, 2021). Initially, PTL kerosene prices are projected to be well above this level. However, by 2050, PTL prices are projected to be at a similar level to those of low-cost biofuels, driven primarily by decreases in renewable electricity and DAC costs.

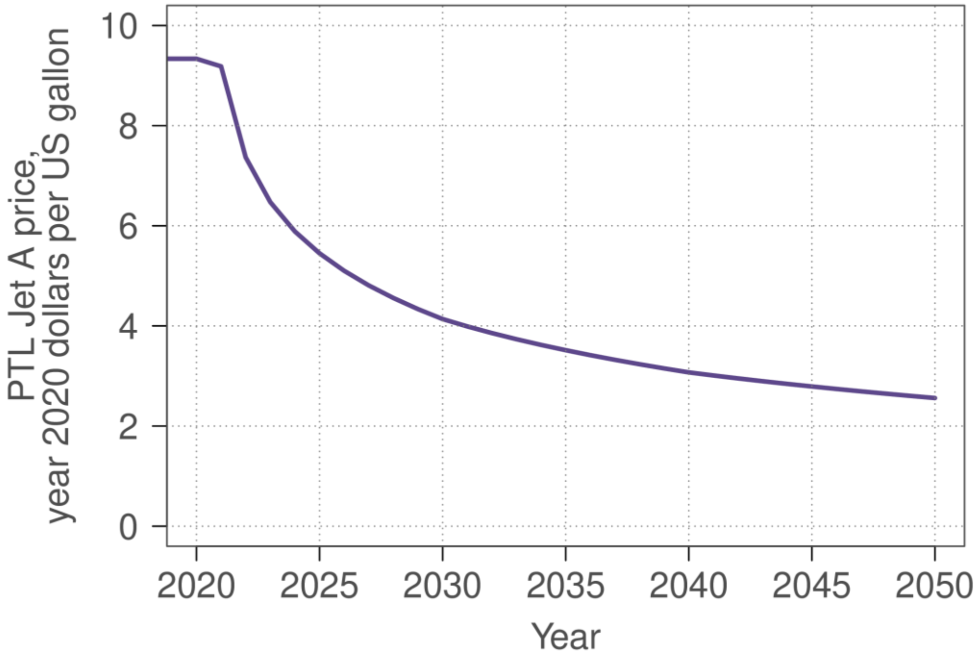

Figure 31 PTL kerosene prices used in these model runs

SCENARIOS FOR AVIATION FUTURES

As discussed above, the potential for new technologies and fuels to reduce emissions depends strongly on future developments which are uncertain. In the main report for this study, three scenarios for future socioeconomic developments which may affect aviation demand are described. This section gives more details on how those scenarios are quantified. The modelled scenarios are designed to cover a wide range of possible futures from futures in which it is particularly difficult to reduce aviation emissions to those in which it is (relatively) straightforward. Each **Scenario** is a combination of a **demand case**, a **fuel supply case**, a **policy case** and assumptions in **technology roll-out**. The assumptions that go into each scenario, by area, are discussed below.

Demand drivers

Many factors affect how aviation demand may change in the future. These include changes in the size and location of population, changes in incomes, changes in the costs and other characteristics of air journeys, and changes in the costs and other characteristics of alternatives to air journeys. These factors are uncertain, and as a result future aviation demand growth is also uncertain (e.g., Dray et al., 2019). This uncertainty has only grown in the wake of the COVID-19 pandemic. As discussed above, the AIM model projects aviation demand growth in response to input projections of key demand drivers. Some of these demand drivers, for example changes in ticket price, are endogenously generated within the model in response to changes in airline costs. Others, such as changes in population and GDP per capita, are exogenous inputs.

Uncertainty in population and GDP per capita developments is important in developing demand characteristics, as both factors have a large impact on outcomes, are uncertain, and are linked to each other (i.e., inputs should be internally self-consistent).

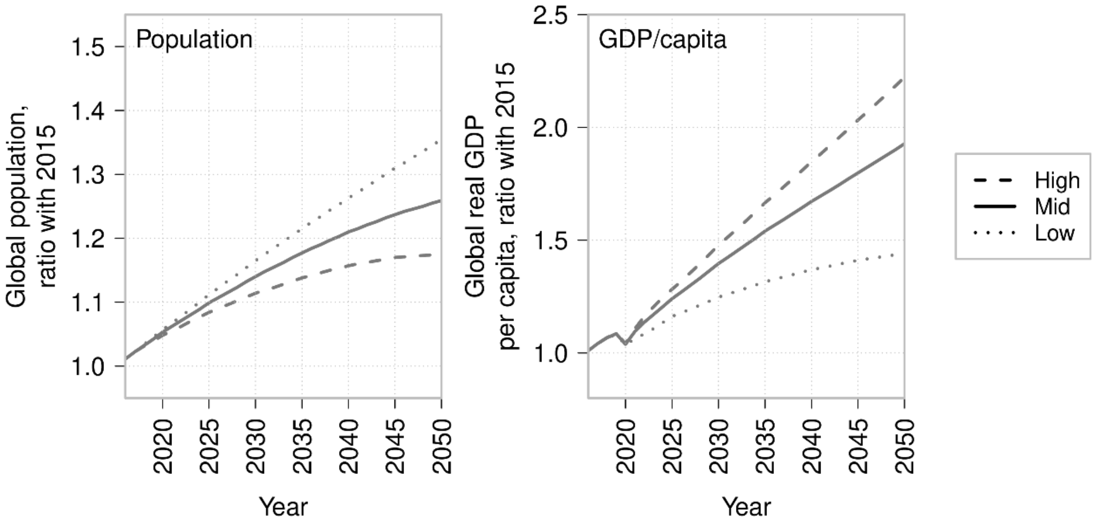

Figure 32 Population and income scenarios used to generate demand projections

Scenarios for how country-level population and income may develop to 2050 and beyond (SSP scenarios) have been generated by O'Neill et al. (2018) as part of the IPCC climate scenario generation process. These scenarios cover a self-consistent range of potential population and income trajectories which matches well to the uncertainty range in these variables from other expert assessments (e.g., Christensen et al. 2018; UN, 2019). The SSP scenarios were generated before the COVID-19 pandemic. However, shorter-term scenarios for economic recovery from COVID-19 to 2026 also exist (e.g., IMF, 2021; World Bank, 2021). To generate input values for aviation demand drivers incorporating the impacts of COVID-19, country-level actual and projected yearly GDP/capita growth rates from IMF (2021) are applied across the pandemic period, transitioning into long-term SSP scenario growth rates afterwards. A full description of the impacts of the COVID-19 pandemic included is given in Dray & Schäfer (2021). The demand cases modelled here, and the data sources for driver trends in each case, are:

- **High demand:** a case where it is difficult to reduce emissions from aviation. Demand growth returns to rates typical of the pre-COVID-19 period. Oil prices are low (as discussed in the next section), reducing incentives to switch to lower-emission fuels. There is high income growth and limited long-term impact of the COVID-19 pandemic. Rapid aviation growth resumes as soon as the pandemic is over and, unless additional policy action is taken, significant growth in emissions is likely. Long-term population and income growth are derived from the IPCC SSP1 scenario (O'Neill et al. 2018), and short-term pandemic recovery is taken from the ‘Upside’ scenario in IMF (2021).

- **Mid demand:** a case where demand growth is similar to post-COVID-19 industry projections. Oil prices are similar to those in the High demand case (reflecting that a world with large-scale production of alternative fuels is more likely to have low oil prices). Population and income follow central-case trends, leading to aviation demand growth that is close to industry projections. Long-term population and income growth are derived from the IPC SSP2 scenario, and short-term pandemic recovery follows the IMF (2021) ‘baseline’ scenario.

Low demand: a case where it is easier to reduce emissions from aviation. Demand growth is low and demand growth decouples from income growth over time (similar to the ‘Decoupled’ scenario in Dray & Schäfer, 2021). Oil prices are relatively high. Long-term economic growth is on the low end of projections and additionally aviation passenger demand growth is suppressed by changes in attitudes to aviation arising from societal changes in the wake of the COVID-19 pandemic and/or increased environmental concerns about flying. Long-term population and income growth are derived from the IPC SSP3 scenario, and short-term pandemic recovery follows the IMF (2021) ‘downside’ scenario; additionally, income elasticities are assumed to decrease over time as demand growth decouples from GDP/capita growth (by factors derived from DfT, 2017).

The corresponding Global average population and GDP/capita trends are shown in **Figure 32**.

Oil Prices

Fuel costs can be a third or more of average airline operating cost in the case that oil prices reach levels seen in 2014 (e.g., ICAO, 2015), although this may reduce over time as aircraft become more fuel-efficient. Changes in aviation kerosene prices tend to closely track changes in oil price (e.g., EIA, 2021a), and increasing aviation fuel cost tends to be reflected in increasing ticket prices (e.g., Wang et al. 2018). Over the longer term, the price and supply potential of alternative aviation fuels will also be affected by oil prices: absent any additional policy action, the supply of SAF which is cost-competitive with fossil-derived aviation fuels will be lower in a world with lower oil prices. These factors mean that oil prices are an important factor in projecting future demand and technology uptake.

Oil prices can be difficult to predict and are also dependent on future policy and technology assumptions. For example, EIA (2021a) project yearly average jet fuel price growth to 2050 for different future scenarios of between 0.7 and 4.4%, depending on a range of assumptions about oil prices, economic growth, policy and the availability of renewables; similarly, there is nearly a factor of five difference between IEA year-2050 oil price projections for different scenarios (IEA 2020, 2021). For this study, two future oil price trends are considered, derived from the IEA SDS and STEPS scenarios:

- For the **High** and **Mid** demand cases, oil prices grow slowly over the short term (to 2025) before gradually decreasing to below $60/bbl (year 2020 USD) by 2050. These developments are derived from the IEA SDS scenario, and imply that increased climate policy ambition acts to keep oil prices relatively low. Lower oil prices increase the challenges involved with SAF introduction, as the price differential between fossil kerosene and SAF is likely to be higher. Lower oil prices are also associated with increased demand. This makes the High demand case particularly challenging to achieve high SAF blends in.

- For the **Low** demand case, oil prices grow over time, reaching a level of around $120/bbl by 2050. These developments are derived from the IEA STEPS scenario, which assumes existing and announced policies affecting the global energy system are maintained, but no additional policy is introduced.

The choice of a given oil price for a given demand case is intended to create illustrative combinations of trends that may make aviation emissions particularly easy or difficult to reduce and does not reflect which oil price is necessarily most likely. Oil price assumptions are shown in **Figure 33**.

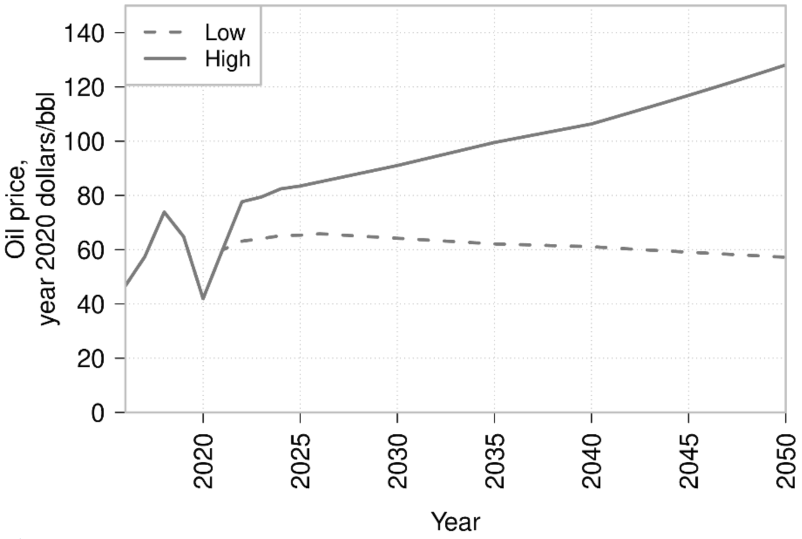

Figure 33 Oil price trends used to generate projection.

Oil price volatility may also have an impact on alternative fuel uptake. Because fuel can be 20-30% of airline direct operating costs and fossil fuel prices can change relatively rapidly, many airlines hedge fuel costs over periods of 1-2 years with the aim of reducing future uncertainty (e.g., Morrell & Swan, 2006). If the prices of alternative fuels are less volatile, this may help promote uptake even in the case that they are above average fossil Jet A prices. Although the average impact of hedging on airline costs is modelled, oil price fluctuations are not modelled, so this effect is not included in the modelling.

Technology packages

The technology assumptions used in this analysis were discussed in detail in the earlier sections of the appendices to this document. Two key uncertainties in technology potential are the amount to which aviation SAF production can be scaled up, and whether or not hydrogen aircraft will come into use. These uncertainties are addressed individually. For SAF production, each set of demand and policy characteristics discussed in this section is used to explore an accompanying set of supply characteristics to meet SAF demand. Hydrogen aircraft are considered via the use of different sets of roll-out assumptions, which are based on the analysed technology packages:

- **Drop-in**: kerosene aircraft technologies, operational strategies, biokerosene, and PTL kerosene become available as discussed above; and

- **H2**: additionally, hydrogen aircraft also become available along with policy mandating their adoption.

Each of these sets of roll-out assumptions is combined with each of the cases for demand and SAF supply described in this section. A future with hydrogen aircraft but no kerosene SAF is not modelled. This is because kerosene SAF is already in use and because, given fleet turnover constraints, significant numbers of kerosene aircraft are still likely in the global fleet in 2050 even if hydrogen aircraft are adopted early and enthusiastically.

Policy Assumptions

Aviation emissions are already targeted by national, regional and global policy. The largest-scale current policies are ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and aviation's inclusion in Emissions Trading Schemes (ETS) including the EU ETS, UK ETS and Swiss ETS. These schemes primarily reduce net aviation emissions via airline purchases of allowances and/or offsets which are used to reduce emissions in other sectors. CORSIA applies to emissions of international flights between participating countries above a year-2019 baseline (e.g., ICAO, 2019b). For 2021, global aviation CO_2 is likely to be below this level, leading to no CORSIA offset obligations, but this will change as demand recovery proceeds. Blending mandates for aviation SAF have also been proposed, including RefuelEU (EC, 2021a) and a UK SAF mandate (DfT, 2021). Other policies promote SAF use via a reduction in carbon costs when using SAF (UK ETS, EU ETS, CORSIA) or via credits associated with SAF use (e.g., SAF has opt-in status in the US Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS)).

The EU ETS, Swiss ETS and UK ETS collectively apply to flights within the EEA/EFTA region (e.g., EC, 2013), within the UK, and between the EEA/EFTA region and the UK, accounting for less than 10% of global aviation CO_2.

Aviation system outcomes across a range of outcomes under the current policy landscape are discussed in Dray & Schäfer (2021). In general, current policies are unlikely to be sufficient to lead to net zero aviation CO_2 emissions at a global level, either through low levels of ambition or through restricted geographic scope. Instead, as discussed in the main report, we consider what would need to be done to meet aviation emissions or fuel blending goals with increasing levels of stringency. Example goals include (with the goals modelled shown in bold):

- Carbon-neutral growth with respect to 2019 (i.e., aviation net emissions do not rise above the year-2019 level).
- **A global SAF mandate at same level as the RefuelEU goal (at early 2022 levels; EC, 2021; 63% SAF blend by 2050).**
- A 50% reduction by 2050 from year-2005 emissions.
- **A global SAF mandate resulting in 100% SAF use by 2050.**

These outcomes are assumed enforced via blend mandate-type policy. Where hydrogen aircraft are available, it is also assumed (after a 5-year transition period) that hydrogen technology is mandatory on new aircraft purchases. Outcomes in these mandate cases are broadly similar to those in a case where uptake is stimulated by carbon pricing set at a level which is just high enough to make the alternative technology cost-effective, although in such a carbon pricing case, airlines would pay additional carbon costs on the fossil kerosene that they use. It is assumed that current policies (e.g., the EU, Swiss and UK ETS; CORSIA) remain in operation at their anticipated specifications as at the start of 2022 to 2050. Where a cap reduction factor is used (e.g., the Linear Reduction Factor (LRF) used in the EU ETS) this factor is assumed to be maintained to 2050. A range of carbon price projections are available for CORSIA and the EU ETS (e.g., Fearnehough et al. 2018; EC, 2021; EC, 2013); however, EU ETS projections do not currently take account of the recent (year-2021) rise in carbon prices. The carbon prices used in this study are based on existing projections adjusted upwards to account for these rises, and are shown in **Figure 34**. These reach around \$2/tCO_2 for CORSIA and \$200/tCO_2 for the emissions trading schemes in 2050. However, because the mandate policies modelled reduce the need for airlines to purchase allowances and/or offsets via these schemes, because the emissions trading schemes remain limited in geographic scope (around 7% of global emissions are covered), and because CORSIA carbon prices are assumed to remain small, there is limited impact on the modelling outcomes from carbon pricing.

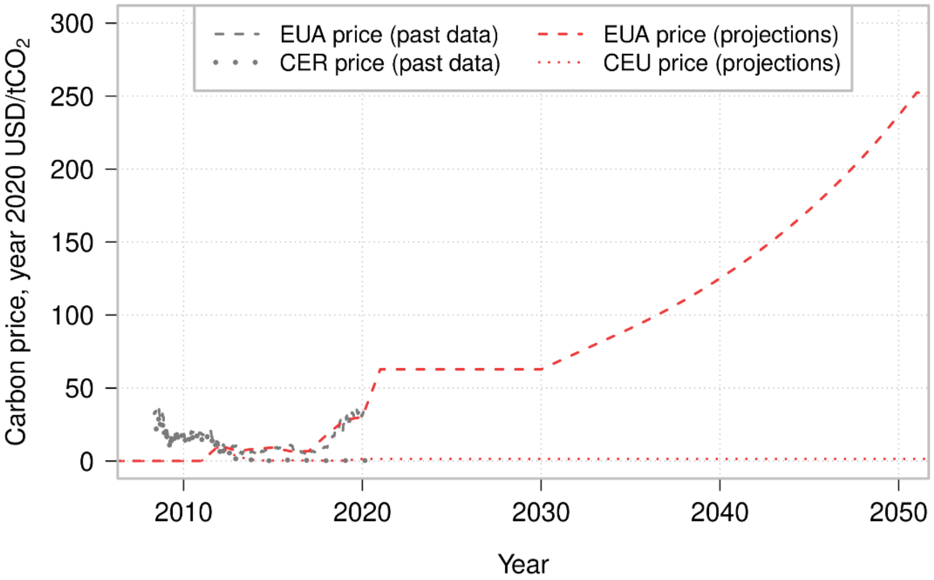

Figure 34 Carbon prices used for existing policy assumptions in this study

For comparison, the different scenarios modelled in this report result in around 15-30 EJ demand for aviation fuel in 2050; year-2015 fuel energy use in aviation was round 11 EJ; and the previous IATA goal of reducing aviation emissions to 50% of year-2005 levels in 2050 would require fossil kerosene use to be below around 4.4 EJ.

Final Scenarios

Each scenario modelled in this report is a combination of a demand case, a corresponding fuel supply case, policy characteristics, and technology roll-out assumptions. The scenarios are chosen to span a wide range of potential alternative fuel requirements necessary to meet ambitious global aviation emissions goals. The final set of six scenarios (A-F) modelled here are described in the main report. This appendix includes an additional two sensitivity cases (G and H), for a total of eight scenarios. These are summarised in **Table 57**. Output metrics and plots for all scenarios including the sensitivity cases are given in the next section.

Table 57 Final modelled scenarios, including extra sensitivity cases (in grey).

Scenario	Technology roll-out	Demand case	Supply case
A: Low (drop-in)	New aircraft, drop-in SAF, and operational measures	Long-term economic growth and demand growth is suppressed. High oil prices, ReFuelEU SAF mandate applied globally.	Standard project development timelines during ramp-up phase. 15% CAGR for biofuels, 21% CAGR for PTL fuels during market expansion phase.
B: Low (H2)	New aircraft, drop-in SAF, hydrogen and operational measures		
C: Mid (drop-in)	New aircraft, drop-in SAF, and operational measures	Economic growth follows central-case trends, aviation demand trends follow post-COVID industry projections. Low oil prices, following IEA SDS scenario. ReFuelEU SAF mandate applied globally.	Accelerated project development timelines during ramp-up phase. 15% CAGR for biofuels, 23% CAGR for PTL fuels during market expansion phase.
D: Mid (H2)	New aircraft, drop-in SAF, hydrogen and operational measures		
E: High (drop-in)	New aircraft, drop-in SAF, and operational measures	High economic growth: high income growth, aviation demand trends follow pre-COVID industry projections. Low oil prices, following IEA SDS scenario. Ambitious global SAF mandate, rising to 100% in 2050.	Accelerated project development timelines during ramp-up phase. 16% CAGR for biofuels, 36% market growth CAGR between 2030-2040, 23% CAGR between 2040-2050 during market expansion phase.
F: High (H2)	New aircraft, drop-in SAF, hydrogen and operational measures		
G: Low demand, high supply (drop-in)	New aircraft, drop-in SAF, and operational measures	Long-term economic growth and demand growth is suppressed. High oil prices, following IEA STEPS scenario. Ambitious global SAF mandate, rising to 100% in 2050.	Accelerated project development timelines during ramp-up phase. 15% CAGR for biofuels, 23% CAGR for PTL fuels during market expansion phase.
H: Low demand, high supply (H2)	New aircraft, drop-in SAF, hydrogen and operational measures		

Additional tables of model outcomes

This section of the appendix supplements the model outcomes presented in the main report with additional global and regional output metrics. Note that the Low Demand, Mid Supply scenarios with 100% SAF (scenarios G and H) are not presented in the main report for this study but are included here as an additional sensitivity case. They are derived from combining the Low Demand Scenario with the Mid SAF Supply Scenario.

Table 58 EJ fuel used in aviation, all sources

Scenario	EJ fuel used in aviation, all sources				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	11.2	12.8	14.3	14.6	15
E: High (Drop-in)	11.2	12.8	17.8	22.2	26.6
C: Mid (Drop-in)	11.2	12.8	17.2	20.6	24
G: Low Demand, Mid Supply (Drop-in)	11.2	12.8	14.2	14.5	15.1
B: Low (H2)	11.2	12.8	14.3	14.6	16.1
F: High (H2)	11.2	12.8	17.8	22.1	28.3
D: Mid (H2)	11.2	12.8	17.2	20.6	25.5
H: Low Demand, Mid Supply (H2)	11.2	12.8	14.2	14.5	16.6

Table 59 EJ kerosene used in aviation, all sources

Scenario	EJ kerosene used in aviation, all sources				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	11.2	12.8	14.3	14.6	15
E: High (Drop-in)	11.2	12.8	17.8	22.2	26.6
C: Mid (Drop-in)	11.2	12.8	17.2	20.6	24
G: Low demand, mid supply (Drop-in)	11.2	12.8	14.2	14.5	15.1
B: Low (H2)	11.2	12.8	14.3	14.3	10.9
F: High (H2)	11.2	12.8	17.8	21.7	18
D: Mid (H2)	11.2	12.8	17.2	20.1	16.8
H: Low demand, mid supply (H2)	11.2	12.8	14.2	14.1	10.7

Table 60 Global average SAF blend, aviation kerosene

Scenario	Global average SAF blend, aviation kerosene, %				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	0	0	5.12	20.2	67.2
E: High (Drop-in)	0	0	6.12	25.8	100
C: Mid (Drop-in)	0	0	5.1	19.9	64.3
G: Low demand, mid supply (Drop-in)	0	0	6.19	25.7	100
B: Low (H2)	0	0	5.12	20.7	71.9
F: High (H2)	0	0	6.12	26.4	100
D: Mid (H2)	0	0	5.1	20.4	65.1
H: Low demand, mid supply (H2)	0	0	6.19	26.3	100

Table 61 CO_2 covered by CORSIA offsets and/or ETS (EU/UK/Swiss) allowances

Scenario	CO_2 covered by offsets/allowances, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	21.5	27.2	36.3	47.4	26.2
E: High (Drop-in)	21.5	27.6	133	189	15.5
C: Mid (Drop-in)	21.5	27.5	123	179	97.8
G: Low demand, mid supply (Drop-in)	21.5	27.2	34.5	46.1	3.51
B: Low (H2)	21.5	27.2	36.3	44.2	7.72
F: High (H2)	21.5	27.6	133	181	5.74
D: Mid (H2)	21.5	27.5	123	171	35.6
H: Low demand, mid supply (H2)	21.5	27.2	34.5	43	0.42

Table 62 Jet A from fossil sources, global use in aviation

Scenario	Fossil Jet A, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	259	297	314	271	114
E: High (Drop-in)	259	297	387	381	0
C: Mid (Drop-in)	259	297	379	382	198
G: Low demand, mid supply (Drop-in)	259	297	309	249	0
B: Low (H2)	259	297	314	263	71.2
F: High (H2)	259	297	387	370	0
D: Mid (H2)	259	297	379	372	136
H: Low demand, mid supply (H2)	259	297	309	241	0

Table 63 Biokerosene use in aviation

Scenario	Biokerosene, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	0	0	16.6	55.2	149
E: High (Drop-in)	0	0	24.3	74.9	225
C: Mid (Drop-in)	0	0	20	70.6	210
G: Low demand, mid supply (Drop-in)	0	0	20	68.9	190
B: Low (H2)	0	0	16.6	55.2	99.7
F: High (H2)	0	0	24.3	74.9	149
D: Mid (H2)	0	0	20	70.6	138
H: Low demand, mid supply (H2)	0	0	20	69	108

Table 64 PTL kerosene use in aviation

Scenario	PTL kerosene, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	0	0	0	11.8	79.1
E: High (Drop-in)	0	0	0.427	54.8	378
C: Mid (Drop-in)	0	0	0	22.4	139
G: Low demand, mid supply (Drop-in)	0	0	0	15.3	153
B: Low (H2)	0	0	0	11.8	78.4
F: High (H2)	0	0	0.423	54.9	260
D: Mid (H2)	0	0	0	22.4	109
H: Low demand, mid supply (H2)	0	0	0	15.3	135

Table 65 Liquid hydrogen use in aviation

Scenario	Hydrogen, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	0	0	0	0	0
E: High (Drop-in)	0	0	0	0	0
C: Mid (Drop-in)	0	0	0	0	0
G: Low demand, mid supply (Drop-in)	0	0	0	0	0
B: Low (H2)	0	0	0	2.88	43.6
F: High (H2)	0	0	0	3.65	85.9
D: Mid (H2)	0	0	0	3.47	72.8
H: Low demand, mid supply (H2)	0	0	0	2.87	48.8

Table 66 Fuel lifecycle CO_2 by modelled scenario

Scenario	Fuel lifecycle CO_2, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	947	1090	1150	1010	497
E: High (Drop-in)	947	1090	1420	1420	136
C: Mid (Drop-in)	947	1090	1390	1420	838
G: Low demand, mid supply (Drop-in)	947	1090	1140	943	115
B: Low (H2)	947	1090	1150	982	312
F: High (H2)	947	1090	1420	1380	82.9
D: Mid (H2)	947	1090	1390	1390	567
H: Low demand, mid supply (H2)	947	1090	1140	914	64.7

Table 67 International direct CO_2 by modelled scenario

Scenario	International direct CO_2, Mt				
	2015	2019	2030	2040	2050
A; Low (Drop-in)	577	660	709	726	748
E: High (Drop-in)	577	661	899	1120	1350
C: Mid (Drop-in)	577	662	868	1040	1220
G: Low demand, mid supply (Drop-in)	577	660	707	718	749
B: Low (H2)	577	660	709	714	551
F: High (H2)	577	661	899	1110	920
D: Mid (H2)	577	662	868	1020	856
H: Low demand, mid supply (H2)	577	660	707	706	536

Table 68 Intra-EEA direct CO_2 by modelled scenario

Scenario	Intra-EEA direct CO_2, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	52.9	57.6	53.6	47.2	46
E: High (Drop-in)	52.9	57.9	71	78.8	91.9
C: Mid (Drop-in)	52.9	57.9	69.2	74	83.9
G:Low demand, mid supply (Drop-in)	52.9	57.6	53.4	47.2	47
B: Low (H2)	52.9	57.6	53.6	45.6	30.2
F: High (H2)	52.9	57.9	71	76	57.3
D: Mid (H2)	52.9	57.9	69.2	71.3	54.2
H: Low demand, mid supply (H2)	52.9	57.6	53.4	45.6	30.2

Table 69 Direct CO_2 for flights to and from EEA countries, by modelled scenario

Scenario	To/from-EEA direct CO_2, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	161	182	182	182	186
E: High (Drop-in)	161	182	235	288	347
C: Mid (Drop-in)	161	182	227	268	315
G: Low demand, mid supply (Drop-in)	161	182	181	180	186
B: Low (H2)	161	182	182	180	142
F: High (H2)	161	182	235	286	242
D: Mid (H2)	161	182	227	266	228
H: Low demand, mid supply (H2)	161	182	181	179	139

Table 70 Global direct CO_2 by modelled scenario

Scenario	Global direct CO_2, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	815	935	1040	1060	1080
E: High (Drop-in)	815	936	1300	1610	1900
C: Mid (Drop-in)	815	937	1260	1500	1720
G: Low demand, mid supply (Drop-in)	815	935	1040	1050	1080
B: Low (H2)	815	935	1040	1040	785
F: High (H2)	815	936	1300	1570	1290
D: Mid (H2)	815	937	1260	1460	1210
H: Low demand, mid supply (H2)	815	935	1040	1030	765

Table 71 Global air revenue passenger-km by modelled scenario

Scenario	RPK, billion				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	6910	8240	10900	13100	14700
E: High (Drop-in)	6910	8250	13700	20000	26500
C: Mid (Drop-in)	6910	8250	13200	18400	23600
G: Low demand, mid supply (Drop-in)	6910	8240	10800	13000	14800
B: Low (H2)	6910	8240	10900	13100	15100
F: High (H2)	6910	8250	13700	19900	26700
D: Mid (H2)	6910	8250	13200	18400	23800
H: Low demand, mid supply (H2)	6910	8240	10800	13000	15400

Table 72 Global air freight tonne-km by modelled scenario (hold freight and freighter aircraft)

Scenario	FTK, billion				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	204	249	304	355	387
E: High (Drop-in)	204	249	372	493	576
C: Mid (Drop-in)	204	249	367	472	548
G: Low demand, mid supply (Drop-in)	204	249	303	348	393
B: Low (H2)	204	249	304	353	404
F: High (H2)	204	249	372	490	577
D: Mid (H2)	204	249	367	470	552
H: Low demand, mid supply (H2)	204	249	303	346	419

Table 73 Number of global flights by modelled scenario

Scenario	Flights, million				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	36.4	41	50.3	58.5	64.4
E: High (Drop-in)	36.4	41.1	60.7	82.6	104
C: Mid (Drop-in)	36.4	41.1	59	77.3	94.6
G: Low demand, mid supply (Drop-in)	36.4	41	50.2	58	65.1
B: Low (H2)	36.4	41	50.3	58.3	66
F: High (H2)	36.4	41.1	60.7	82.1	105
D: Mid (H2)	36.4	41.1	59	76.8	95.7
H: Low demand, mid supply (H2)	36.4	41	50.2	57.7	67.6

Table 74 Fossil Jet A use, EEA/UK departing flights

Scenario	Fossil Jet A, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	53	58.9	54.8	42.6	17.8
E: High (Drop-in)	53	59.1	71.5	67.8	0
C: Mid (Drop-in)	53	59.1	69.9	67.9	32.4
G: Low demand, mid supply (Drop-in)	53	58.9	54	40.6	0
B: Low (H2)	53	58.9	54.8	41.7	10.9
F: High (H2)	53	59.1	71.4	66.3	0
D: Mid (H2)	53	59.1	69.9	66.5	19.8
H: Low demand, mid supply (H2)	53	58.9	54	39.6	0

Table 75 Biokerosene use, EEA/UK departing flights

Scenario	Biokerosene, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	0	0	2.94	11.2	25.7
E: High (Drop-in)	0	0	4.48	13.5	40.9
C: Mid (Drop-in)	0	0	3.68	12.9	39.9
G: Low demand, mid supply (Drop-in)	0	0	3.67	12.3	31.5
B: Low (H2)	0	0	2.94	11.2	17.6
F: High (H2)	0	0	4.48	13.6	27.1
D: Mid (H2)	0	0	3.68	12.9	26.8
H: Low demand, mid supply (H2)	0	0	3.67	12.4	18.1

Table 76 PTL kerosene use, EEA/UK departing flights

Scenario	PTL kerosene, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	0	0	0	1.94	13.1
E: High (Drop-in)	0	0	0.0788	9.78	69
C: Mid (Drop-in)	0	0	0	3.99	27.3
G: Low demand, mid supply (Drop-in)	0	0	0	2.54	25.4
B: Low (H2)	0	0	0	1.96	13
F: High (H2)	0	0	0.0781	9.85	47.4
D: Mid (H2)	0	0	0	4.02	23.3
H: Low demand, mid supply (H2)	0	0	0	2.56	22.7

Table 77 Hydrogen use, EEA/UK departing flights

Scenario	Hydrogen, Mt				
	2015	2019	2030	2040	2050
A: Low (Drop-in)	0	0	0	0	0
E: High (Drop-in)	0	0	0	0	0
C: Mid (Drop-in)	0	0	0	0	0
G: Low demand, mid supply (Drop-in)	0	0	0	0	0
B: Low (H2)	0	0	0	0.338	6.74
F: High (H2)	0	0	0	0.511	15.5
D: Mid (H2)	0	0	0	0.495	13
H: Low demand, mid supply (H2)	0	0	0	0.344	7.35

Additional figures including sensitivity cases

The main conclusions from the simulations carried out for this study are shown in the main report. This section of the appendix supplements the model outcomes presented in the main report with additional plots of global and regional output metrics. Note that the Low Demand, Mid Supply scenarios with 100% SAF (Scenarios G and H) are not presented in the main report for this study but are included here as an additional sensitivity case. They are derived from combining the Low Demand Scenario with the Mid SAF Supply Scenario.

A range of system output metrics for the main scenarios and sensitivity cases are given in **Figure 35**. This includes numbers of passengers, flights and passenger-km compared to historical data for these metrics (ICAO, 2020a) and alternative projections for passenger-km and freight-km (Airbus, 2021; Boeing, 2021; IATA, 2021); projected ticket prices per passenger-km compared to historical data on revenue per passenger-km (ICAO, 2020a); global airline fleets compared to historical fleet size data (FlightGlobal, 2016); fuel use by type, compared to historical fuel use data (IEA, 2016); electricity used in fuel production; and CO_2 by scope, compared to historical data (IEA,2016). Note that the historical fuel use and emissions data shown includes military flights, which are not modelled here. Direct CO_2 is all CO_2 produced by combustion in aircraft engines and does not account for reductions in CO_2 from SAF production. Fuel lifecycle CO_2 additionally includes CO_2 from the fuel production process which, in the case of SAF, significantly reduces totals. Net CO_2 is direct CO_2 adjusted both for the reduction in fuel lifecycle emissions of SAF, and offsets and allowances via CORSIA and emissions trading which result in emissions reductions in other sectors.

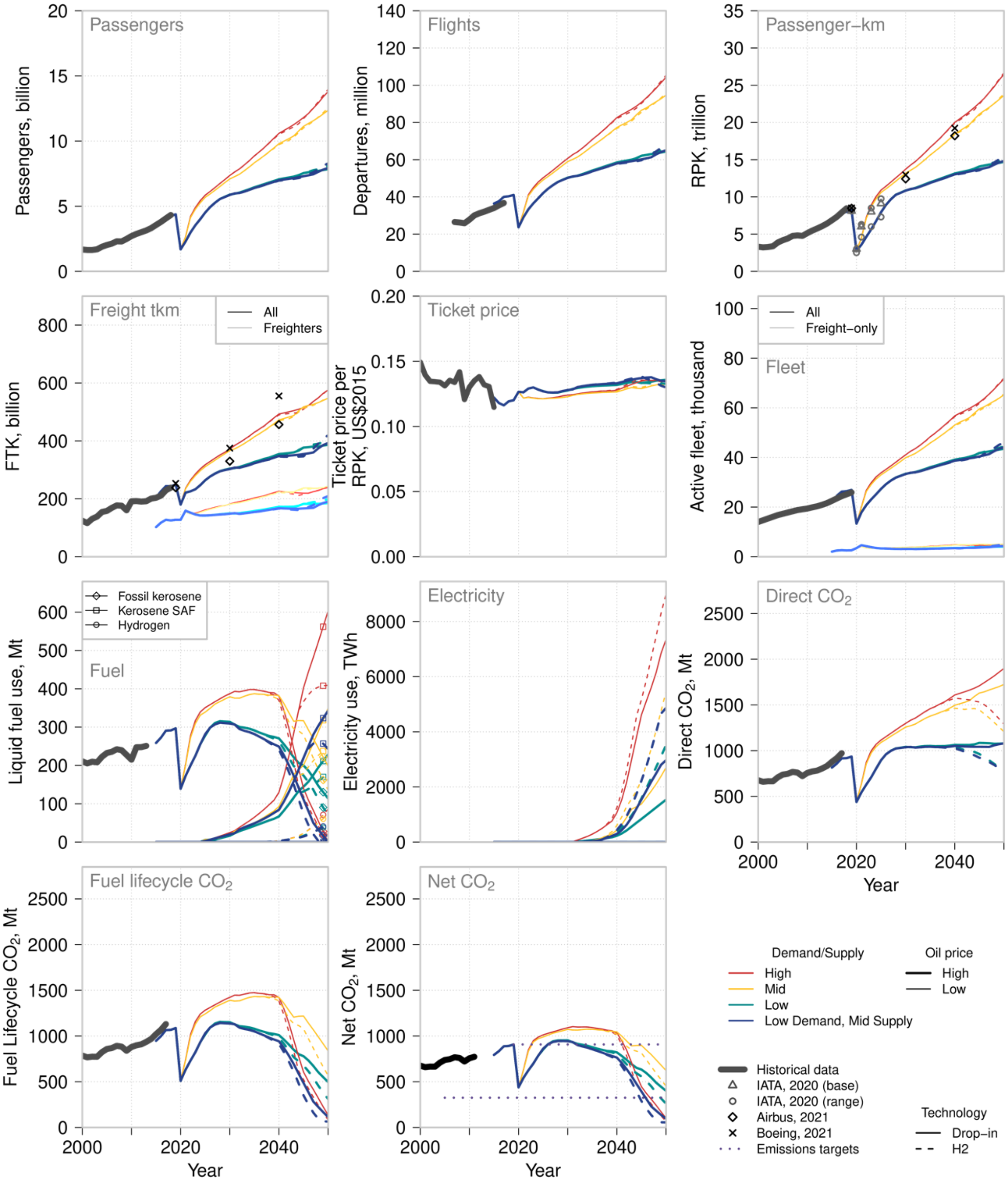

Figure 35 System output metrics (demand, fuel use, emissions) for the different scenarios investigated in this study

For this study, the chosen targets for the different scenarios were specified in terms of fuel blends. However, many aviation targets are specified in terms of emissions. These include IATA's previous (reducing aviation emissions to 50% of year-2005 levels by 2050) and current (reducing aviation emission to net zero by 2050) industry targets, and the CORSIA-associated target of carbon-neutral growth from year-2019 levels. Dotted lines indicating these targets are shown on the net CO_2 panel of **Figure 35**. All scenarios, including sensitivity cases, fall well under the carbon-neutral growth target by 2050. This is not surprising, given the ambitious SAF and hydrogen assumptions used. However, carbon-neutral growth is overshot on a net-CO_2 basis for a few years around 2030 for the low demand scenarios, and for a longer period for the mid and high demand scenarios. The reasons behind this overshoot are discussed in the main report.

A discussion of fleet sizes by technology and fuel used is given in the results section of the main report. After 2040, due to higher rates of SAF production capacity ramp-up and greater availability of hydrogen aircraft for those scenarios that use them, yearly emissions reductions are rapid across all scenarios. The IATA 2050 emissions target is met on a net emissions basis for the scenarios with 100% SAF targets (High; Low demand, mid supply). For the scenarios with RefuelEU-level targets (Mid, Low), outcomes are close to this goal but whether or not it is met depends on demand and technology characteristics. It is possible to meet the goal with Low demand (either the main or sensitivity case) and availability of hydrogen aircraft, whereas with Mid demand, or Low demand without hydrogen aircraft, CO_2 emissions fall slightly above the threshold.

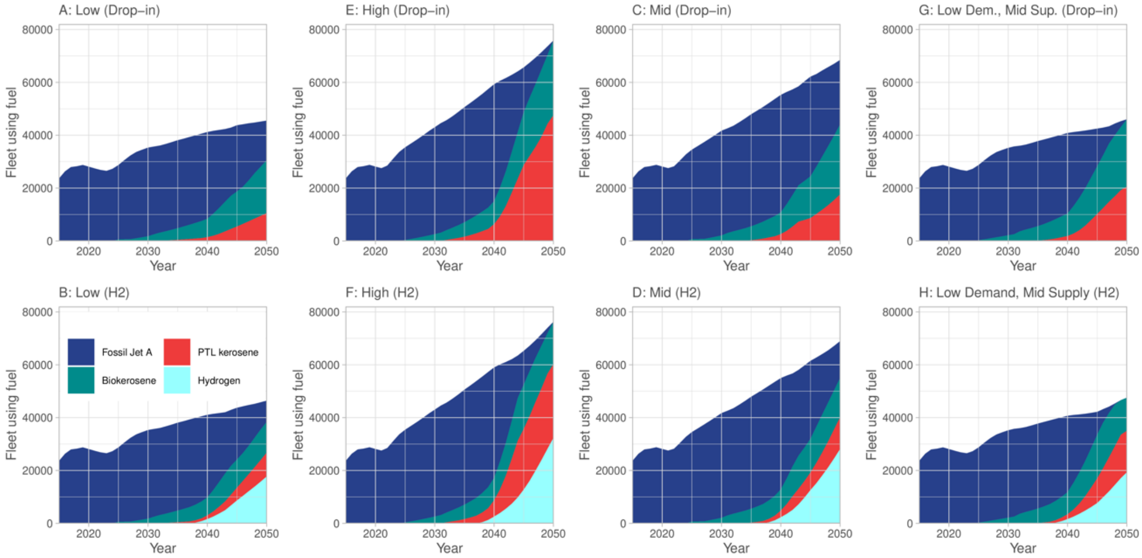

Figure 36 Aircraft fleets using different fuels (equivalent 100% fraction for blended fuels) by scenario over time

Figure 36 shows the corresponding proportion of the aircraft fleet using different fuels for each main scenario modelled. For SAF, the fleet size shown corresponds to the number of aircraft that could be supplied with 100% SAF at the levels used (in reality, SAF will be used at lower blends in more aircraft). SAF has been divided into biokerosene and PTL kerosene to illustrate the dependence on PTL kerosene for scenarios with higher overall fuel demand. This is because biomass resources are constrained which limit the economically feasible size of biomass plants and speed with which they can be developed. In general, supply and use of lower-cost biokerosene pathways is relatively consistent across the different scenarios modelled. The lower demand scenarios are associated with lower PTL production capacity ramp-up rates.

Compared to the scenarios with SAF only, the scenarios with hydrogen aircraft show slightly greater GHG mitigation potential. The impacts of making hydrogen aircraft available are generally only seen post-2040, due to the relatively late introduction date for hydrogen aircraft and constraints on their uptake from fleet turnover. Over the 2040-2050 period, however, a significant number of hydrogen aircraft can still enter the system, leading to an up to 40% fraction of the year-2050 fleet using hydrogen, as discussed in the main report. Once significant numbers of hydrogen aircraft enter the system, smaller amounts of SAF are required to maintain the same mandated blend limit. The typical impact of this is to reduce demand for the highest-cost SAF pathways. By 2050, because the price of PTL kerosene is projected to decrease strongly, the highest-cost pathways are likely to be biokerosene pathways. A typical example of this effect is shown in **Figure** . The right-hand panel in **Figure** shows SAF uptake by pathway in scenario A: Low (Drop-In), which has RefuelEU[14]-level mandates. The left-hand panel shows the corresponding case for scenario B: Low (H2). The impact of hydrogen aircraft is minimal until 2040. After 2040, the uptake of most SAF pathways is unaffected. However, use of the Ethanol-to-Jet pathway, which combines relatively high projected prices with high projected production capacity, is significantly reduced after this point[15].

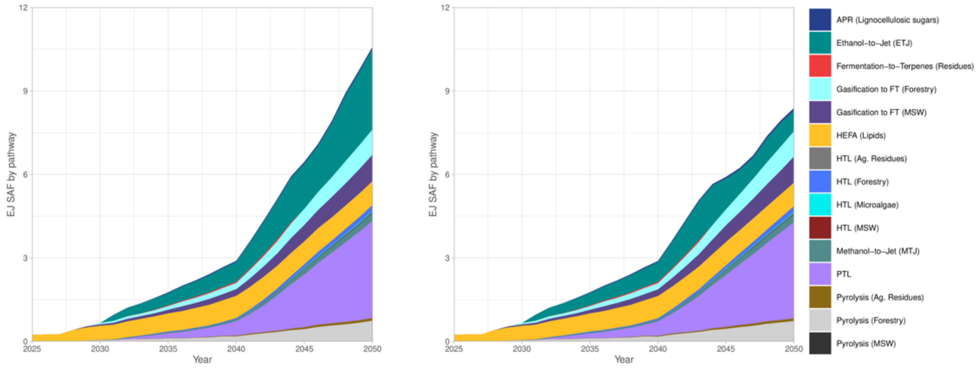

Figure 37 Differences in fuel use by pathway for the Low scenario with (right; Scenario B) and without (left; Scenario A) hydrogen availability

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[14] SAF mandates in this scenario reach 63% in 2050, i.e., they do not reflect year-2022 revisions to RefuelEU.

[15] Because the price trends for each pathway include production cost savings from factors relating to production scale-up (e.g., economies of scale), pathways affected by hydrogen scale-up in the hydrogen scenarios are assumed to have no change in cost assumed after 2040.

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