A ROUTE TO NET ZERO EUROPEAN AVIATION

Destination 2050 – A route to net zero European aviation

Preface

Aviation has brought enormous benefits to European society and its economy. It has allowed people to visit other cities and countries and facilitated the transport of goods in ways that previous generations could only have dreamed of. Passenger traffic has enjoyed remarkable growth over the last ten years, reaching a total of over 11.1 million movements in the 44 European countries of the ECAC area[1] in 2019.

Yet with this growth, the role of aviation and its environmental impact are now the subject of greater scrutiny in society, most notably in relation to carbon emissions. While climate change already had a high profile in Europe, the entry into force of the Paris Agreement undoubtedly contributed to pushing this to the top of the political agenda. Recognising this, the current College of European Commissioners (2019-2024) led by Commission President Ursula von der Leyen has said that making Europe the first climate-neutral continent will be the *'greatest challenge and opportunity of our times'* and with it, her Commission's number one priority as laid out in the European Green Deal.

It is right to expect the aviation sector to meet its responsibilities in this regard. Aviation accounts for around 2-3% of CO_2 emissions globally, and 4% in Europe. While the fuel efficiency of aircraft operations has been improving by an average of over 2% per year between 2009 and 2019, we acknowledge that further action is needed to bring down the absolute level, even if traffic levels increase. We must do this in an ambitious way in order to meet the EU's goal of net zero CO_2 emissions by 2050. We believe that this is desirable and should be achievable – not only for European society and the economy as a whole, but also for the aviation industry and future generations of travellers.

Our five associations, representing aircraft manufacturers, airlines, airports and air navigation service providers in Europe, have therefore come together to plan a route to achieve this – an initiative we have called "Destination 2050" to reflect our common end goal. Recognising that the whole European air transport ecosystem must act together decisively, our intention is to identify the measures which our members can apply to achieve this decarbonisation collectively. In some cases these may be new measures, while in others there may be existing programmes that need to be approached in a new and better way.

We asked the Netherlands Aerospace Centre (NLR) and SEO Amsterdam Economics to support us in providing a scientific basis for this project. They have identified measures across four pillars which are presented in this report:

1. **Aircraft and engine technology**
2. **Air traffic management and aircraft operations**
3. **Sustainable Aviation Fuels**
4. **Smart economic measures**

Destination 2050 does not describe the only pathway to net zero CO_2 emissions. Assumptions may change and other factors and opportunities may enter into the equation, such as the role of intermodal travel. Equally, the report does not address the financing of the tremendous effort required for a socially compatible transformation that ensures European citizens' and businesses' connectivity.

The impact of the COVID-19 pandemic and its negative consequences for aviation have been a complicating factor in producing this report, but we do not see the downturn in traffic since March 2020 or the higher profile

[1] See https://www.ecac-ceac.org/member-states

of the crisis as an excuse for inaction. Once passenger traffic has returned to 2019 levels, we expect the number of flights to resume its upward trend. The time to start implementing our plan is now.

The undersigned five associations have used the conclusions of this report to develop a set of commitments, representing our contribution to the EU Pact for Sustainable Aviation, a forthcoming initiative resulting from the *Round Table Report on the Recovery of European Aviation*[2] (November 2020). In fact, we cannot undertake this decarbonisation journey on our own. To be successful, we will need support from European and national policy makers to create the right policy frameworks and, in some cases, to provide financial assistance to develop and apply new technologies. We take the lead but call on policy makers to play their part, as well (both at a European and worldwide level) to help our industry achieve its climate goals.

Together we are confident that we can find a route to net zero European aviation.

Thomas Reynaert, Managing Director, Airlines for Europe (A4E)

Tanja Grobotek, Director Europe Affairs, CANSO (Civil Air Navigation Services Organisation)

Montserrat Barriga, Director General, ERA (European Regions Airline Association)

Olivier Jankovec, Director General, Airports Council International-EUROPE (ACI)

Jan Pie, Secretary General,
Aerospace & Defence Industries Association of Europe (ASD)

[2] See: https://canso.org/eu-aviation-maps-a-sustainable-post-crisis-future-in-round-table-report/

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A Route To Net Zero European Aviation

CUSTOMER: A4E, ACI-EUROPE, ASD, CANSO, ERA

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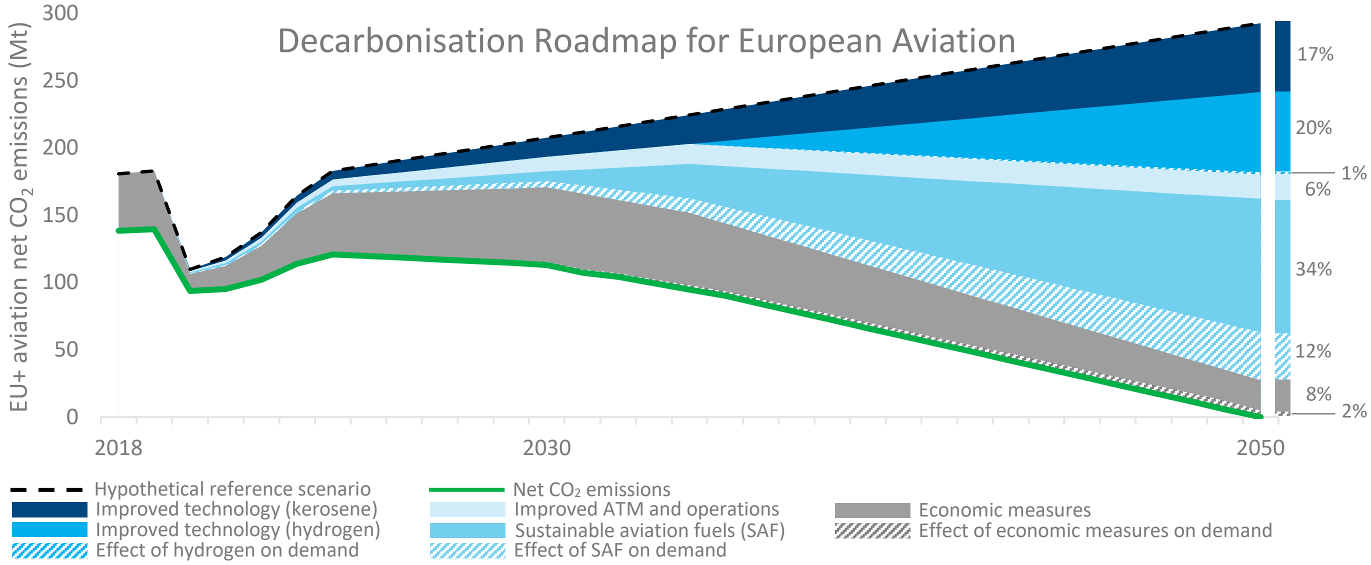
Destination 2050

Net zero CO_2 emissions[1] from all flights within and departing from the EU[2] can be achieved by 2050 through joint, coordinated and decisive industry and government efforts. The European aviation industry is committed to reaching this target and contribute to the goals set in the European Green Deal and the Paris Agreement. Destination 2050 shows a possible pathway that combines new technologies, improved operations, sustainable aviation fuels and economic measures. Absolute emissions are reduced by 92%, while the remaining 8% is removed from the atmosphere through negative emissions, achieved through natural carbon sinks or dedicated technologies.

Royal Netherlands Aerospace Centre and SEO Amsterdam Economics conducted this study commissioned by the representatives of European airports, airlines, aerospace manufacturers and air navigation service providers. It assesses to what extent four groups of sustainability measures are able to reduce carbon emissions until 2050, strongly influenced by policies and actions. The effects of these measures are compared to a hypothetical reference scenario taking into account continuous demand growth and the recent COVID-19 impact. These sustainability measures result in the following net CO_2 emissions reductions in the year 2050:

- 111 $MtCO_2$ through improvements in aircraft and engine technology:
  - 60 $MtCO_2$ by hydrogen-powered aircraft on intra-European routes and
  - 51 $MtCO_2$ by kerosene-powered or (hybrid-)electric aircraft;
- 18 $MtCO_2$ through improvements in air traffic management (ATM) and aircraft operations;
- 99 $MtCO_2$ through using drop-in sustainable aviation fuels (SAF);
- 22 $MtCO_2$ through economic measures (carbon removal projects only).

The combined cost of these sustainability measures is modelled to impact ticket prices, resulting in a lower air travel demand. This would avoid 43 $MtCO_2$ whilst maintaining an average compound annual passenger growth rate of 1.4%.



Results are presented for all flights within and departing from the EU region[2]. Improving aircraft and engine technology, ATM and aircraft operations, SAF and economic measures all hold decarbonisation potential. Modelled for 2030 and 2050, the impacts are linearly interpolated. The base year for this study is 2018.

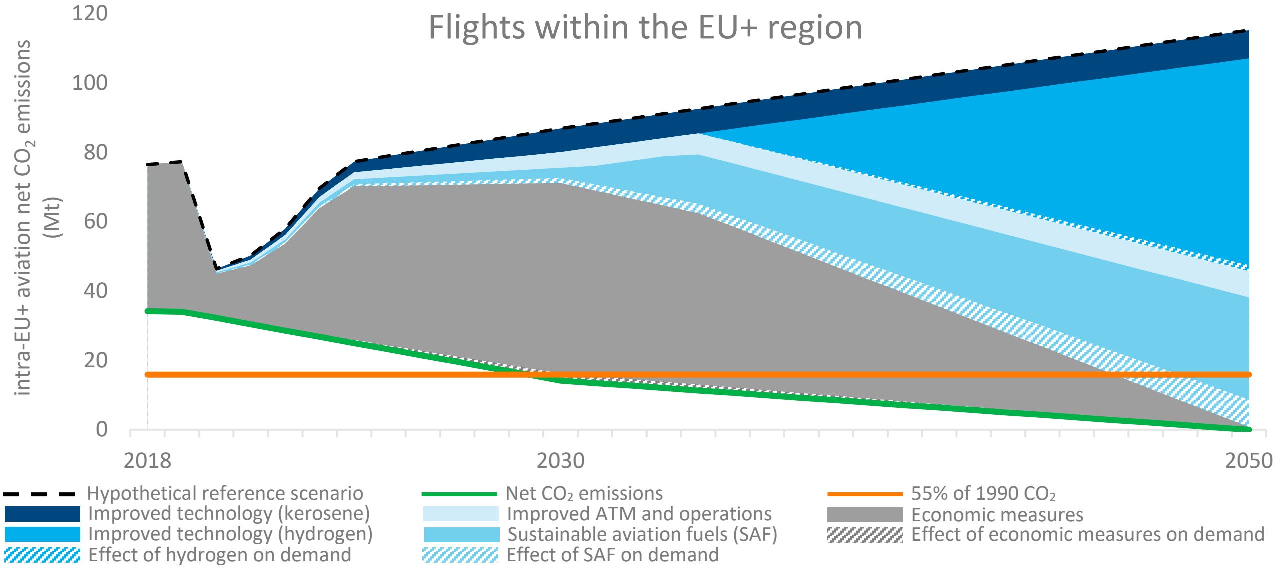
[1] While acknowledging that aviation is also responsible for non-CO_2 climate impacts, the scope of this study is limited to a quantitative assessment of CO_2 emissions. Further study is required to develop a roadmap to take these non-CO_2 emissions into account.
[2] Specifically, the European Union (EU), the United Kingdom (UK), and the European Free Trade Association (EFTA).

A pathway to 2050

Implementing these measures **could make 2019 the peak year in absolute CO_2 emissions** from European aviation, thereby surpassing the industry target of carbon neutral growth from 2020 onwards. In the year 2030, net CO_2 emissions are reduced by 45% compared to the hypothetical reference scenario as a result of continued fleet renewal, improvements in ATM and aircraft operations and a substantial reliance on economic measures. Compared to the CO_2 emissions in the year 1990, on which European Green Deal targets are based, this however means a 36% increase of net CO_2 emissions from European aviation. This is due to the fact that most substantial emission reductions measures – a next generation of aircraft and substantial uptake of sustainable aviation fuel – take more time to materialise. It is nonetheless **essential that the foundations for post-2030 reductions are laid in the coming years**, to realise net zero CO_2 emissions in 2050 and reduce reliance on economic measures.

A detailed look at flights within the EU

For flights within the EU[2], the results highlight that net zero CO_2 emissions in the year 2050 can be achieved with **close to zero economic measures**. The largest contribution is made by **hydrogen-powered aircraft introduced in 2035** followed by sustainable aviation fuels. Net emissions can be limited to **13 $MtCO_2$ in the year 2030, estimated to be 55% below the emission levels in 1990** and thereby contributing to the implementation of the European Green Deal.



Intra-EU[2] only. Modelled for 2030 and 2050, the impacts are linearly interpolated. The base year for this study is 2018.

Recommendations to industry and government

The measures leading to net zero CO_2 emissions from European aviation need to be realised through **collective policies and actions by governments and industry**. Both should work towards **global commitment to a net zero carbon future for aviation**, to avoid differentiated policies, carbon leakage and transfer of activity. Europe should maintain and evolve its leading position in sustainable aviation by the following policies and actions:

Industry should

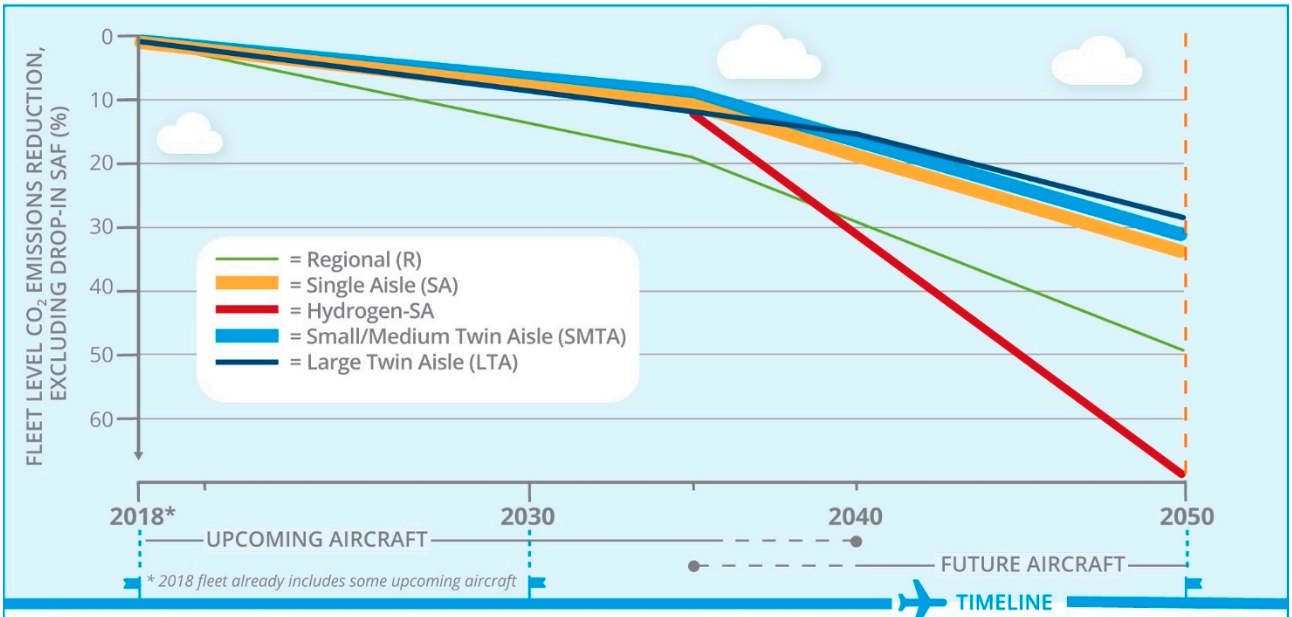
- Continue to substantially invest in decarbonisation
- Develop more fuel-efficient aircraft and bring these into operation through continued fleet renewal
- Develop hydrogen-powered and (hybrid-)electric aircraft and associated supporting (airport) infrastructure and bring these into the market
- Scale up drop-in SAF production and uptake
- Implement the latest innovations in ATM and flight planning
- Compensate remaining CO_2 emissions by removing carbon dioxide from the atmosphere

Governments should

- Support industry investments by direct stimuli or by reducing investment risk through a consistent and long-term policy framework
- Stimulate further development and deployment of innovations by funding research programmes and promoting carbon removal technologies
- Work with the energy sector to ensure sufficient availability of renewable energy at affordable cost
- Support the development of the SAF industry
- Contribute to optimising ATM, in particular by fully implementing the Single European Sky

Improvements in aircraft and engine technology

By 2050, improvements in aircraft and engine technology and subsequent **fleet replacement** hold the largest promise for decarbonising European aviation. This includes the **introduction of a hydrogen-powered single-aisle aircraft on intra-European routes in 2035**. The generation of commercial passenger aircraft to be developed in the next 10 years has potential to realise a **step-change in energy efficiency**. Introduced from 2035 onwards, these aircraft types are forecast to reduce fuel burn by 30% or more per flight compared to predecessors. Range and capacity optimised **hybrid-electric** regional aircraft are anticipated to bring down CO_2 emissions by 50% per flight in that market segment. Future small aircraft and rotorcraft, introduced from 2030, may become drivers for larger aircraft development.



JOINT AND COLLABORATIVE INDUSTRY AND GOVERNMENT ACTIONS REQUIRED

Market segment	Seats	Aircraft-level CO_2 emissions reduction: Upcoming aircraft*	Aircraft-level CO_2 emissions reduction: Future aircraft**
Regional (R)	20 - 100	25% excl. drop-in SAF	50% excl. drop-in SAF
Single Aisle (SA)	101 - 240	15% excl. drop-in SAF	30% excl. drop-in SAF
Hydrogen-SA	165		100%
Small/Medium Twin Aisle (SMTA)	241 - 350	18% excl. drop-in SAF	30% excl. drop-in SAF
Large Twin Aisle (LTA)	>350	19% excl. drop-in SAF	30% excl. drop-in SAF

**) with respect to previous generation; **) with respect to upcoming generation*

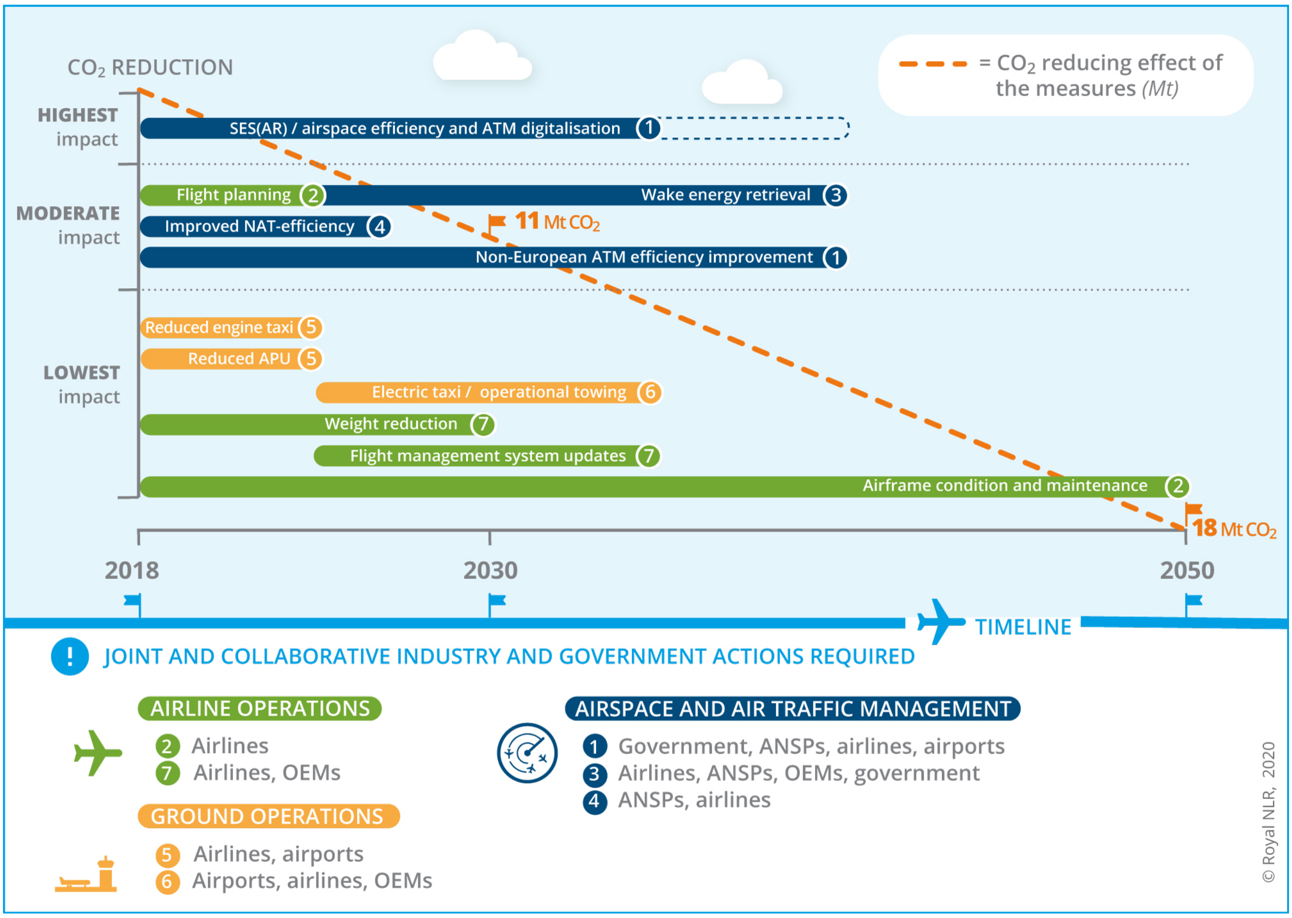
Continued replacement of current aircraft with upcoming models would reduce emissions until 2040. Next-generation future aircraft would yield aircraft-level CO_2 emissions reduction of 30 to 50% compared to upcoming aircraft types. Specifically for the intra-European market, a hydrogen-powered aircraft would enable zero-CO_2 flight. At fleet level the CO_2 emissions reduction by upcoming and future aircraft reaches levels of 28 to 67% in 2050.

Future aircraft availability by 2035 requires technology readiness by 2027 to 2030. The proposed Partnership for Clean Aviation provides a well-structured stimulus framework to realise this. A **collaborative research programme should also address more disruptive technologies modelled in this study**, such as hydrogen-powered or other zero-CO_2 emission aircraft. Collaboration and cross-pollination with other European and national R&D programmes and instruments should be ensured. New technologies should be swiftly incorporated in commercial products, helped by **efficient new certification for disruptive technologies**. Additional improvements should be delivered by accelerating previous R&D results for market uptake, through new product offerings or upgrades to in-production aircraft. Expedited replacement of older aircraft by state-of-the-art models may realise CO_2 emission reductions even earlier.

Besides substantially reducing fuel consumption and fostering green technologies by design, the policies and actions recommended in this roadmap would more firmly **establish the European aviation sector as leading the way towards sustainable aviation**. With environmental concerns intensifying around the world, this offers Europe an important first-mover advantage.

Improvements in air traffic management and aircraft operations

Improvements in ATM and aircraft operations are estimated to be a **crucial opportunity to reducing CO_2 emissions in the short to medium term**. Ensuring full and complete implementation of most measures by 2035 at the latest would, furthermore, allow such benefits to continue yielding impacts between 2035 and 2050.



An array of improvements in ATM and aircraft operations yields a 5 to 6% system-level CO_2 emissions reduction in 2030 and 2050 compared to the reference scenario. Requiring actions from all industry actors and governments, most of these improvements could be realised by 2035. Within each of the three groups (highest / moderate / lowest impact), the measures have not been sorted according to impact.

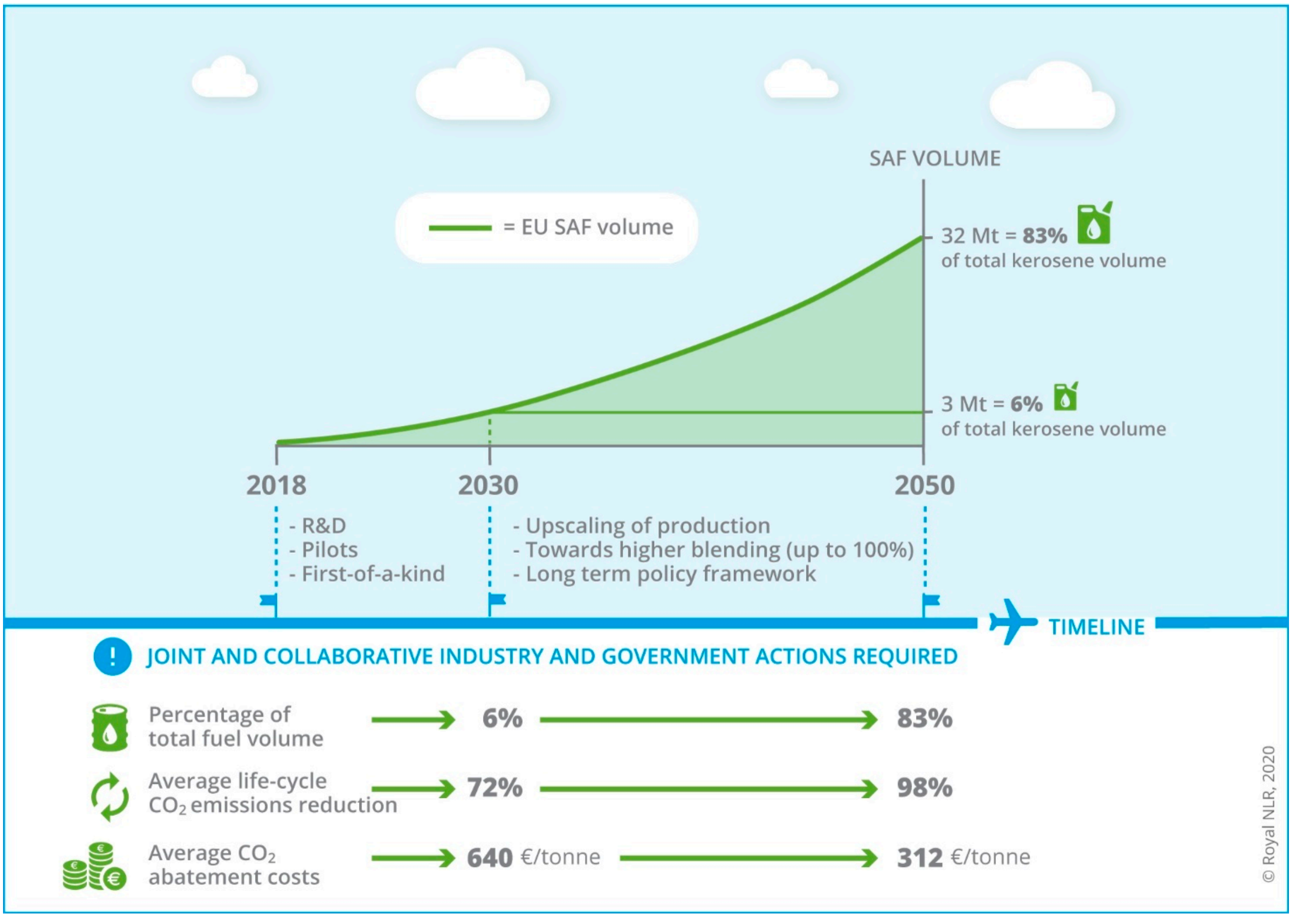
For Europe's residents and visitors to enjoy the full benefits of the Single European Sky, it is **imperative to move more towards a network-centric and digital ATM system and requires political willingness to implement many of the SESAR solutions**. Regulation and R&D efforts must optimally support that goal. First and foremost, such a system would include a renewed set of KPIs with clearly defined accountabilities; a seamless upper airspace; and an R&D policy ensuring steady progress of new technology development and deployment. Better quantifying **the anticipated benefits following from fuel and CO_2 optimized routing** are near-term priorities.

Innovation in communication, navigation and surveillance equipment and processes should also be encouraged, such that these can be swiftly put into practice. Beyond SES and SESAR, European governments and industry should **globally stimulate regions and States to improve ATM efficiency**.

Finally, regulations and incentives should **enable and encourage the rapid decarbonisation of ground operations**. Electric operational towing or taxiing solutions should be developed for all common aircraft and, when parked, aircraft should use renewable energy. Along with possibly stimulating or supporting companies to make such investments, European governments have a crucial role to ensure the supply of renewable energy can match its increased demand.

Sustainable aviation fuel

SAFs deliver a **major contribution** to achieving net zero carbon emissions in 2050. The supply of SAF may increase from 3 Mt in 2030 to 32 Mt in 2050, equal to **83% of the total kerosene consumption**. The SAF contribution is directly linked to the development of industrial production capacity and strongly influenced by a supporting long-term policy framework. SAF contribution in 2030 may be increased if a strong political support is given to SAF development. Over time, life-cycle CO_2 reduction increases to nearly 100% while production costs decrease.



Over time, SAF production volumes and life-cycle CO_2 reductions increase while production costs decrease.

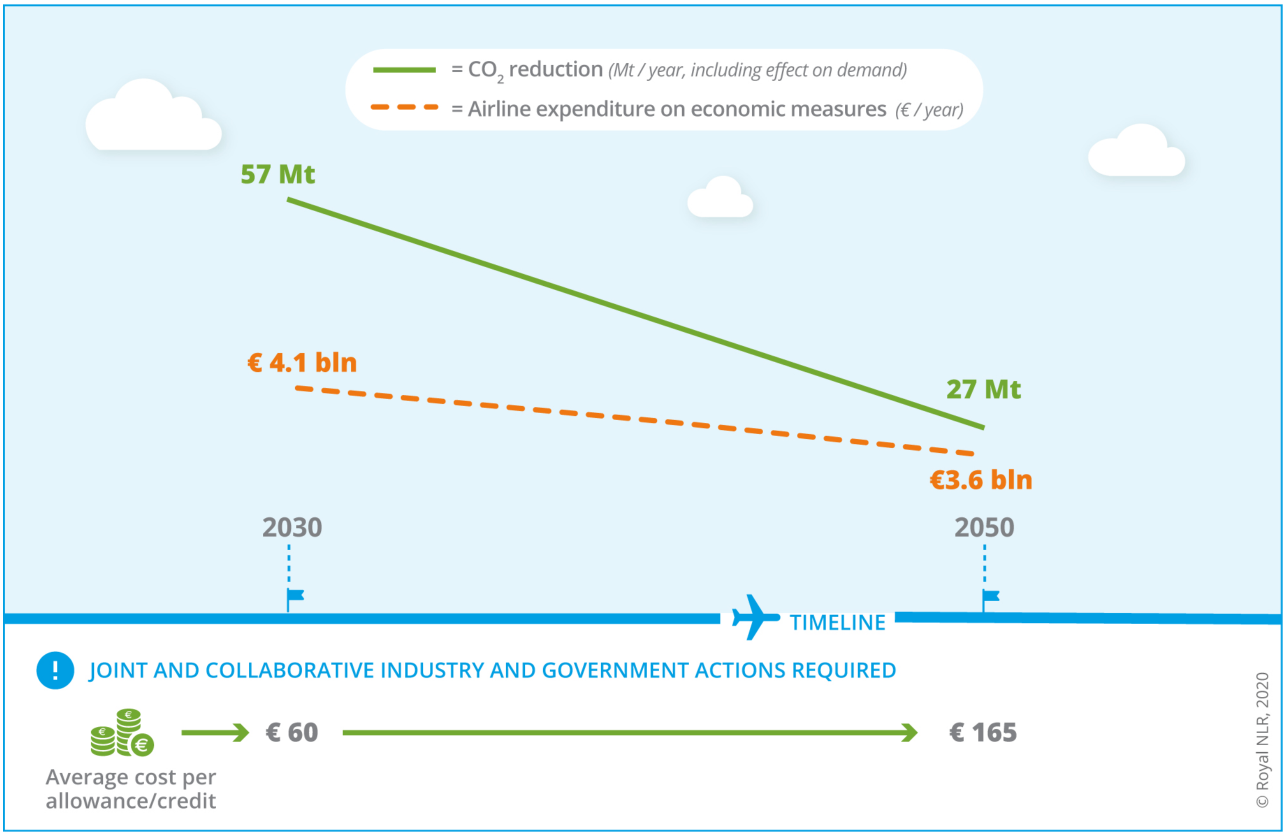
Crucial steps must be taken to **scale up and commercialise SAF deployment**. While making **robust and transparent sustainability criteria** the foundation of a long-term policy framework, a **diversified and sustainable feedstock base** should be established. This would combine biofuels from wastes, residues and non-food (lignocellulosic) crops as well as e-fuels from renewable electricity and CO_2 sourced from direct air capture. Multiple production pathways should be tested in pilot and first-of-a-kind facilities. This increases technological learning, reduces risk and decreases production costs. If the price gap with fossil fuels is overcome, SAFs could fulfil the entire kerosene demand from intra-European flights, necessitating increasing the blending ratio allowed by **ASTM certification from 50% currently to 100%**.

To effectively address the price difference with fossil fuel throughout the value chain and thereby make SAF more affordable, policies need to include measures to de-risk investments and boost production and off-take. These measures could include financial incentives (e.g. carbon pricing, subsidies, auctioning mechanisms and capital grants) and regulatory measures such as the implementation of an **EU wide blending obligation**. The timing and conditions for implementing these measures are currently being investigated in ReFuelEU Aviation. To further reduce cost and increase emissions reductions, a transparent **monitoring and accounting framework** should be implemented, similar to the framework for renewable electricity. This would give airlines the possibility to claim the use of SAF in the most economically efficient way across the fleet, regardless of where SAF has been physically uplifted.

Economic measures

In the short term, smart economic measures are central in the reduction of carbon emissions from aviation. Such measures assign a price to CO_2 emissions ensuring that airlines take climate costs explicitly into account in their business decisions. **To ensure cost-effectiveness, economic measures must be market-based.** The European Emission Trading Scheme (EU ETS) is the mechanism that is implemented in Europe and which is complemented by the ICAO CORSIA scheme for international flights. They trigger the acceleration towards the energy transition and **bridge the gap until breakthrough technologies and SAFs become widely available**. By 2030, economic measures are expected to reduce net CO_2 emissions by 27% compared to the reference scenario.

Over time, breakthrough technologies and the use of SAF reduce the role of economic measures. The price of allowances and carbon credits will increase as they become increasingly scarce. This will eventually lead to a price whereby carbon removal projects become economically attractive to investors. In 2050, any remaining emissions can therefore be balanced by **carbon removal projects**, which are assumed to lead to the issuance of additional emissions allowances and carbon credits. A global approach is critical to prevent market distortion and carbon leakage.



Smart economic measures are a key mechanism to reducing carbon emissions, especially in the short term when radical breakthrough technologies and SAFs are not yet widely available. The compliance costs to European airlines would add up to around 3.6 billion euros by 2050 – € 165 per tonne CO_2 – as allowances and carbon credits become increasingly scarce.

Guaranteeing the quality of carbon credits through both industry action and policy intervention is key to realising these necessary reductions in CO_2. Implementing the global economic measure CORSIA is crucial to keeping international aviation on track to reduce emissions and contribute to the net zero ambition globally. Earmarking of revenues ensures the economic measures fully contribute to the development of aviation decarbonisation solutions. **Direct Air Capture** is seen as important enabling technology for deployment in the short to medium term in order to create high quality carbon allowance and credits.

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CUSTOMER: A4E, ACI-EUROPE, ASD, CANSO, ERA

AUTHOR(S):

Elisabeth van der Sman	NLR
Bram Peerlings	NLR
Johan Kos	NLR
Rogier Lieshout	SEO
Thijs Boonekamp	SEO

NLR – Royal Netherlands Aerospace Centre
SEO Amsterdam Economics

Contents

1 Introduction

Since the foundation of the first airlines over a century ago, aviation has developed to become a crucial element of modern society. Connecting people, businesses and families around the globe, it has contributed to global economic wealth development and increased our understanding and appreciation for different continents and cultures. With that understanding of the world we live in, however, also comes increased knowledge of how our consumption and travel patterns affect our planet. Over the past few years, sustainability has grown to become a top priority for governments, consumers and industry. Various sectors – such as energy generation, industry and automotive – are making progress in reducing the environmental impact of both their own activities and their products and services.

Maintaining the benefits that aviation brings to the global community, the European air transport industry also has committed to play its part in that sustainability transition (Aviation Round Table, 2020). Notwithstanding the achievements realised in terms of reducing fuel consumption *per passenger kilometre*, reduced circa 45% between 1968 to 2014 (Kharina & Rutherford, 2015) and 80% since the introduction of the first jet aircraft (EUROCONTROL, 2019c), absolute CO_2 emissions have continued to increase. Before the impact of COVID-19 drastically reduced air travel, aviation was responsible for 2 to 3% of global anthropogenic CO_2 emissions and it is expected that these numbers are to rise tenfold if aviation does not change its course while other industries do (Cames, Graichen, Siemons, & Cook, 2015; Pidcock & Yeo, 2016; Becken & Pant, 2020). Social phenomena such as *flygskam* (flight shame) and wider questions about future mobility are also affecting the industry's licence to operate and grow (Topham, 2019; BBC, 2019; EUROCONTROL, 2019c).

This report, initiated by European representatives of (regional) airlines, airports, aerospace manufacturers, and air navigation service providers and prepared by Royal Netherlands Aerospace Centre and SEO Amsterdam Economics, identifies pathways to substantially reduce aviation carbon emissions. Potential carbon emission reductions from future aircraft and engine technology, improvements in air traffic management and aircraft operations, the use of sustainable aviation fuels and economic measures are first identified. These are subsequently modelled and assessed against a hypothetical reference scenario that includes activity growth as well as the recent COVID-19 impact in order to identify the extent to which these efforts can help realise European and international goals. The report focusses on areas where the initiators and governments (both European and Member States) play a leading role in developments. Additional initiatives besides the ones included in this study are welcomed and other actors are encouraged to take responsibility where they can. This concerns both the CO_2 emissions considered in this study as well as other environmental or sustainability impacts.

In addition to quantifying potential improvements, policies and actions are defined to help make the possibilities identified a reality. As such, this report – as well as the five initiating parties – hope to inspire all stakeholders in the aviation industry and governments to take action now to make Europe's climate ambitions for 2030 and 2050 a reality.

The remainder of this chapter is structured as follows. Section 1.1 presents the context of the study, providing among other an overview of current environmental goals, the climate effect of aviation and past efforts to reduce this. Next, Section 1.2 goes into detail on the approach taken and Sections 1.3 and 1.4 formally define the objective and scope of the project. Last, Section 1.5 details the structure of the report and thereby serves as a reading guide to the remainder of the report.

1.1 Context

This section discusses the context of this study in greater detail. Although some aspects have been highlighted in the introductory paragraphs of this chapter, a thorough overview and understanding of this context is deemed critical for the correct appreciation of the results presented in this report.

Section 1.1.1 first discusses the various international environmental goals and related policy developments. Next, the costs and benefits of the aviation industry are put into perspective in Section 1.1.2. Then, relevant characteristics of industry itself are discussed in Section 1.1.3. Last, Section 1.1.4 treats the impact of climate change on society and the aviation sector in particular.

1.1.1 Climate and CO_2 emissions reduction goals and policy developments

According to the latest reports of the Intergovernmental Panel on Climate Change (IPCC), the rise of global average temperatures – when compared to pre-industrial levels – has to be limited to 1.5° to 2° Celsius to prevent doing further and irreversible harm to our planet (NASA, 2020; Sustainable Aviation, 2020a; Lamontagne, Reed, Marangoni, Keller, & Garner, 2019; Becken & Pant, 2020). During the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in 2015, the world set a climate goal based on these insights: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change" (UNFCC, 2015, Art. 2). The IPCC has determined that in order to meet the 1.5° or 2° scenarios, net zero carbon must be achieved by 2050 or 2070[3], respectively (IPCC, 2018b).

> **DEFINITION: NET ZERO CARBON AND CARBON NEUTRALITY**
> The IPCC (2018a) states that "[n]et zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period". It does not limit CO_2 removal to either natural (e.g. afforestation efforts) or artificial sinks (e.g. dedicated technologies, such as Direct Air Capture and Storage). Carbon reductions through avoided emission projects in other sectors, defined as activities that "result in a lower emissions scenario compared to a hypothetical business-as-usual scenario as a result of a specific intervention" (Carrillo Pineda & Faria, 2019), are not compatible with the IPCC definition.
>
> Carbon neutrality is used by the IPCC as synonym for net zero CO_2 emission. There are also organisations that use a broader definition of carbon neutrality, in which it includes avoided emission projects. As these are excluded from this analysis, the text refers to 'net zero carbon' or 'net zero CO_2'.

More recently, the European Commission announced its European Green Deal aiming to become a climate neutral (requiring net zero greenhouse gas emissions) continent by 2050 and presented its proposal for a European Climate Law (EC, 2019i; EC, 2020d). With that, the Commission subscribes to the 1.5° C IPCC scenario. "All relevant climate-related policy instruments" are to be reviewed and possibly revised by June 2021 (EC, 2019i, pp. 4-5). Possible changes include reductions in the amount of free allowances for aviation in the EU Emissions Trading Scheme (EU-ETS) and updates to both to the Renewable Energy Directive[4] (Simon, 2019) and the Energy Taxation Directive[5]. The Commission has furthermore noted that "the price of transport must reflect the impact it has on the environment"

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

[4] Council Directive 2018/2001/EU, an update to the original renewable energy directive, 2009/28/EC.

[5] Council Directive 2003/96/EC, recently reviewed by the European Commission (2019e). The European Commission has communicated to "look closely at the current tax exemptions including for aviation and maritime fuels" (EC, 2019i, p. 10).

and that "fossil-fuel subsidies should end" (EC, 2019i, p. 10). For 2030, the European Commission proposed a reduction of greenhouse gas emissions of 55% with respect to 1990 (Simon, 2020a) whereas the European Parliament voted for a higher reduction of 60% (Simon, 2020b).

Specific to the aviation sector, various industry and governmental organisations have also formulated objectives (Peerlings, 2020). The International Civil Aviation Organisation (ICAO) set goals for annual fuel efficiency improvements (2% p.a. through 2050) and carbon-neutral growth (CNG) from 2020 (ICAO, 2016). The newly-launched Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which starts its pilot phase in 2021, was designed to achieve that latter goal. That target is also supported by the International Air Transport Association (IATA) and Air Transport Action Group (ATAG), alongside the goal of reducing net emissions to 50% of 2005-levels by 2050 (IATA, 2020d; ATAG, 2020a). Going beyond that, the **one**world airline alliance committed to net zero carbon by 2050 (oneworld, 2020). At a European level, different participants in the aviation chain such as ACI EUROPE, the International Airlines Group (IAG) and Sustainable Aviation UK have committed to reaching net zero CO_2 emissions by 2050 (ACI Europe, 2019; IAG, 2019; Mace, 2019; Sustainable Aviation, 2020a)[6]. Air France and British Airways offset carbon emissions of all domestic flights since January 2020 and easyJet has done so for all flights from November 19th, 2019 (Air France, 2019; British Airways, 2019; easyJet, 2019). Finally, ICAO (2019b) has prioritised the development of "a long-term global aspirational goal for international [civil] aviation CO_2 emissions reduction" in October 2019, targeting its definition in 2022 (ICAO, n.d.).

> **EU-ETS AND CORSIA**
> The EU-ETS and CORSIA are two important elements of the existing environmental aviation policy context in Europe. Although both are economic measures, there are important differences between the two. The EU-ETS is a so-called cap and trade system. Sectors to which the EU-ETS applies can emit no more emissions than allowed by the cap and need emission allowances matching their emissions. Businesses get part of their allowances for free and can buy additional allowances on the market. If there are no more allowances, no more greenhouse gases can be emitted. As the cap is progressively reduced, the total amount of CO_2 emissions is reduced as well.
>
> CORSIA, on the other hand, is an offsetting scheme. This means that there is no cap on the total amount of CO_2 emitted into the atmosphere. Rather, the scheme requires participants (airlines) to offset the amount of CO_2 they emit on top of a pre-determined baseline value. Offsetting regularly takes the form of planting trees (such that an equivalent amount of CO_2 is captured and stored in biomass) or financing CO_2 reductions in other industries. This way, the underlying market mechanism aims to abate CO_2 emissions in the most cost-effective way.
>
> Additional details on EU-ETS and CORSIA are provided in Sections 6.3.1 and 6.3.2, respectively. The two mechanisms are compared side-by-side in Table 34 in Section 6.3.3.

It is important to note that the targets just discussed concern emissions reductions expressed in absolute terms, whereas goals in the past often used to discuss emissions reduction per passenger or per passenger-kilometre. A well-known example are the goals set by a high level group commissioned by the European Commission in Flightpath 2050 and the related Strategic Research and Innovation Agenda submitted by the Advisory Council for Aviation Research and Innovation in Europe. These aim to reduce CO_2 and NO_X emissions per revenue passenger kilometre by 75% and 90% respectively, and decrease perceived noise levels by 65%, all with respect to aircraft from the year 2000 (EC, 2011). Furthermore, these goals have steered the various Clean Sky programmes (Clean Sky, n.d.). The challenge with such relative efficiency metrics is that the absolute emissions levels could continue to increase even if efficiency continued to improve.

[6] The UK commitments likely follow from the advice by the UK Committee on Climate Change (2019) to its government to include international aviation and shipping in its (binding) national net zero 2050 targets

1.1.2 Aviation as part of society

The European Parliament notes the aviation sector supports around 5 million jobs and contributes € 110 billion to the European GDP per year (Erbach, 2018). If secondary – indirect, induced and catalytic – effects are included, these numbers rise to 12 million jobs and a € 700 billion plus GDP contribution (ATAG, 2019). Similarly, the recent Aviation Round Table (2020) notes almost 10 million jobs and € 672 billion in economic activity. Given EU totals of 227 million jobs and € 17 trillion total GDP, aviation is estimated to be directly responsible for 1 in every 100 EU jobs (approximately 5 per 100 with secondary effects) and slightly more than 1% of the EU GDP (rising to over 4% with secondary effects) (IMF, 2019b; eurostat, 2019; Aviation Round Table, 2020). Without aviation, leisure and business travel would not be the same as we know it today, and modern conveniences such as next-day global deliveries would be limited. Put differently: through the connectivity it provides, aviation has grown to become an unmistakable component of modern society and people's need for mobility.

Benefits, however, do not come without costs. Limiting the present discussion to the scope of this report – CO_2 emissions as part of broader environmental impact – pre-COVID worldwide commercial aviation was computed to be responsible for between 2 and 3% of anthropogenic CO_2 emissions (ATAG, 2018; EEA, EASA & EUROCONTROL, 2019; Erbach, 2018). The most detailed computation states 2.4% (Graver, Zhang, & Rutherford, 2019), equal to 918 million tonnes in 2019 (Graver, Rutherford, & Zheng, 2020). To that figure, passenger travel contributed the most at 85%, with freight carriage (including belly cargo) causing the remaining 15% (Graver, Rutherford, & Zheng, 2020). In Europe, departing flights in 2016 were responsible for 171 million tonnes of CO_2 – approximately one-fifth of global aviation emissions. European commercial aviation emissions have almost doubled between 1990 and 2016 (EEA, EASA & EUROCONTROL, 2019) and correspond to 4.3 to 5.6% of total EU CO_2 emissions[7] and 3.6 to 3.9% of total EU greenhouse gas emissions[8] in 2016 (UNFCCC, n.d.; EEA, 2019). Taking other greenhouse gases and global warming effects into account, the contribution from global aviation is approximated to be two to three times as large as CO_2 alone (Grewe, et al., 2017; Grewe, 2019; Lee, 2018; Lee D. , et al., 2020; Lee D. , et al., 2009; EASA, 2020).

> **CO_2 AND NON-CO_2 INFLUENCES ON GLOBAL WARMING**
> In addition to CO_2, there are other effects that have a positive or negative influence on global warming. This influence is measured as radiative forcing (RF), expressed in Watts (of energy) per square metre (of the Earth's surface area). Whereas the CO_2 contribution to RF is "well-understood" (Lee, 2018, p. 2), substantial uncertainty exists about other sources – such as contrail formation and induced cirrus cloudiness.
>
> Following the recent publication of EASA's updated analysis of the non-CO2 climate impacts of aviation (EASA, 2020), the European Commission commented that "unlike CO_2 impacts, which directly correlate to the amount of fuel burned, the complexity of measuring non-CO_2 climate impacts – and the uncertainty regarding trade-offs between the various impacts – makes targeted policy development in this area more challenging" (EC, 2020j). As further discussed in Section 1.4.2, non-CO_2 effects are not included in the present study.

1.1.3 Workings of the aviation industry

What started out with linen and wood in a grass field over a century ago has evolved into a truly global industry, built up of an intricate and complex network of stakeholders, suppliers, integrators, operators and authorities that contribute to air transport. Despite the tremendous growth that the aviation industry has seen, profit margins are limited and risks are substantial (Doganis, 2010).

[7] 3,941,273 kilotonnes without land use, land use change and forestry (LULUFC); 3,185,038 with LULUFC (UNFCCC, n.d.).
[8] Total EU greenhouse gas emissions in 2016 were 4,441 million tonnes (EEA, 2019), yielding a share of 171 / 4441 = 3.85%. The European Aviation Environmental Report states 3.6% (EEA, EASA & EUROCONTROL, 2019).

Innovation is a key driver for the aviation industry. The sector generally takes a long-term perspective. Aircraft are designed to have a lifespan of 20 to 30 years. It can take 15 years to develop from concept to production. This is partially explained by the focus on safety and associated stringent certification requirements. Programmes normally break even only after ten to twenty years of production (Sadraey, 2013; Buxton, Farr, & Maccarthy, 2006; Johansson, 2014) and manufacturers are often said to bet their entire company's worth when committing to a new aircraft (Raymer, 2002). Especially in times of major change – such as the transitions from wood to metal aircraft, or from propeller-driven types to jets – not all manufacturers manage to survive, either because they committed to the new technology too early, committed to the new technology not early enough, or committed to the wrong technology. Manufacturers often develop families of aircraft, with each type offering different capacity and range. Similarly, new concepts are regularly based on designs already in production. Due to the complexity of the product, intermediate upgrades are difficult: a new engine usually requires changes to the wing, which in turn affects other parts of the aircraft. Nevertheless, continuous and incremental developments are incorporated over the production lifetime of aircraft.

These characteristics have a clear impact on the capability of the airlines together to take up novel aircraft in their fleets. Long financial lifetimes make it very costly to replace existing technology frequently and airlines are dependent on what new products are offered in the market. Another difficulty for airlines is that network and fleet planning have a much longer time horizon than the day-to-day operations. Seemingly good decisions (buying an expensive but fuel efficient new aircraft) might end up very different if circumstances change (decrease in oil price). Given limited profits, an intense focus on operating costs is unsurprising.

Infrastructure planning challenges that airports face see a similarly long time horizon. Alike as well are the significant investment costs related to infrastructure, comparable to what is observed in aircraft development. This is true for terminal expansions or changes, but even more so for the addition of runways or new airport development. When airports are located close to residential areas – as is quite common in Europe – land may not be readily available and surrounding communities may be concerned about the impact on their local environment or on global warming, as the London Heathrow expansion case shows (Morgan, 2020). Notwithstanding the validity of these interests, pre-COVID aviation growth projections show the "capacity crunch" currently faced by various airports throughout Europe is unlikely to lessen (EUROCONTROL, 2018b) – causing increasing delays and preventing more and more people from travelling by air.

1.1.4 Effects of climate change on society and aviation

According to the UN IPCC there is scientific consensus that the climate is changing. As a result, the chance of extreme weather events increases. Such events have a significant human cost, reduce economic productivity and increase the costs associated with damage prevention or restoration.

Over the past 30 years damages resulting from climate-related weather events increased by a factor 20 (Swiss Re, 2018). In 2017 the weather-related damages amounted to $ 330 billion in 2017, making it the most costly year on record. Around two-thirds of the damages were caused by hurricanes in the North Atlantic (Munich Re, 2018). In addition, climate-related weather events are a main cause of humanitarian crises, such as food shortages. In 2018, around 2 million people were displaced as a result of climate related weather events such as drought, floods and storms (WMO, 2019). In 2017, between 8,000 and 10,000 people lost their lives due to extreme weather events (Swiss Re, 2018; Munich Re, 2018), with heat being the most deadly. Adapting to climate change is also costly, especially for small island economies and low-income countries. Required investments for developing countries are estimated at $ 140 – 300 billion in 2030 and $ 280 – 500 billion in 2050 (IMF, 2019a).

Weather related damages in Europe amounted to $ 24 billion in 2017 (Swiss Re, 2018). Going forward, the EEA expects that the damages will be largest in Southern Europe (EEA, 2017). Extreme weather events may also enhance the speed in which the climate changes. The emissions from wildfires in Italy and Portugal in 2017 for instance were among the highest ever recorded (EC, 2019g). By the year 2100, two-thirds of the European population could be affected by weather-related disasters, compared with 5% in 2018 (EC, 2018b).

The aviation sector is affected by climate change through changes in temperatures, precipitation, wind and storm patterns and sea-levels.

Temperature

The years 2015 – 2018 were the four warmest on record (WMO, 2019). Europe experienced extreme heatwaves over this period. Human-induced warming had already reached 1° C above pre-industrial levels (1850-1900) and is increasing at approximately 0.2° C per decade (EC, 2018b). Temperatures in Europe are expected to rise faster than the global average. In winter, warming is estimated to be strongest in north-eastern Europe and Scandinavia. In summer warming is expected to be strongest in southern Europe. How does warming affect the aviation sector? Warmer air is less dense which reduces the lift of aircraft. This means that the operational capacity of runways is reduced. Airlines may experience runway length issues and could be forced to reschedule heavier aircraft to cooler times of day, reduce payloads or depart with a higher thrust setting causing more noise and emissions (ICAO, 2018a). Furthermore, airports may need to invest more in air conditioning systems. Extreme heat also causes damage to runways and taxiways (EUROCONTROL, 2018a). In regions where temperatures and drought increase, there is a heightened risk of desertification and sand storms, which may disrupt airport operations and damage aircraft. In February 2020, sand storms in the Canary Islands for instance led to the closing of most of its airports. Extreme cold on the other hand, may lead to the freezing of airport equipment. Furthermore, there will be a larger need for aircraft de-icing, with anticipated associated increases in emissions. This reduces the efficiency of airport operations and may lead to delays and cancellations (ICAO, 2018a). Temperature changes may also lead to changes in demand patterns (EEA, 2017), not only in terms of destination (region) but also in terms of seasonality. Demand for destinations which face extreme heat and water scarcity may decline. The same holds for winter sport destinations that are affected by a reduction in snowfall (ICAO, 2018a). Demand changes not only affect airports and airlines but also the ANSPs.

Precipitation and humidity

Expectations with respect to precipitation (rain and snow) differ regionally. In Europe, wet regions are likely to get wetter (Northern and Eastern parts) especially during winter, while dry regions (South of Europe) are getting dryer especially in summer (EEA, 2017). Heavy precipitation reduces the efficiency of airport operations. Snow-clearance for instance may cause delays and cancellations. In extreme cases, drainage systems may be inadequate causing damage to airport infrastructure and assets and disrupting operations for a longer period of time. Less rain and longer periods of drought calls for active water management (EUROCONTROL, 2018a). In some regions there may be an increase in the level of humidity which increases the chance of morning fog (ICAO, 2018a). At airports without a modern ILS, this also leads to disruptions.

Wind patterns

Temperature differences lead to changes in wind directions and speeds. The northern parts of central and western Europe may see an increase in extreme wind speeds, whereas the opposite is true for southern Europe. Changes to the prevailing wind directions affect runway use. Strong crosswinds reduce airport capacity and disrupt operations when winds are too heavy to take off or land. Air turbulence may also increase which can cause re-routings, less comfortable flights and heightened maintenance costs (EUROCONTROL, 2018a).

Storm patterns

In some regions storm frequency and intensity may increase, whereas in others they may decrease (ICAO, 2018a). Northern, north-western and central Europe may see an increase in severe autumn and winter storms. Also there could be an increase in the number of cyclones in central Europe. In the Mediterranean the number of cyclones may decrease in number, but increase in intensity. Heavy storms reduce airport and airspace capacity, causing delays, cancellations, re-routings and additional fuel burn. Furthermore, storms may damage infrastructure and equipment. Tropical storm Jebi, for instance, led to the inundation of Kansai airport in 2018, leaving thousands of passengers stranded (WMO, 2019). With more heavy storms, the risk of lightning strikes also increases. Although aircraft are designed to withstand lightning, it may cause damage to aircraft (EUROCONTROL, 2018a; ICAO, 2018a).

Sea-level rise

Rising temperatures also lead to a rise in sea-levels due to the melting of glaciers and ice. Over the 1993-2018 period, the average sea-level rose by 3.15 mm per year. The 2018 sea-level was the highest ever recorded (WMO, 2019). There is scientific consensus that sea-level rise will continue and possibly at an increasing pace (ICAO, 2018a). A temperature increase of 1.5 ° to 2 °C, for instance, could trigger an irreversible loss of the Greenland ice sheet which could lead to 7 meters of sea level rise, directly affecting coastal areas and low-lying lands and islands in Europe (EC, 2018b). Airports are sometimes located near large bodies of water away from built areas, which makes them vulnerable to sea-level rise. Research indicates that a one metre rise in sea-level is expected to increase the risk of inundation at 96 European airports when no further protectionist measures (such as building higher levees) are taken (EUROCONTROL, 2018a). Airport infrastructure may need to be adapted or relocated which comes at a significant cost (ICAO, 2018a).

To sum it up, extreme weather events reduce the efficiency of airport and airline operations, which may lead to delays and flight cancellations. Disruptions in one region may have knock-on effects in other regions. Reduced operational efficiency leads to additional costs. Damage to infrastructure and equipment as well as additional maintenance further inflates costs.

A survey among European aviation stakeholders[9] showed a quarter of them is already experiencing the impacts of climate change (EUROCONTROL, 2018a). On a global scale 74 percent of the stakeholders is experiencing the impacts of climate change, as indicated by a survey[10] of the ICAO Committee on Aviation Environmental Protection (CAEP) (ICAO, 2018a). Both surveys indicate that most stakeholders expect their business to be impacted by climate change in the future. The most severe impacts are expected from increasing temperatures, changes in wind conditions and increased precipitation. Sea-level rise was indicated as a potential risk by fewer respondents, probably because the issue is more localised (ICAO, 2018a; EUROCONTROL, 2018a).

To limit the impacts of climate change, aviation stakeholders can implement adaptation measures. This requires a risk analysis and a corresponding adaptation strategy (ACI World, 2020a). The survey among European stakeholders showed that 52 percent have already started implement adaptation and resilience plans (EUROCONTROL, 2018a). On a global scale the percentage is somewhat lower: 30 percent (ICAO, 2018a).

In addition to mitigation, the aviation sector also needs to take action to reduce its climate impact. Limiting the climate impact will reduce the costs of adaptation measures in the future.

[9] In total 93 responses were received including airlines, airports, ANSPs, civil aviation authorities and manufacturers across Europe. The authors indicate that there may be a degree of self-selection bias with organizations that have a larger interest in the issue or are already taking measures being more likely to take part in the survey.
[10] In total 88 responses were received including airlines, airports, ANSPs and member states.

1.2 Approach

European aviation industry trade organisations ACI EUROPE, Airlines for Europe (A4E), ASD Europe, European Regions Airline Association (ERA) and CANSO initiated this study and jointly identified the need to develop a roadmap for 2020 up to 2050 listing current and proposed future policies and actions that can contribute to meeting international climate goals as set out in Section 1.1.

Rather than choosing either a top-down or bottom-up methodology, the current report fuses elements of the two in order to combine the strengths of both. In this hybrid approach, an ambition level was determined that is both consistent with realistic expectations of future developments in the areas of aircraft and engine technologies, air traffic management and aircraft operations, sustainable aviation fuel, economic measures, as well as with (international) climate and sustainability policymaking. These expectations were based on an extensive literature review to which iteratively input was given by industry and research professionals – the full list of which is included in Appendix B. Using this approach, this report presents a possible pathway towards the decarbonisation of international aviation in Europe.

Notwithstanding the rigour with which this study was conducted, it is emphasised here that there are uncertainties to this document – as holds for any work aiming to predict a thirty-year future. Conclusions and recommendations will have to be updated as time progresses. Some developments might not bring the benefits anticipated from them, whereas others – possibly even breakthroughs entirely unforeseen today – might surpass expectations. Similarly, while some policies and actions now focus on developing innovative technologies and associated measures, others will need to follow that support the delivery of their benefits to all stakeholders. It is thereby emphasised that this report presents *a* pathway towards decarbonising European aviation but does not necessarily present the *only* way.

Uncertainty, however, can also lead to inaction – inaction that no-one can afford. As such, this report is presented as a well-supported foundation for tackling the challenge of decarbonising aviation and guiding government and industry action in the crucial following years to come.

1.3 Objective

This report has the objective to identify opportunities to achieve net zero CO_2 emissions from all flights within and departing from the EU[11] by 2050. Following the definition of 'net zero' carbon by the IPCC (2018a), this means that all possibly remaining carbon emissions will have to be removed from the atmosphere through negative emissions, achieved through natural carbon sinks (e.g. forests) or dedicated technologies (carbon capture and storage).

Destination 2050 considers improvements in aircraft and engine technology; improvements in ATM and aircraft operations; sustainable aviation fuels; and economic measures. Most significantly, solutions of this kind will allow retaining the social and economic benefits of aviation, while delivering substantial improvements in the level of CO_2 emissions. The report does not merely list possible improvements, but also pays attention to the way these improvements can be realised. This way, this study does not aim to be just an overview of opportunities, but a document that initiates action from all parties involved.

[11] The exact geographical scope of this study is defined in Section 1.4.1.

This report is targeted at various audiences. First: industry professionals, which are the ones to commit to researching, developing and implementing the innovations that are required. Second: European and national policy makers, which play an essential role in setting the conditions that make innovation and market introduction possible, and ensure that aviation can continue to benefit Europe's economy and society. Last, fitting with the scale of the effort ahead and the societal expectations concerning this topic, this report also hopes to inform a wider array of opinion leaders interested in the decarbonisation of European aviation. Section 1.5 at the end of this chapter highlights the most relevant sections of this report for each of these audiences.

1.4 Scope

This study is limited in scope in terms of geography (Section 1.4.1), emissions and emissions accounting (Sections 1.4.2 and 1.4.3) and flights considered (Section 1.4.4). Last, Section 1.4.5 defines and shortly explains the four areas in which improvements are sought in the context of this study.

1.4.1 Geographical scope

In geographical scope, the study is limited to commercial flights departing from airports within the European Union (EU), the United Kingdom (UK), and the European Free Trade Association (EFTA), consisting of Iceland, Liechtenstein, Norway and Switzerland. This is visualised in Figure 1. For brevity and legibility reasons, EU+ is used to refer to EU27 + UK + EFTA, unless explicitly stated otherwise.

Figure 1: Geographical scope: commercial flights departing from airports within the European Union (EU), the United Kingdom (UK), and the European Free Trade Association (EFTA), consisting of Iceland, Norway, Switzerland and Liechtenstein.

Norway and Iceland cooperate with current EU targets in aiming to reduce GHG emissions in 2030 by at least 40% compared to 1990 levels. Both countries take part in the EU ETS since 2008 and as of 2021 will implement Effort

Sharing regulation and LULUCF regulation. In 2017, Switzerland and the EU agreed to link their emissions trading systems. The agreement entered into force on January 1st, 2020. Switzerland keeps a separate system, but its scope is similar to the EU ETS and also includes aviation. The linking has resulted in the mutual recognition of EU and Swiss emission allowances (EC, 2019g).

1.4.2 Emissions

This study is limited to CO_2 emissions. Although, as described in Section 1.1, the impact of aviation on climate change is wider, these effects are less well understood.

Although other emissions and climate effects, such as NO_X, noise and contrail formation, are not modelled, some attention is paid to these in a qualitative sense – in case impacts are expected to go hand in hand with the reduction of CO_2 emissions, or imply trade-offs. Carbon dioxide emissions related to surface airport access (both ingress and egress), aircraft production and maintenance, and energy supply and heating of (airport) buildings are not taken into account in this report, either due to resource limitations or data availability, or because these types of emissions are addressed in other programmes[12].

1.4.3 Emissions accounting

To assess aviation's carbon emissions in the EU+, all emissions from a flight *departing* from country of origin A towards country of destination B are attributed to country A. This aligns with the UNFCCC reporting framework and the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The EU greenhouse gas emission inventories assign emissions from international aviation to countries where the associated fuel is bunkered, and as such also only incorporate emissions from departing flights (eurostat, 2019). These data are also submitted to the UNFCCC, and represent the official data for international and EU climate policies. The global characteristic of the aviation industry is also reflected in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), which state that "emissions from fuel use on […] aircraft engaged in international transport should not be included in national totals. To ensure global completeness, these emissions should be reported separately."

Arriving flights from outside the EU+ are excluded from the scope in order to respect international accounting standards, and to avoid double counting of aviation emissions. Nevertheless, various parties in the air transport system are making an effort to also reduce emissions on inbound intercontinental flights. The accounting rules applied for this study do not undermine the importance of such efforts.

1.4.4 Flights

The analyses in this study primarily focus on scheduled passenger flights on subsonic aircraft. For these flights, impacts of sustainability measures on emissions, passenger demand and number of flights offered are taken into account. In

[12] For example, in 2019, ACI EUROPE has celebrated the 10 year anniversary of its Airport Carbon Accreditation programme, which focuses on reductions of emissions of airports under direct control of airport operators. At the higher levels of the programme, it also requires monitoring of airline and other third party emissions, as well as associated stakeholder engagement.

addition, emissions from scheduled cargo operations are considered. However, estimation of demand impacts for air freight – either carried in passenger or all-cargo aircraft – are out of scope.

Non-scheduled passenger and cargo operations are out of scope for the quantitative assessments. This includes all charter flights, general and business aviation, cargo flights carried out by integrators (such as UPS, DHL and FedEx), and all other forms of air traffic not included in OAG Schedules Analyser (Official Airline Guide, 2019)[13].

In addition, the study is limited to operational emissions generated by commercial aircraft. Although this includes both air and ground components (such as taxiing and the use of auxiliary power units for ground power), emissions related to airport facility operation and aircraft manufacturing or maintenance are (as substantiated in Section 1.4.2) not considered. Finally, modal shifts (to e.g. high-speed rail or future developments such as Hyperloop) are not part of the study, although the importance of air-rail complementarity is acknowledged.

1.4.5 Improvements

As indicated earlier in this introduction, this report looks at the possible reductions in CO_2 emissions that can be delivered by four groups – or pillars – of improvements:

- improvements in aircraft and engine technology, including alternative energy sources, which are materialised through replacement of current aircraft by new types;
- improvements in air traffic management (ATM) and aircraft operations, which can be implemented without replacement of current aircraft;
- drop-in sustainable aviation fuels; and
- economic measures.

These pillars are slightly different and more extensive than the ones adhered to by e.g. IATA, being “technology”, “operations”, “infrastructure” and a “global market-based measure” (IATA, 2020b). Specifically, sustainable aviation fuels[14] are taken separately from other technology developments. Operations and infrastructure improvements, the latter of which IATA describes as the modernisation of air traffic management, however, are grouped in the present report. The scope for economic measures is expanded beyond global market-based measures. Figure 2 provides a graphical overview of the different groupings.

Recent industry publications, such as ATAG’s Waypoint 2050 (ATAG, 2020b), adhere to a structure more closely matching Destination 2050: taking (drop-in) sustainable aviation fuels separately from technology and grouping operations and infrastructure together.

[13] General and business aviation is estimated to account for about 2% of total aviation CO_2 worldwide (ICCT, 2019). Integrator and charter flights are likely to account only for a small share of aviation emissions.
[14] Which is an appropriately more narrow scope than the “low-carbon fuels” mentioned by IATA (2020b).

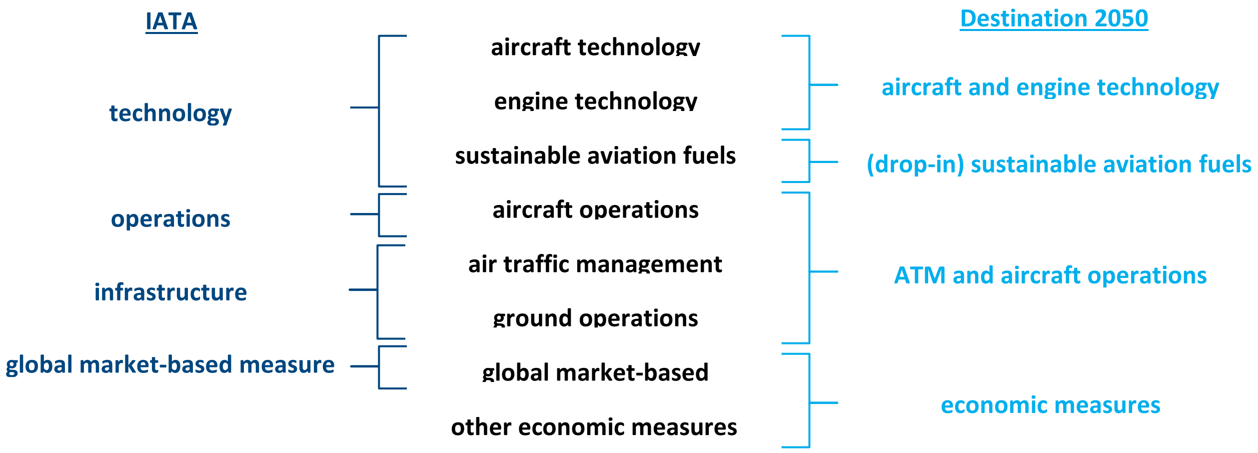

Figure 2: Comparison of groups ('pillars') of improvements between IATA (2020b) and Destination 2050

1.5 Reading guide

The main body of this report starts with presenting the reference scenario used as a basis for the analyses presented in this report. This is the subject of Chapter 2.

Then, Chapters 3, 4, 5 and 6 each discuss one of the four groups of measures considered in the study:

- improvements in aircraft and engine technology;
- improvement in ATM and aircraft operations;
- sustainable aviation fuels; and
- economic measures.

Each of these chapters is structured in a similar fashion. Following an introduction, the main content of each chapter is formed by a number of sections that detail possible improvements and measures and estimate their impact. Then, drivers and barriers – or: challenges – that influence the effectiveness and adoption speed of the measures are treated. As political and societal pressures to reduce CO_2 emissions are drivers for all measures, these are not repeated in the specific chapters. The last section of each of the Chapters 3, 4, 5 and 6 discusses policies and actions that are needed to realise the benefits discussed. Often, these policies and actions are specifically intended to strengthen drivers and mitigate or circumvent barriers.

Following the chapters related to the four groups of measures, Chapter 7 discusses a number of possible changes to the air transport system at large, thereby spanning multiple domains. Next, Chapter 8 discusses the impact modelling of the various potential improvements. Chapter 9 presents the main findings of this study and presents the path forward to Destination 2050. This includes a comparison with current industry and governmental targets and lists a number of policies and actions that are relevant to all measures considered in this study. A list of references and supplementary appendices are included at the end of the report.

In addition to Chapter 9, which presents the key results, and Chapter 8, which summarises input values used for the impact modelling, readers interested in the details of the measures and the methodology using which their impacts are assessed are recommended to focus their attention on Chapters 3, 4, 5 and 6. Specific sections in each these chapters present key actions and policies, of which industry professionals and policymakers should take note. Last, Section 1.1 and the parts of Chapters 3 through 6 that discuss drivers and barriers are suggested to audiences interested in deepening their understanding of the system-level challenges of decarbonising European aviation.

2 Reference scenario

A hypothetical 'no-action' scenario is used as a reference for evaluating the impacts of the sustainability scenario developed in this study. The reference scenario is based on EUROCONTROL's Challenges of Growth forecast. The impact of COVID-19 is taken into account by assuming that traffic gradually recovers to pre-crisis levels by 2024. Growth factors per flight region are subsequently applied to schedule data from OAG. Emissions are determined at flight level using a combination of EUROCONTROL's Base of Aircraft Data and the ICAO Emissions Databank. Load factors and aircraft size are assumed to increase by 0.3% per year.

In the reference scenario traffic increases to 11.3 million departing flights and 1.4 billion passengers in 2050. CO_2 emissions in 2050 are estimated at 320 Mt. Compared to 2018 levels, this comes down to increases of 55% (flights), 87% (passengers) and 67% (CO_2 emissions).

2.1 Introduction

Destination 2050 seeks to identify different sustainability measures that could be implemented in the aviation sector, and assess the impacts of these measures against a reference scenario. Estimated impacts are expressed in terms of (i) passengers, (ii) aircraft movements, and (iii) CO_2 emissions. For the horizon years 2030 and 2050, Chapter 8 presents the reduction of CO_2 emissions resulting from the proposed sustainability measures, compared against the reference scenario presented in this chapter.

The reference scenario is a hypothetical 'no-action' growth scenario with regards to fuel efficiency improvements, operational improvements and sustainable aviation fuels. This means that CO_2 emissions in the reference scenario are estimated based on the assumption that aircraft deployed until 2050 have the same fuel efficiency as in the base year, 2018. It should be noted that such a scenario is purely hypothetical. Even without additional sustainability measures, fuel efficiency is likely to improve due to already implemented climate policies and a continued focus of airlines to reduce fuel consumption. However, distinguishing between improvements in a 'business as usual' scenario compared to an ambitious technology scenario requires additional assumptions on what is 'business as usual'. Thus, using a hypothetical 'no-action' scenario is the best way to provide a full picture of all the sustainability measures taken.

This chapter is structured as follows. Section 2.1 describes the assumptions made in the reference scenario regarding the development of air traffic, load factors, aircraft size and fuel efficiency. Section 2.3 presents the reference scenario in terms of passengers, aircraft movements and carbon emissions.

2.2 Assumptions

This section lists assumptions concerning traffic scenario, load factor development and aircraft size growth and environmental regulation.

2.2.1 Traffic forecast

An individual route level forecast for 2030 and 2050 is made, allowing estimation of the impact of various sustainability measures at a detailed level. The worldwide airline schedule of 2018 forms the basis for the supply-side forecast. This schedule is obtained from OAG Schedules Analyser, which provides information on scheduled passenger flights by airline, route and aircraft type deployed. In addition, the source provides information on the elapsed time between scheduled departure and arrival[15], which is used to estimate fuel consumption and emissions for each flight (see box). On the demand side, origin-destination (O&D) 2018 passenger booking data from OAG Traffic Analyser forms the basis for the analysis.

> EMISSIONS MODEL
> For the study we apply a highly detailed emissions model which estimates fuel consumption for each individual aircraft operation during each flight phase. For the climb, cruise and descent phases the fuel consumption data is based on EUROCONTROL's Base of Aircraft Data (BADA). BADA is used extensively in the (scientific) literature to estimate fuel consumption. It does not contain data for all aircraft types in operation, but recommends which types to use as synonyms. For the LTO phase, fuel consumption is taken from ICAO's Engine Emissions Databank. This databank contains fuel consumption data for individual engine types in the LTO phase. To each aircraft type we attach a common engine type based on the EUROCONTROL ANP database. CO_2 emissions are directly related to fuel consumption and follow directly from the model.

The number of passengers and aircraft movements in the reference scenario are estimated on the basis of external industry forecasts. EUROCONTROL's Challenges of Growth (Regulation and Growth scenario) (2018b)[16] is used as the basis for the reference scenario. It provides a forecast of flight movements until 2040, by individual (European) country.

We updated this scenario to reflect the impact of the COVID-19 crisis. Since the outbreak of the coronavirus organizations such as ICAO, IATA, ACI and EUROCONTROL published traffic projections for the short and medium term. As the virus spread and travel restrictions were tightened or reimplemented, these projections were revised downward. The latest projections indicate that passenger traffic does not return to pre-crisis levels before 2024.

Table 1: Projections for passenger traffic by industry organizations

Source	Forecast
ACI World (2020b)	International markets are expected to recover to pre-crisis levels in 2024, domestic markets in 2023
ACI Europe (2020a)	A survey among industry forecasters shows that full recovery is not expected before 2024/2025
EUROCONTROL (2020b)	Five year forecast indicates that traffic does not recover before 2024
IATA (2020c)	Passenger numbers and RPKs are expected to recover in 2023 and 2024 respectively

However, uncertainties remain large and the projections indicate that the uncertainties are on the downside, meaning that recovery may take longer than currently anticipated. Based on the latest projections, we assume that passenger traffic recovers to 2019 levels in 2024.

The crisis might also change the way that we travel over the long-term. Surveys indicate that 30 – 40 percent of air travellers expect to fly less for both leisure and business purposes when the pandemic is over (Rockland Dutton, 2020;

[15] It should be noted that that airline schedules are "padded" by airlines to allow for ATC/airport related delays. Therefore their use is conservative and may slightly overstate flight or block times and hence emissions.
[16] EUROCONTROL's Regulation and Growth forecast includes currently foreseen measures, namely a carbon price due to market based measures (EU-ETS and CORSIA) combined with an improvement in load factor and increase in aircraft size. The modelling tools in this report control for these measures to prevent any double counting. The reference scenario does not include any additional measures to address the climate impact of aviation.

Barclays, 2020). In its updated long-term forecast, IATA (2020a) assumes that air traffic follows a lower growth trend after the crisis. Boeing (2020) however assumes that traffic levels will return to those previously anticipated.

We assume no structural changes to the long-term trend to make sure we do not underestimate future traffic and CO_2-emissions. For the period after recovery, until 2040, growth rates are sourced from EUROCONTROL's Challenges of Growth forecast. Challenges of Growth breaks down the growth rates in 5-year brackets. For the period 2040-2050, we apply the growth rate reported for the period 2035-2040.

The forecast by EUROCONTROL does not provide a detailed breakdown of traffic by destination region. Therefore, growth rates are differentiated by destination world region based on the Airbus Global Market Forecast (GMF) 2019-2038. This source provides RPK growth rates between 2019 and 2038 for 144 different region-pairs. Aggregate growth rates based on EUROCONTROL are adjusted based on this regional breakdown, while keeping the overall growth rate aligned with the values based on EUROCONTROL.

The sources used for our analysis present forecasts until 2038 (Airbus GMF) and 2040 (EUROCONTROL). Therefore, assumptions need to be made on the growth forecast for the years thereafter. By analysing economic and aviation-specific forecasts until 2050, we conclude that relative growth rates of both European GDP and forecast air traffic do not differ substantially from growth rates forecast for the period 2030-2040 (OECD, 2018b; Economist Intelligence Unit, 2015; EUROCONTROL, 2013). Hence, we assume that growth rates reported for the latest time bracket (2035-2040 in the case of the used EUROCONTROL forecast, and 2028-2038 for the regional breakdown based on Airbus GMF) continue during the period 2040-2050. Given the fact that the external forecasts do not provide data beyond 2040, this extrapolation leads to additional uncertainty. As traffic volumes grow, it could be argued that growth rates gradually decrease, which is also supported by the lower growth rates towards the end of the horizon in the forecasts consulted. As such, maintaining the growth rates for the period beyond 2040 possibly slightly overestimate demand and emissions.

EUROCONTROL does not publish country-level forecasts specifically for air cargo operations. Overall, EUROCONTROL forecasts a 3.5% annual growth rate for air cargo operations. Both Airbus (2019) and Boeing (2019b) present similar growth rates for cargo traffic, and publish detailed growth rates for 131 global traffic regions. Therefore, the more detailed Airbus forecast is used to estimate the increase of cargo operations between 2018 and 2050.

The next chapters present measures to reduce CO_2 emissions from aviation across the four pillars described in Section 1.4.5. Based on these measures, a sustainability scenario is defined. This sustainability scenario is compared against the reference scenario to estimate the impacts of the measures in terms of CO_2-emissions. Figure 3 presents a schematic overview of the approach. Chapter 8 describes the impact assessment in more detail.

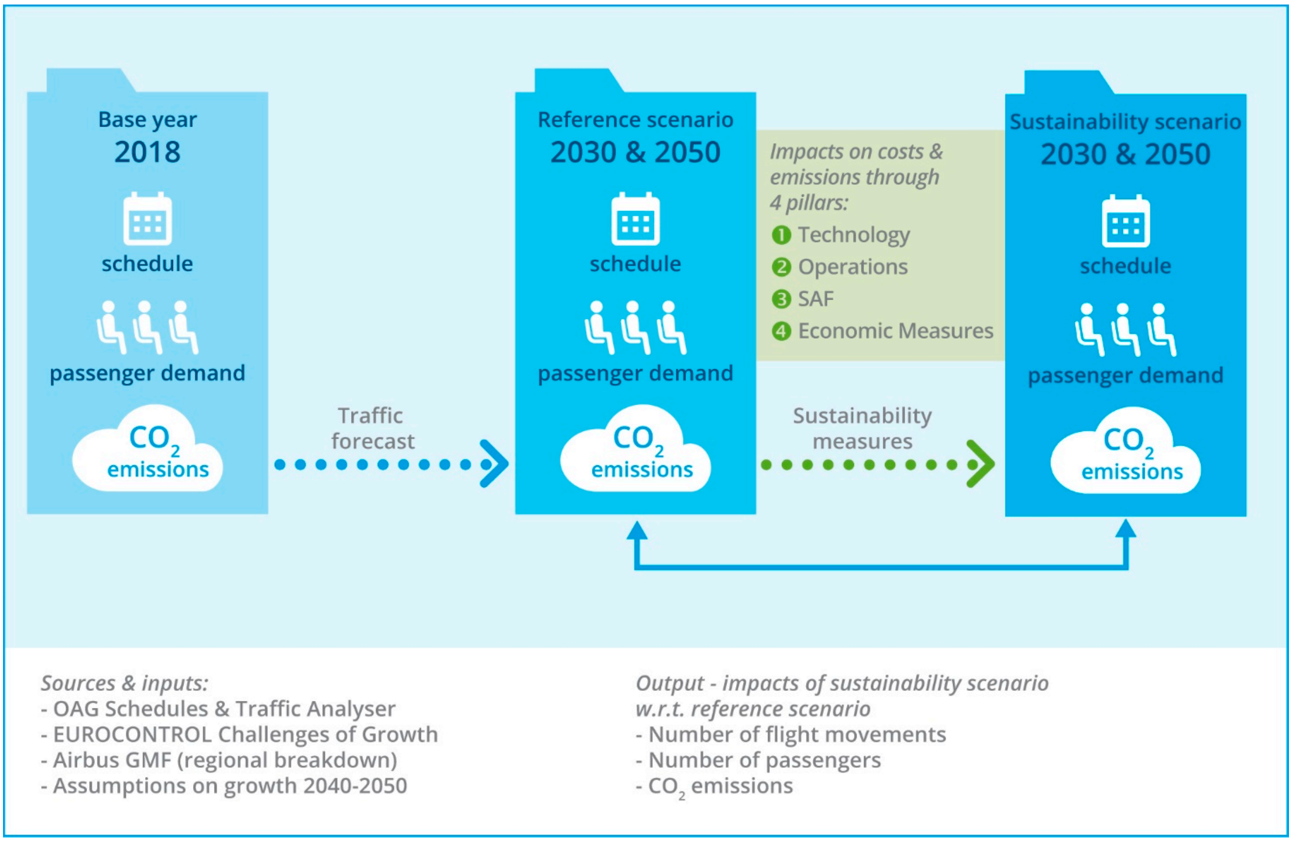

Figure 3: Schematic overview of the approach

2.2.2 Load factor and aircraft size growth

Historically, the average number of passengers per flight has increased. It is expected that this trend will continue during the following decades, particularly considering airport and airspace capacity constraints. Airline operations become more (fuel) efficient by deploying aircraft with a larger seat capacity – up to a certain extent – and achieving a higher load factor.

EUROCONTROL Challenges of Growth forecasts that the average number of passengers per flight increases by 0.6% per year. This can be broken down into two components: load factor growth and aircraft size growth. First we estimate to what extent load factor growth can realistically contribute to the increase in number of passengers per flight. Data from IATA shows that worldwide industry load factors have increased by 0.58% per year between 2000 and 2018 (IATA, 2019c) (see Figure 4). During the period until 2050, it is assumed that this growth rate slows down, as further increases in load factor become progressively more difficult to achieve. Hence, it is assumed that passenger load factors are capped at 90 percent in 2050, which is deemed ambitious but realistic. In 2018, the average global load factor was 81.9% (IATA, 2019c), implying an annual load factor growth rate of 0.3%.

As an example, Table 2 presents average load factors of the five largest European airlines. There are relatively strong differences, particularly between network carriers and LCCs. The current high load factors of LCCs indicate that average load factors of over 90 percent are possible to achieve, supporting this assumption.

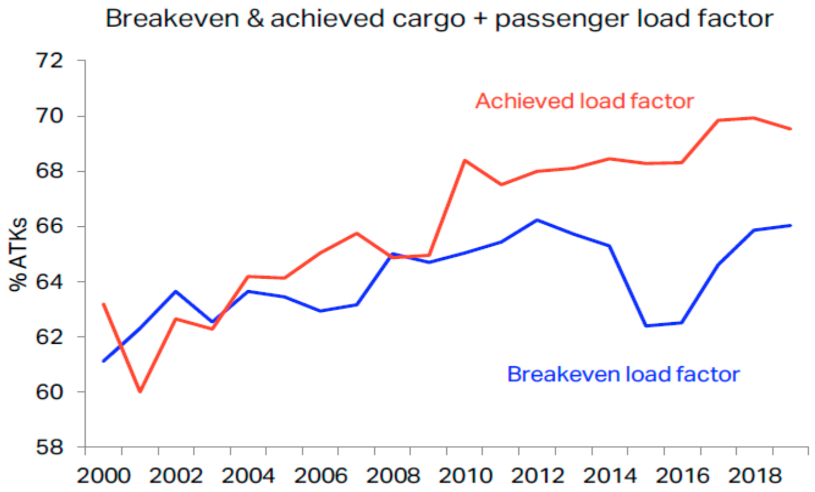

Figure 4: Between 2000 and 2018 load factors increased by 0.58% per year (IATA, 2019c)

Table 2: Load factors of five largest European airline groups (source: airlines' annual reports)[17]

Airline	Financial year	Load factor (RPKs / ASKs)
Lufthansa Group	2018	81.4%
Air France-KLM	2018	88.1%
IAG	2018	83.3%
Ryanair	2018-2019	96.0%
easyJet	2017-2018	92.9%

The remaining growth in the number of passengers per flight will be achieved through an increase in aircraft size. The average number of seats per flight is expected to increase by 0.3 percentage points per year until 2050. This is consistent with the historically observed trend of increasing aircraft size. As an example, exit limits of the Boeing 737 show that the average number of seats per type increases with each generation (see Table 3). In addition, production numbers show a shift towards the larger type: of the Classics 55% of the produced 737s were -300s, while 25% were -400s. In the Next Generation series 17% of the produced aircraft were -700s, and 72% -800s (Brady, 2019).

Table 3: Seat capacity for three generations of Boeing 737 (Boeing, 2013)

	Classic	Next Generation	MAX
Type	**737-300**	**737-700**	**737 MAX-7**
Seats (exit limit)	149	149	172
Type	**737-400**	**737-800**	**737 MAX 8**
Seats (exit limit)	188	189	210

[17] To align with the reporting in airlines' annual report, this table presents load factors based on revenue passenger kilometres (RPKs) and available seat kilometres (ASKs), while in this report passenger numbers are used as a main indicator. Calculating load factors based on RPKs and ASKs puts a higher weight on longer-distance flights. If load factors tend to be lower on shorter flights, load factors based on passengers and available seats will turn out lower.

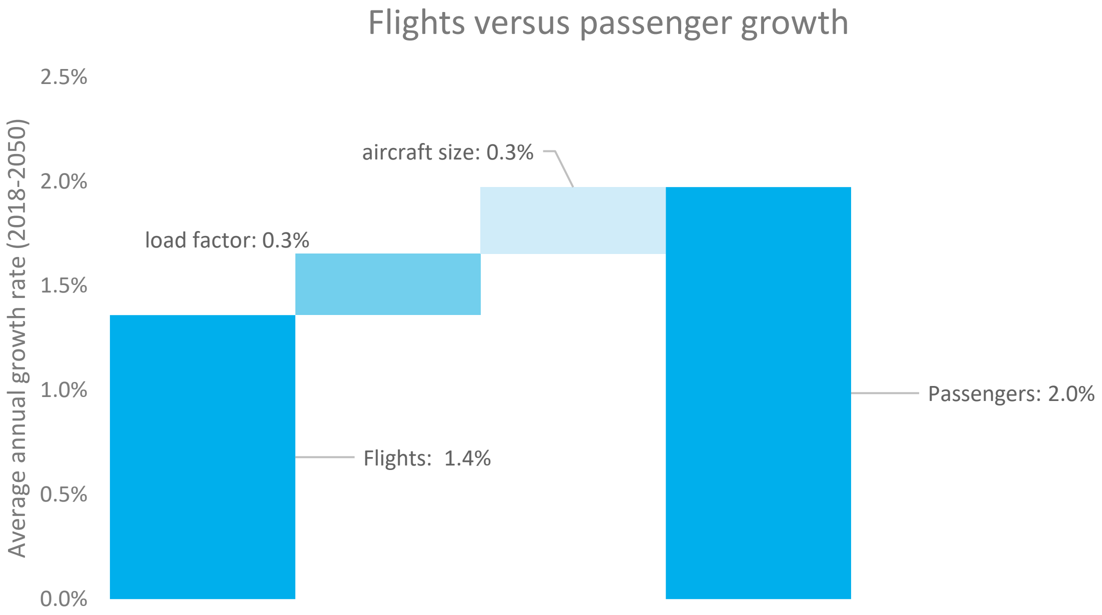

Figure 5: Forecast load factor and aircraft size growth between 2018 and 2050

2.2.3 Environmental regulation

The reference scenario assumes that no additional measures are taken in response to the Paris Agreement. This is in line with EUROCONTROL's most-likely scenario, which is a continuation of currently foreseen measures.

With regard to technology, operations and SAFs, the reference scenario is a hypothetical no improvements scenario. This means that in the horizon years aircraft are no more fuel efficient than in the base year, and operational efficiency remains unchanged as well. Moreover, the amount of SAFs deployed on commercial flights remains negligible.

With regard to economic measures, currently (foreseen) policies (EU-ETS and CORSIA) are taken into account through a mark-up on ticket price. It is assumed that 100% of the additional costs are passed on to the consumer. Most of the incurred costs are sector-wide cost increases, for which economic theory suggests that these are fully passed through (Koopmans & Lieshout, 2016). In some cases, cost increases might not apply to all competitors in a market. This could for example be the case for competition in international hub markets, in which some airlines are not subject to local or European measures. In such cases, airlines might choose to absorb (part of) the cost increase to avoid losing market share. Such choices are difficult to model, as they are highly dependent on the market and the financial situation of airlines. Therefore, we also assume 100% pass through in these cases, as a simplified assumption. As such, demand impacts might be slightly overstated. However, considering the relatively low profit margins in the sector, the extent to which airlines can absorb costs is limited.

Besides the cost impacts of (potential) environmental measures, people become increasingly aware of the impacts of flying on climate change. Although relevant, such trends and developments have not been taken into account in EUROCONTROL's forecasts, and neither are they explicitly included in our forecast.

2.3 Results

This section presents the results of the reference scenario development, spanning a forecast for flights and passengers (Section 2.3.1) and CO_2 emissions (Section 2.3.2).

2.3.1 Flights and passengers

The total number of flights departing from EU+ airports increases from 7.6 million in 2018 to 12.4 million in 2050, an increase of 1.4% per year (see Figure 6). The annual growth rate of scheduled cargo operations (3.0%) is higher than for passenger operations (+1.4%), but accounts for only a very limited share of the total number of flights[18].

The number of air passengers increases by 2.0% per year between 2018 and 2050, increasing from 751 million departing passengers in 2018 to 1.4 billion passengers in 2050 (see Figure 6).

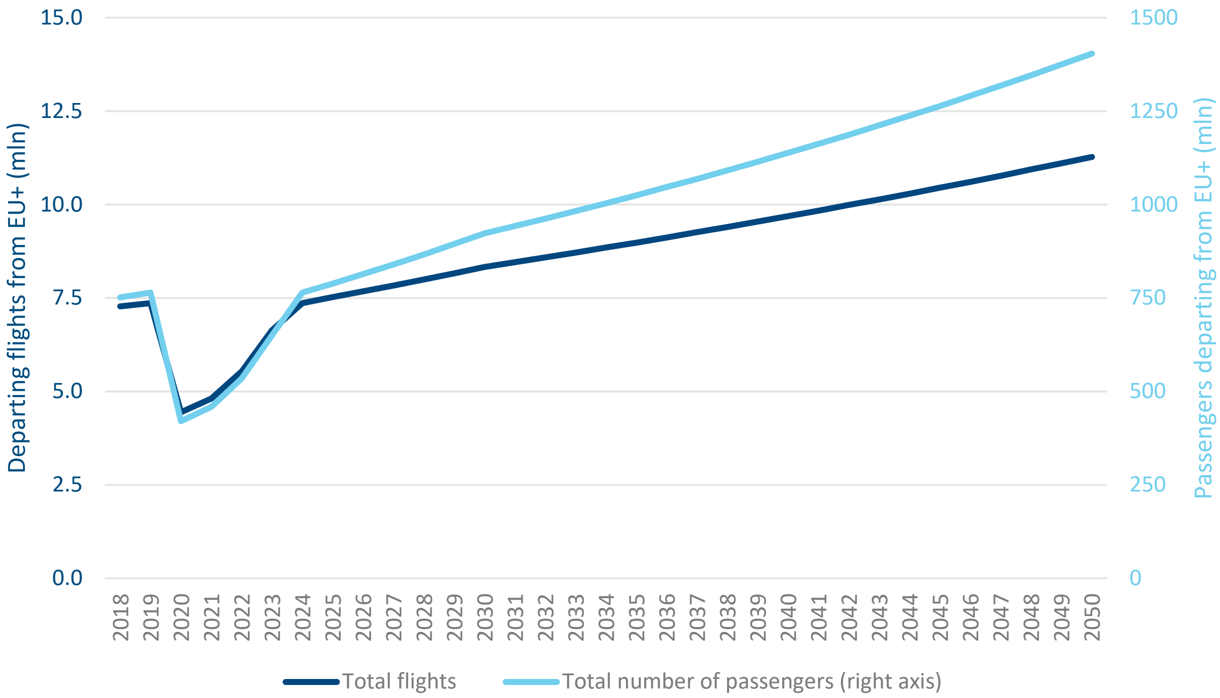

Figure 6: Forecast flights and passenger growth from EU+ airports between 2018 and 2050

Figures 7 and 8 present the growth rates of operations and passengers, respectively, by world region. The majority of flights are within Europe. The share of intra-European flights slightly decreases from 89% in 2018 to 87% in 2050, but remains by far the most important destination region. In terms of passengers, the share of European destinations is slightly smaller: 83% in 2018 decreasing to 80% in 2050. The strongest growth is expected in flights to the Middle East: 3.3% in terms of flights and 3.8% in terms of passengers. In 2050, this is the second largest destination region, especially in terms of flights. 41% of the intercontinental flights departing from the EU is bound to this region. The large hubs in the Middle East (Istanbul, Dubai, Abu Dhabi and Doha) also provide connections between Europe and other world regions, most notably Asia/Pacific and Africa. In terms of passengers, Middle East, North America and

[18] Interestingly, both EUROCONTROL and Airbus foresee a stronger growth in air cargo operations than for passenger operations. Recently however, air cargo growth has slowed down following worldwide trade tensions, whereas passenger demand continued to grow. Over the long term however, worldwide international trade is expected to continue its growth, which is a key driver of cargo traffic. The COVID-19 pandemic led to a surge in cargo operations, compensating the strong reduction in belly capacity.

Asia/Pacific are the largest intercontinental destination regions, respectively accounting for 27%, 25% and 24% of the intercontinental passengers.

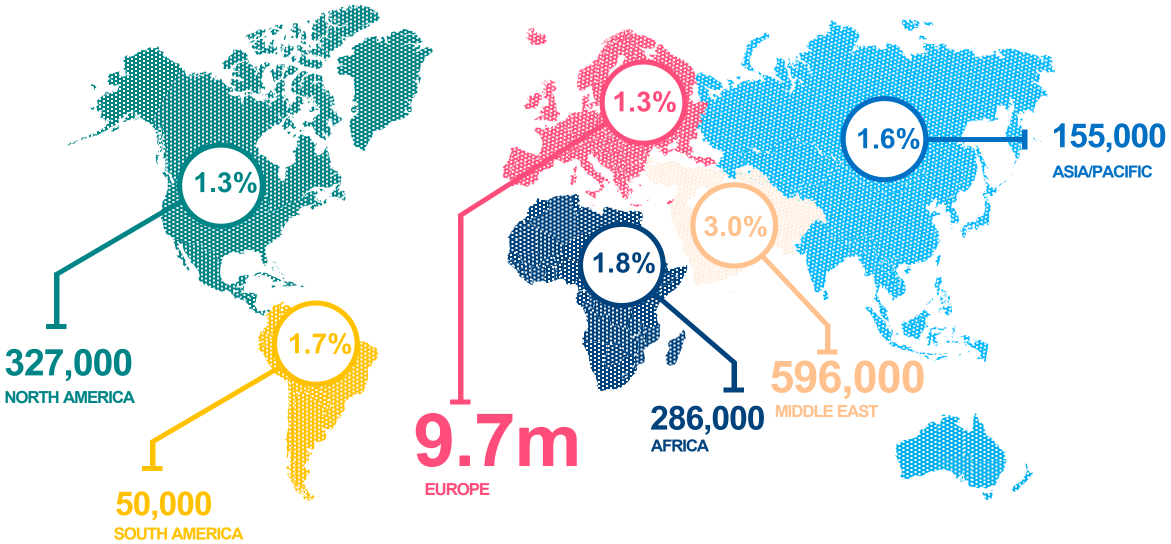

Figure 7: Passenger flights from EU by destination world region. Flights in 2050, growth rates w.r.t. 2018

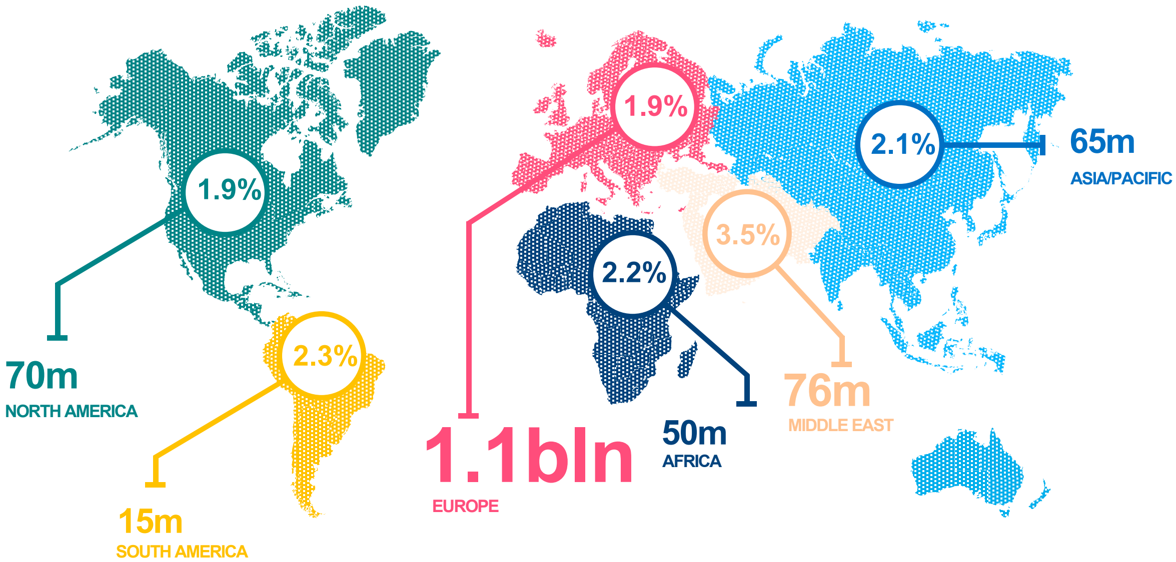

Figure 8: Passengers from EU by final destination world region. Passengers in 2050, growth rates w.r.t. 2018

While the majority of flights is intra-European, intercontinental flights produce a relatively high share of emissions with a limited number of flights. Figure 9 plots the cumulative number of flights and CO_2 emissions against the flying distance. The figure shows that while over 90% of the flights take place on a route shorter than 3500 kilometres, these flights account for only 46% of the CO_2 emissions. This means that the majority of CO_2 emissions stem from intercontinental flights.

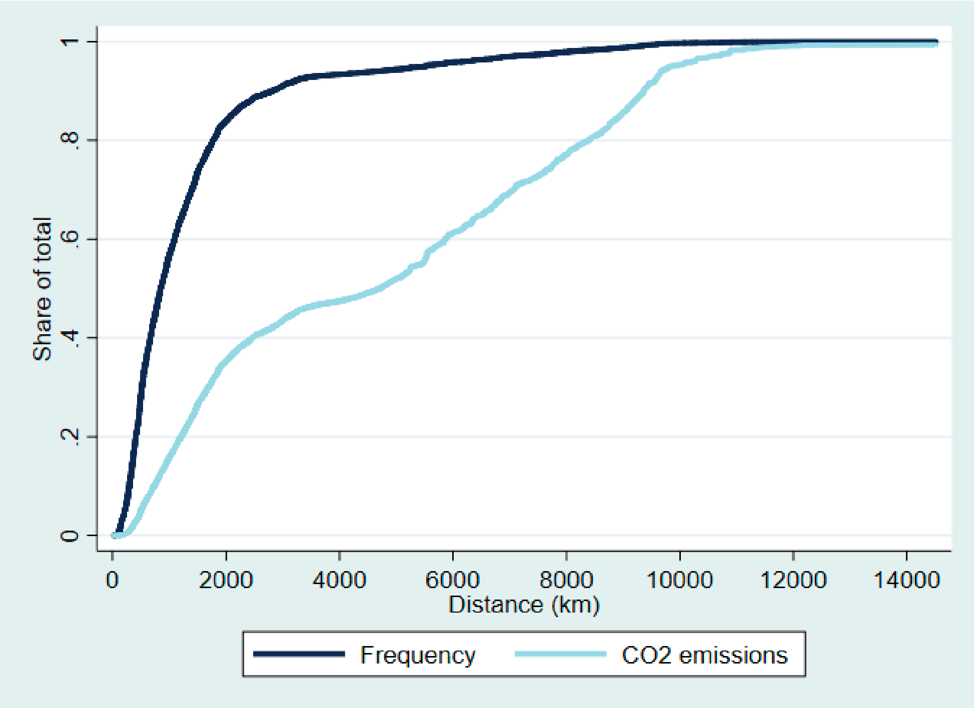

Figure 9: The 10% of the flights on routes over 3500 km account for the majority of CO_2 emissions

2.3.2 Emissions

In the reference scenario, CO_2 emissions from EU+ aviation are expected to increase by 1.6 percent per year until 2050 (see Figure 10). In 2018, estimated CO_2 emissions for both passenger and cargo operations accrue to 189 Mt, increasing to 192 Mt in 2019. The majority of these emissions, respectively 181 and 183 Mt, arise from passenger operations. In 2030 aviation emissions are 16% higher than in 2018, and by 2050 CO_2 emissions are 67% above 2018 levels. Emissions from scheduled cargo operations increase more rapidly (3.1% per year) than those from passenger operations (1.5%), but account for a limited share of total emissions. In 2050, 93% of EU+'s commercial aviation emissions are caused by passenger flights, while cargo flights account for the remaining 7 percent – increasing from 5 percent in 2018.

In the reference scenario, CO_2 emissions from intra-EU+ aviation add up to 115 Mt by 2050. Flights to destinations outside the EU+ are expected to emit 178 Mt of CO_2 in the reference scenario. All these emissions need to be removed to comply with the net zero goal for 2050. Hence, sustainability measures should in total yield a reduction of at least 293 Mt of CO_2.

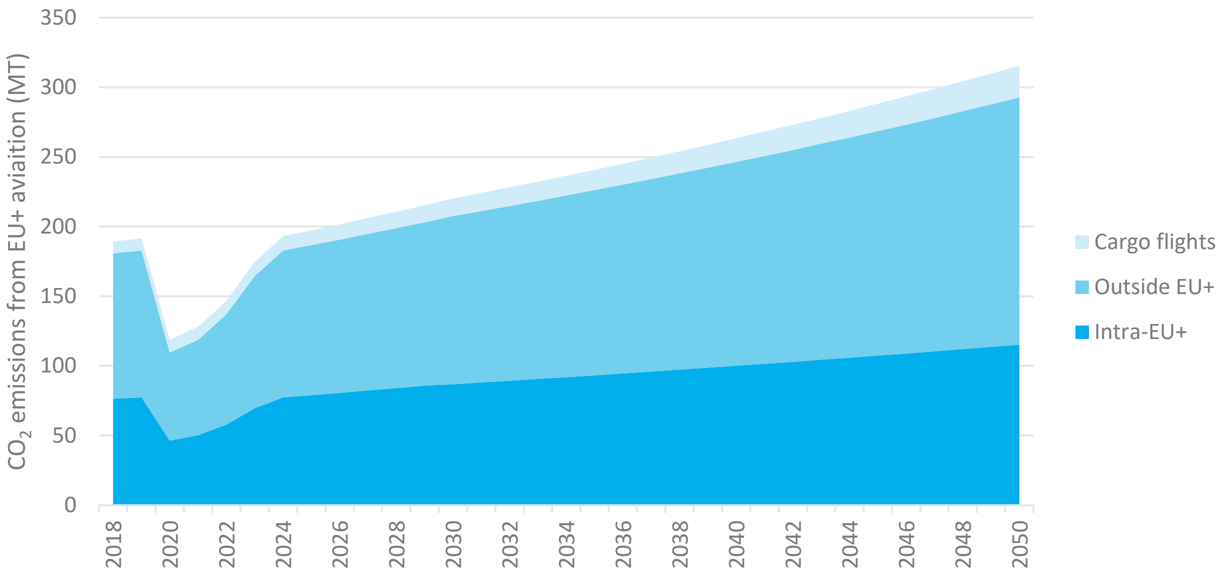

Figure 10: CO_2 emissions from EU aviation in reference scenario

3 Improvements in aircraft and engine technology

In terms of improvements in aircraft and engine technology, which enter the market through fleet replacement, this study distinguishes between upcoming and future aircraft. The former are currently available but have not completely materialised in fleets or will be in the next few years and bring fuel efficiency improvements of 15 to more than 25% compared to their predecessors. The latter are still to be developed.

For the largest share of aircraft – large single aisle and twin-aisle models – potential improvements in fuel efficiency of 30% are foreseen, combining contributions from major propulsion technologies, as well as wing, fuselage and tail technologies. For regional aircraft, an improvement of 50% is modelled, based on more aggressive advances in (hybrid-electric) propulsion technology and optimised capacity and range. Future regional, single aisle and medium sized twin aisle aircraft are anticipated to enter into service between 2030 and 2035 and future large twin aisle aircraft in 2040. Fleet-level impact of both upcoming and future aircraft is computed assuming a 22.5-year market penetration timeline. In addition to aircraft powered by kerosene (or sustainable drop-in fuels), a hydrogen single aisle aircraft is modelled to enter service in 2035.

In order to realise the modelled efficiency improvements of future aircraft, individual enabling technologies should be available at least five years prior to anticipated entry into service. The proposed European Partnership for Clean Aviation addresses the need for a stimulus programme, focused on achieving the required technology readiness for adoption in an aircraft development programme. Industry partners should take the lead in such stimulus programmes in terms of technology development and make sure relevant results are integrated into commercial products. In addition to realising the required improvements in fuel efficiency, this further establishes the leading position of European aerospace manufacturing. Research and technology infrastructures must therefore be better supported. Certification requirements of disruptive technologies should be clear and linkages between other R&D-efforts (supporting infrastructure; hydrogen; drop-in sustainable aviation fuels) are to be ensured. Additional opportunities are presented by (re-) assessing the market potential of innovations developed in the past and their possible commercialisation as retrofittable product upgrade. Last, expedited replacement of older aircraft by state-of-the-art models may realise CO_2 emission reductions even earlier.

3.1 Introduction

This chapter presents possible technological improvements to aircraft and engines that contribute to reduction of emissions of aircraft in the period between 2020 and 2050. The analysis is mostly limited to technology development that enters the market through completely new aircraft (i.e., with a new type certificate) or through a major upgrade of an already existing aircraft type. Such major upgrades typically involve major changes in the airframe and new engines.

Upcoming and future technology

Consistent with other works (Sustainable Aviation UK, 2016; Sustainable Aviation, 2020a), this study distinguishes between upcoming[19] and future technology. Upcoming technology is defined as technology that has already entered into service and is still in production, or is estimated to enter into service in the next few years. The improvement potential of upcoming technology until 2025 is relatively well-known, as well as the timeframe during which these improvements can be delivered. Nevertheless, uncertainties do exist. This is even more so for future technology. Although impact estimates at aircraft-level are sometimes available, empirical evidence of how these innovations affect overall aircraft performance does not exist. As such, modelling assumptions are based on desk research.

Aircraft size classes

In addition to the split between upcoming and future technology, the analysis distinguishes between several aircraft size classes in terms of seating capacity. These are defined and named as shown in Table 4. The share of 2018 CO_2 emissions per class is computed in the present study, using the methodology described in Section 2.1.

Table 4: Aircraft classes and share of 2018 ASKs and CO_2 emissions within the scope defined in Section 1.4

Class (abbreviation)	Seating capacity	Example(s)	Share of 2018 ASKs	Share of 2018 CO_2 emissions
Small (S)	0 – 19		0.01%	0.02%
Regional (R)	20 – 100	ATR42, ATR72, Embraer E175	2.99%	3.78%
Single aisle (SA)	101 – 240	Airbus A320 family, Boeing 737	56.4%	51.6%
Small/medium twin aisle (SMTA)	241 – 350	Airbus A330, Boeing 787	27.8%	30.3%
Large twin aisle (LTA)	351 +	Airbus A350, Boeing 777	12.8%	14.3%
Total			**100%**	**100%**

Even though the small aircraft class, comprised of general aviation and commuter aircraft and rotorcraft, is responsible for only a fraction of current CO_2 emissions, it is specifically included as the impact of innovation on emissions is estimated to materialise most quickly there. Compared to seat categories as defined by ICAO CAEP (ICAO, 2013, p. 20), the upper boundary of the SA-class is raised from 210 to 240 to reflect the recent growth of single aisle aircraft[20] and the expectation that that trend will continue (as discussed in Section 2.2.2). No separate category for very large aircraft (VLA, encompassing previous types as the Boeing 747 and Airbus A380) is taken into account, as no new aircraft of that class are currently expected.

Performance improvements and retrofits

Besides completely new aircraft or engine options, manufacturers provide smaller product enhancements during an aircraft's and engine's production life and retrofits can (and should) be carried out on aircraft and engines that are already in service. Where such product enhancements and retrofits are known or have been announced and they have significant impact on the aircraft's emissions, they are taken into account as well (such as previously the introduction of winglets, or the upgrade of flight management systems described in Section 4.2.1). Still during the entire 2020 – 2050 time frame, currently unknown product enhancements and retrofits may be introduced, for example based on the CleanSky programmes, the European Framework Programmes, or the Horizon2020 programme. Taking a conservative approach in this regard, these unknown product enhancements and retrofits by aircraft manufacturers have not been taken into account in the impact modelling.

[19] Referred to as 'imminent technology' by Sustainable Aviation UK (2016) and 'known aircraft' by Sustainable Aviation (2020a).
[20] The Airbus A321neo as it is currently offered with a maximum seating capacity of 244 (Airbus, 2020a), but is typically equipped with a two-class cabin with 206 seats (Flottau, 2015).

Significant, but smaller improvements that are largely at the discretion of an airline and maintenance organisation, are treated in Section 4.2, such as weight reduction of cabin furniture and optimised maintenance intervals for weight or fuel efficiency.

The remainder of this chapter will address various technological improvements in greater detail, with Section 3.2 discussing upcoming technology and Section 3.3 treating future technology. Last, Sections 3.4 and Section 3.5 discuss drivers and barriers and present the policies and actions, respectively.

3.2 Upcoming technology

This section presents the improvement potential of upcoming technology: the return on previous efforts and investment in research and development. As defined in Section 3.1, upcoming technology is currently available in the marketplace or is estimated to enter service in the next few years, but has not fully materialised yet in airlines' fleets.

Table 5 shows the upcoming aircraft that are currently foreseen in the regional[21], single aisle and twin aisle classes[22]. Upcoming aircraft that are a direct successor of a current airframe – including a new engine – are assumed to enter the future fleet by one-to-one replacement. This is the case for the aircraft for which Table 5 shows a 'legacy type' (Embraer E2, Airbus A320neo, Boeing 737MAX, Airbus A330neo, Boeing 777X). Table 5 furthermore summarises the improvement potential in terms of fuel burn per ASK and per flight[23] and entry into service of various upcoming aircraft with respect to a reference aircraft. Seating capacities for upcoming and reference aircraft as well as fuel consumption improvement data stem from the same source as much as possible, to ensure consistency[24]. These capacity comparisons provide a rough indication of the extent to which performance improvements depend on aircraft growth and seat densification efforts (Hepher, 2013), or on technology improvement. In case legacy and reference aircraft are different, this is because manufacturers chose to express the improvement potential of a new model with respect to another (possibly competing) type. The data presented in the table is either based on results from operational experience, or direct or media claims from OEMs[25]. Because the future fleet of the reference scenario used in this report is a mere extrapolation of the current fleet (with current aircraft models) composition with respect to air traffic growth, 2018 aircraft market shares per route are assumed to remain unchanged for both fleet replacement as well as fleet growth.

For current or previous generation aircraft that are not replaced by a designated successor[26], an improvement based on the class-average is assumed. Table 6, summarising further details provided in Appendix A, defines the improvement of a hypothetical class-averaged aircraft entering into service ('EIS (upcoming)') with respect to a hypothetical reference aircraft, entered into service in the past ('EIS (reference)'). An unweighted averaging of both the performance improvement and entry into service dates (of both upcoming and reference aircraft) at aircraft (sub)type level is used. Averaging performance is furthermore warranted as the introduction of replacement aircraft

[21] Following the recent suspension and possible abandonment of the Mitsubishi SpaceJet (formerly: Mitsubishi Regional Jet) development (Perrett, 2020), this aircraft is not included in the overview.
[22] Because of the limited contribution to CO_2 emissions by small aircraft, combined with the multitude of concepts currently being developed (as reviewed by e.g. ERA, 2020; Thomson, 2020), these have not been included in the current review.
[23] The fuel burn improvement per flight was computed by subtracting the change in seating capacity from the improvement per ASK, the latter sourced from literature.
[24] If fuel consumption improvements were based on unknown capacity data, typical seating capacity numbers were used. This is indicated with a superscript 'T'.
[25] Given the fact that OEMs often have to pay substantial compensation to their customers if their products do not realise performance estimates communicated earlier on, these claims are assumed to be unbiased.
[26] Examples include the regional Bombardier CRJ-series, the single aisle Airbus A318, the small/medium twin aisle Boeing 767, the twin aisle Airbus A340 and the large twin aisle Boeing 747. The Boeing 757, a single aisle aircraft with the seat capacity of small twin aisles, is another prime example.

Table 5: Fuel efficiency improvement potential and entry into service of upcoming aircraft types, relative to reference types. For one-to-one replacements, legacy types are indicated.

Class	Upcoming			Legacy		Reference			Fuel efficiency improvement		Source(s) and remarks
	Type	EIS	Seats	Type	EIS	Type	EIS	Seats	Per ASK	Per flight	
R	ATR 72-600	2011	72			CRJ700	2001	70	47.7%	46.3%	ATR (2020), Aircraft Commerce (2009)
R	E175-E2	2021	80	E175	2005	E175	2005	76	16%	10.7%	Embraer (2016, p. 20)
R	E190-E2	2018	97	E190	2005	E190	2005	97	17.3%	17.3%	Embraer (2016, p. 20), Gerzanics (2018)
SA	A220-100	2016	120[T]			E190 (est.)	2005	106	20%	6.8%	Bombardier (2015), Embraer (2016, p. 20)
SA	A220-300	2016				E190	2005			6.8%[27]	Bombardier (2015), Embraer (2016, p. 20)
SA	E195-E2	2021	120	E195	2006	E195	2006	106	25.4%	7.9%	Embraer (2016, p. 20), Hemmerdinger (2019)
SA	A319neo	2019	160	A319	1996	A319	1996	156	19%	16.4%	Leahy (2016, p. 18), Aviation Week & S. T. (2007, p. 63)
SA	A320neo	2016	189	A320	1988	A320	1988	180	20%	12.0%	Leahy (2016, p. 18), Aviation Week & S. T. (2007, p. 63)
SA	A321neo	2016	240	A321	1994	A321	1994	220	23%	13.9%	Leahy (2016, p. 18), Aviation Week & S. T. (2007, p. 63)
SA	A321neoLR	2018	206			757-200	1983	200[T]	30%	27.0%	Leahy (2016, p. 20), Polek (2015), Sustainable Aviation UK (2016, p. 68), Boeing (2007)
SA	A321neoXLR	2023	200[T]			757-200	1983	200[T]	20%	17.0%	Airbus (2019b; 2019c), Boeing (2007), Airbus S.A.S. (2020b)
SA	B737MAX7	2021	153[T]	B737-700	1997	737 NG	1997 / 2014	128[T]		20 / 14%[28]	Boeing (2013; 2014; 2019a), improvement difference between early and late 737NG-models mostly dependent on winglets. Based on current fleet materiality, the winglet-equipped type is used as reference.
SA	B737MAX8	2017	178[T]	B737-800	1998			160[T]			
SA	B737MAX9	2018	193[T]	B737-900 / -ER	2001 / 07			177[T]			
SA	B737MAX10	2020	204[T]								
SMTA	A330-800	2020	250	A330-200	1998	A330-200	1998	246	14.2%[29]	12.6%	Fehrm (2017)
SMTA	A330-900	2018	294	A330-300	1994	A330-300	1994	290	14%	12.6%	Leahy (The A330neo - Powering into the future, p. 10)
SMTA	B787-8	2011	242[T]			767-300ER[30]	1988	261[T]	20%	27.3%	Boeing (The Boeing 767 Family; 787 Dreamliner; 2005; 2018), Trimble (2014), Norris (2012)
SMTA	B787-9	2014	290[T]			767-400ER (est.)	2000	296[T]	20%	22.0%	Boeing (The Boeing 767 Family; 787 Dreamliner; 2005; 2018), Russell (2018)
SMTA	B787-10	2018	330[T]						25%	13.5%	
LTA	A350-900	2015	314			777-200ER	1995	301	30%	25.7%	Leahy (2007, p. 26)
LTA	A350-1000	2018	369			777-300ER	2004	360	25%	22.5%	Hepher (2013)
LTA	B777-8	2024	355	B777-200 (ER / -LR)	1995 / 2006	777-200 ER / -LR	1995 / 2006	375 / 279	21.7% / 20.8%[31]	27.0% / 8.8%	Norris & Anselmo (2016), Boeing (777, n.d. - a; 1998; 2015) and Norris (2020)
LTA	B777-9	2021	395	B777-300 (ER)	1998 / 2004	777-300ER	2004	365	20%[32]	11.8%	Norris & Anselmo (2016), Hepher (2013) and Boeing (2009)

[27] Data from Broderick (2018), Miller (2019), SeatGuru (2020) comparing a 140-seat A220-300 with a 100-seat E190 and a 40% decrease in fuel burn per ASK yields a 0% improvement per flight. As such, the performance for the A220-300 is assumed identical to the A220-100, i.e. 6.8% per flight, and no information is provided regarding seats and the improvement per ASK.

[28] Given a 14 to 20% increase in fuel efficiency per ASK would be largely negated by the increased seat count, it is assumed these numbers hold per flight.

[29] Ferhm (2017) notes the seat mile fuel consumption of an A330-200 is 116.5% of that of an A330-800. As such, the A330-800 is (1 – 1/1.165) = 14.2% more efficient than the A330-200.

[30] The 20% fuel efficiency improvement realised by the 787-8 over the 767-300ER is with respect to a reference aircraft without retrofitted winglets (Trimble, 2014).

[31] Norris & Anselmo (2016) state the 777-8 is 13% more efficient than the 777-300ER, which is 10% more efficient than the 777-200ER. As such, the difference between the 777-200ER and the 777-8 is (1 – 0.87 × 0.90) = 21.7%. The 777-300ER is 9% more efficient than the 777-200LR, yielding a 777-8 performance improvement over the 777-200LR of (1 – 0.87 × 0.91) = 20.8%.

[32] Leeham News (2014) shows data from which the 777-9 (395 seats) can be derived to be 8.3% more efficient compared to a 777-300ER (configured with 344 seats). As this data is so different compared to other sources, this estimate is assumed to be erroneous and as such neglected.

with much better or worse performance is unlikely, as such types would face substantial competitive disadvantages in terms of acquisition and operational cost[33], respectively.

For the aircraft where no one-to-one replacement is identified this class-average improvement factor is applied to incorporate efficiency improvements for all aircraft types. In case these aircraft are older (and therefore generally less fuel efficient) than the reference aircraft with respect to which the fuel efficiency improvement of the average upcoming aircraft is expressed in Table 6, these figures might be under-estimating the improvement potential. An example would be the replacement of Boeing 747-400 aircraft (in the LTA class), which entered service in 1989 – prior to the EIS reference of 2001. For aircraft that entered service after the indicated EIS reference date (such as the Airbus A380), the opposite will be true, yielding an over-estimation of the improvement potential. Overall, these effects are estimated to nullify each other.

Table 6: Class-averaged fuel efficiency improvement potential and entry into service of upcoming aircraft classes with respect to average reference fleet at indicated year

Class (abbreviation)	Fuel efficiency improvement per ASK	Fuel efficiency improvement per flight	EIS (upcoming)	EIS (reference)
Regional (R)	27.0%	24.8%	2017	2004
Single aisle (SA)	[34]	14.8%	2018	2001
Small/medium twin aisle (SMTA)	18.6%	17.6%	2016	1996
Large twin aisle (LTA)	23.5%	19.2%	2020	2001

The higher improvement per flight in the regional class is caused by the fact that it includes the replacement of a jet (CRJ700) by a turboprop (ATR72) aircraft. Given the trend of 'classic' regional jets (such as the CRJ-series) to outgrow their class and move to the single aisle market, the implied assumption of a larger share of turboprops is deemed warranted.

Table 7 shows what portion of (2018) ASKs and CO_2 emissions is attributed to aircraft that do not have a one-to-one replacement as identified in Table 5, and which improvement potential is therefore modelled using the class-averaged data. These shares are fairly high in the twin aisle classes. In the small/medium class, this is due to the high materiality of Boeing 787 (which does not have an upcoming replacement) aircraft already in the fleet. In the large class, this is caused by Airbus A380 aircraft not having a direct replacement.

Table 7: Share of 2018 ASKs and CO_2 emissions for which potential improvements due to upcoming aircraft are modelled using class-averaged data. The remainder is modelled using the one-to-one replacements indicated in Table 5 ('legacy' replaced by 'upcoming').

Class (abbreviation)	Share of 2018 ASKs for which class-averaged data is used, per class	Share of 2018 CO_2 emissions for which class-averaged data is used, per class
Regional (R)	65.12%	62.13%
Single aisle (SA)	11.67%	13.88%
Small/medium twin aisle (SMTA)	42.65%	41.26%
Large twin aisle (LTA)	59.43%	65.69%

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[33] Although fuel(-related) costs can be expected to rise following increasing oil or carbon prices, this is not likely to dramatically influence the ratio of operating (including fuel-related costs) and non-operating cost (including acquisition cost or cost of ownership) in the timeframe where the upcoming aircraft are introduced into the fleet.
[34] Due to the calculation methodology and data base, no improvement figure per ASK is listed for the single aisle class. Further information is provided in Appendix B and footnote 28 on page 31.

3.3 Future technology

The previous section discussed the potential benefits of technological developments on upcoming aircraft. This section looks further ahead. As such, it also takes a somewhat more fundamental approach. Section 3.3.1 therefore starts with a thorough review of technological developments. Subsequent sections discuss how these technologies can be combined, what CO_2 reductions might thereby be realised and a notional timeline of possible entry into service of future concepts utilizing these technologies. Section 3.3.2 does so for aircraft powered by kerosene, either fossil-based or in the form of drop-in sustainable aviation fuels (discussed more extensively in Chapter 5), drawing from the recently proposed Partnership for Clean Aviation. Section 3.3.3 then looks at hydrogen-powered aircraft, based on the recent study by McKinsey & Company (2020), including aspects as hydrogen production, availability and cost.

3.3.1 Technological developments

Whereas in some studies historical fuel efficiency improvements have been analysed to project the average yearly fuel efficiency increase due to technology development, this study is taking an evidence-based approach, taking into account published global research and innovation programs, including European, national, and industrial programs. Many technological improvements of aircraft have been investigated in numerous research studies globally and in particular in European research and innovation programmes (Framework Programmes, Horizon2020, in particular Clean Sky 1 and 2), national programmes and regional initiatives. Some of these technologies have been incorporated in currently flying and upcoming aircraft, other technologies performed below initial expectations and therefore were not implemented. Many technologies are still being matured further, while still new technologies are invented. Together they provide valuable estimates about what future fuel efficiency improvements can be expected at aircraft level.

This study distinguishes between technologies with a major contribution to fuel efficiency and technologies with a minor contribution to fuel efficiency. The boundary value is set at an indicative fuel efficiency improvement of 5% with respect to current aircraft. Major technologies are drivers for the introduction of new generations and hence will be discussed in more detail. Minor technologies are important as well (as will be explained with a number of examples), but such technologies are not considered individually, because it is unclear which developments will make it to commercial programmes. Next, the integration of technologies in aircraft concepts is considered and how technologies taken into commercial aircraft programmes. Finally, major cross-links between the development of technologies for different aircraft categories are identified.

The list of technologies starts from the technologies in the technology overview in (IATA, 2013), which is also referenced in (IATA, 2020d). The reference (IATA, 2013) provides one of the most complete overviews of technologies with their fuel efficiency benefits that have been obtained with a single study approach. The list is extended with technologies that have been considered in aircraft concept studies (discussed later on), and has been further extended with some specific technologies. Some of these technologies were already partly mentioned as future concepts and technologies in (IATA, 2013); other technologies come from recent other developments that became known to the authors from literature study and/or were provided by ASD partners.

Technologies with major fuel efficiency improvements are mainly found in the following categories: propulsion architectures and the thermodynamic cycle, non-drop-in fuels and energy sources, wing and tail, and fuselage. These are treated next in further detail.

Major propulsion architectures and thermodynamic cycles

In the propulsion technologies a split is made between conventional jet fuel propulsion technologies and alternative fuel propulsion technologies. As these alternatives often include substantial changes to the aircraft configuration, they are also considered at that level rather than individually.

For jet fuel (conventional or drop-in) based engines, major fuel efficiency improvements are expected from ultra-high bypass ratio (UHBR) engines and from next generation concepts such as open rotor configurations, more radical thermodynamic cycle changes, and turbo-electric propulsion architectures. Radical thermodynamic cycle changes may include adaptive cycles to optimise the engine's behaviour over a larger design range, intercooled, recuperated bottoming cycle to re-use heat from the turbine, or composite cycles combining gas turbines with other engines such as a piston engine or a steam turbine.

Turbo-electric propulsion architectures are based on innovation in a number of technologies which need to be combined to obtain fuel efficiency gains. These technologies including high-power electrical generators, electrical motors for aircraft, high-power distribution system, and possibly distributed propulsion and boundary layer ingestion.

Some propulsion architecture changes can be considered as well in combination with relocation of the engines, for example open rotor tail installation and UHBR over wing or tail cone installation with boundary layer ingestion for reduced net fuselage drag.

Non-drop-in fuels and energy sources

Non-drop-in fuels and energy sources for aircraft and associated propulsion technologies are widely investigated. An important class of non-drop-in fuels are liquids and compressed gasses. Such non-drop-in fuels are used in aircraft engines that have been adapted for the fuel, such as discussed in Goldmann et al. (2018) or in fuel cell based propulsion systems.

Hydrogen especially has recently received increased attention, even though challenges remain. For once, it requires extreme cooling to become liquid, or significant compression to increase the energy density towards the energy density of current jet fuel. Both as liquid at cryogenic temperature and compressed (at 700 bar) the volumetric density of hydrogen is still less than one third of the energy density of jet fuel. As a larger fuel tank is needed to store the same amount of energy during flight, using hydrogen for aircraft propulsion requires changes to the aircraft architecture as well. Concept architectures discussed by McKinsey & Company (2020) as well as presented by Airbus (2020d) – the ZEROe concept aircraft – address this by stretching the fuselage[35] (for shorter-range aircraft) or moving towards hybrid or blended wing bodies (for longer-range aircraft), which increase the amount of fuselage volume available for energy storage. Moreover, not all challenges with respect to storing and distributing liquid hydrogen (LH_2) within the aircraft, combusting hydrogen in an efficient and low-NO_X manner, and refuelling infrastructure and technology have been addressed. Important advances are expected in the coming five to ten years (McKinsey & Company, 2020). Similarly, implications for airport infrastructure are currently being researched and clarified.

Another important class of non-drop-in energy sources is based on electricity, which, in many studies, is stored in batteries. Currently, however, the battery's low specific energy (or, equivalently, high weight) would be a major constraint to the use of batteries as an aviation fuel option. The specific energy is in the range of 200 Watt-hour per kilogramme, which is 60 times lower than jet fuel. Although improvements are expected (Warwick & Norris, 2020), this gap is not expected to be bridged soon. Volumetric energy density is also lower than for jet fuel, but of less concern than the gravimetric energy density. Another important constraint is the need to have specific power for a high discharge rate of the battery during certain flight phases (e.g., take-off). In current batteries, high power seems to

[35] Or, for a constant fuselage length, trading seating capacity for space for fuel tanks.

result mostly in low specific energy and vice versa. Battery improvements are being investigated for other sectors than aviation as well, although requirements are often different.

Fuel cells generate on-board electricity from hydrogen. Currently their specific power is 1-2 kW/kg for the core fuel cell stack, excluding additional components for cooling, compression and so on, which is limiting their application currently to demonstrators for very small aircraft. In case of other non-drop-in fuels, reformers may be used to generate the hydrogen on-board aircraft.

The mechanical propulsive power in propulsion concepts associated with electricity as energy source is provided by high power electric motors that drive propellers or ducted fans. The propulsors may be distributed on the wing and/or aft-fuselage, potentially using wing and/or fuselage boundary layer ingestion. Full-electric, battery-based, electric propulsion is emerging on the market for 2-seaters with a conventional aircraft architecture. Upscaling to higher power levels requires major developments in all components, as previously mentioned. In addition, the electrical power distribution system for the propulsive power needs to be developed for power values much higher than in present aircraft. This is similar to the electric part of turbo-electric architectures, mentioned before.

For large aircraft, hybrid-electric configurations have been studied and may provide environmental benefits in a shorter timeframe. A recent overview of electric and hybrid-electric concepts, designs and major design parameters is presented by Brelje & Martins (2019). In such configurations the thrust is provided by both thermal engines and electric motors.

When aircraft size and power requirements increase, the weight penalty associated to hybrid- and especially battery-electric systems grows. The same occurs for fuel cells, which at higher power output, require larger cooling systems which increase system weight. As such, for twin-aisle aircraft utilizing hydrogen, direct combustion is foreseen. For the single-aisle class of aircraft, configurations combining fuel cells with direct combustion are anticipated. This way, some of the benefits of fuel cell systems (increased reduction of climate impact thanks to zero NO_X-emissions, as well as reduced noise) can still be enjoyed in larger aircraft (McKinsey & Company, 2020).

Wing and tail

In the category of wing and tail technologies, major fuel efficiency improvements are expected from improved aerodynamics such as from natural laminar flow, hybrid laminar flow, and active flow control (e.g., the Clean Sky BLADE demonstrator (Clean Sky JU, 2018)). Each of these technologies can be applied to both wings and tails, whereby the wings contribute the largest portion to potential increases in fuel efficiency. In addition, high aspect ratio wing technology is expected to contribute to reduction of induced drag. For higher aspect ratio wings, load and flight control needs to be innovated, including movables and smart alternatives for movables. There is a whole range of technology concepts that have been investigated, including folded wing (to appear in the upcoming Boeing 777X) and morphing wing concepts, up to first studies on major configuration changes such as strut/truss-braced wings. Such technologies have shown to be enablers for wings with higher aspect ratios and increasing fuel efficiency. In these studies wing folding is an enabler for wing span extension, while satisfying airport constraints.

Major fuselage technologies

In the fuselage-category, major promising technologies for improvement of fuel efficiency are coming from the use of carbon fibre-reinforced plastic (CFRP) materials. Their application in fuselages started on Airbus A350 and Boeing 787. Further applications to other families can be expected in future. Also further innovations are being investigated based on innovative matrix materials in CFRPs enabling lighter designs and increased multi-functionality, with cabin, systems integration and flexible cargo/passenger concepts, as for example investigated in the Clean Sky 2 Joint Technical Programme (Clean Sky JU, 2015). Windowless cabins may be another contributor to fuel efficiency improvement on its own (due to weight reductions). Nevertheless, given the important effects on the passenger experience, weight-adding alternatives may have to be provided to compensate for the lack of windows, which in turn might counteract the fuel efficiency improvement.

Minor technologies and their relevance for fuel efficiency improvement

Technologies with minor fuel efficiency improvements are emerging for almost any part of component of future aircraft. Some of these minor technological improvements, as found in literature, are new materials, riblets, advanced wing and flight control technologies such as advanced wingtips, gapless movables, multi-functional structures, adaptive camber, span load control, manoeuvre load alleviation, active load alleviation, relaxed stability augmentation, advanced fly-by-wire (including fly-by-light), morphing wings, advanced landing gear (compact, faired undercarriage), and all-electric non-propulsive systems (such as flight control actuators, APU, etc.).

A feasible combination of several minor technologies may add up to a major reduction on aircraft level, if they do not counteract. In addition, some minor technologies are relevant enablers for the major efficiency improvements. This holds for example for many minor wing-related technologies, which contribute to the major wing concepts. For example, electric flight controls and actuators (from the all-electric non-propulsive systems) and multifunctional wing structures are potential weight-savers and therefore enablers for high aspect ratio wings. Some technological improvements with minor fuel efficiency improvement may be very relevant for other objectives, such as innovative cabin/cargo configurations (higher density/modular cabin and flexible passenger/cargo) for competitiveness. The aspect of combining technologies is further elaborated next.

Integration of technologies into aircraft concepts

Aircraft concepts are defined and evaluated to investigate the integration of technologies at aircraft level. Studies may concern conventional tube-wing-tail configurations or alternative configurations, such as box wing aircraft, C-wing aircraft, double bubble fuselage aircraft, and blended wing body aircraft. Examples are listed in Appendix D. In addition, integration of technologies have been demonstrated in large ground demonstrators, representative for sections/parts/systems of an aircraft and sometimes tested in wind tunnels with representative flight conditions. Furthermore the integration of technologies has been demonstrated as well in flight tests in existing aircraft or scaled flight demonstrators.

Introduction of future technologies on the market

After successful evaluation of technologies in aircraft integration studies, further steps have to be taken before the technology enters into service in airline fleets. Beneficial technologies may enter into service in different ways: as retrofit, into an existing product line from a particular point in time (product enhancements through performance improvement packages (PIPs) of technologies), into a new family member, a new family generation, or even a new family.

Economic, business and other factors are important drivers for decision-taking. Some technologies requiring smaller changes in certification and production may enter in a performance improvement programme. Other technologies require such large investments (in particular in modifications and related certification) that they are only taken into service through a new family member or generation.

In this report we can only sketch potentially successful directions of technological pathways for certain aircraft classes, without aiming to predict the future decision process of aircraft manufacturers, influenced by many external factors. In particular the timing of the start of commercial aircraft development programmes is sensitive. Nevertheless, technologies need to be sufficiently developed before they are taken into their final development towards entry-into-service in commercial aircraft development programmes. Timely technology readiness is needed to achieve the environmental benefits associated with the technologies, as well as to put a competitive aircraft on the market.

Introduction of future aircraft technologies on the market may also require changes elsewhere in aviation. In particular, changes in the on-board energy source for propulsion may require significant adjustments to the infrastructure at airports. It is important for airports to have visibility on such technologies and their estimated entry into service timelines as soon as possible, to be able to plan infrastructure development accordingly.

Technological pathways for the different aircraft categories and cross-links

Technological pathways may be different for the single aisle (SA), small/medium twin aisle (SMTA), and large twin aisle (LTA) classes of aircraft. However, for conventional configurations many future technologies are scalable for these various categories. Technology developments for one of the categories can often be re-used for the other categories. The benefits may be somewhat different, since the scaling is not always linear and the operational characteristics of the categories are different, such as the percentage of time that is spent in the different flight phases (e.g., cruise, climb, descent, ground).

In addition, some technologies may lead to small changes in operational characteristics (e.g., open rotor configurations may have a slightly lower cruise speed than current turbofans). In this report, for the evaluation of the impact on CO_2 emission, it is assumed that the future technologies will not significantly change the operational characteristics of aircraft and stay in line with the traffic scenario underlying this study. Some more disruptive system changes are qualitatively discussed in Chapter 7.

Technology pathways for aircraft technologies using non-drop-in fuels and energy sources for propulsion are quite different. Fully-electric and hybrid-electric battery-based aircraft are likely to become technologically feasible for aircraft with an increasing number of passengers and/or growing flight range as the specific energy of batteries increases. A similar reasoning applies for hydrogen-based fuel cell or hydrogen combustion technologies regarding specific power. This process therefore enables a learning curve towards the application of non-drop-in fuels and energy sources based technology in large(r) passenger aircraft. Introduction of these technologies for the largest aircraft and longest ranges is not expected before 2050.

For non-drop-in alternative liquids and compressed gasses as fuels, it is expected that novel aircraft architectures and designs are an important technological pathway. For such a radical change, efficiency and effectiveness of the technology development process from concept development to certification is an enormous challenge.

3.3.2 Kerosene-powered or (hybrid-)electric aircraft

The previous section reviewed and described individual as well as related technological developments that have the potential to contribute to substantial reductions in CO_2 emissions. This is done through the process of fleet replacement. This section shows how technologies are combined on modelled future kerosene-powered or (hybrid-) electric aircraft concepts in the different classes identified in Section 3.1. The modelling of estimated impacts and product availability is largely based on the proposed Clean Aviation programme (Clean Aviation Partnership, 2020), and supported by additional literature.

> **THE PROPOSED EUROPEAN PARTNERSHIP ON CLEAN AVIATION**
> The Clean Aviation Strategic Research and Innovation Agenda is a proposal to guide aircraft development in the upcoming Horizon Europe framework programme. It addresses all aircraft segments: the medium and long-range segments, that are currently the highest contributors to aviation carbon emissions, as well as short-range segments and mobility solutions, with a regional flying demonstrator and several ground demonstrators to test the maturity of hybrid-electric propulsion solutions. Specific markets in Europe, such as regional aviation, offer opportunities to develop, test and demonstrate hybrid, full-electric and hydrogen solutions. The experience gained in this market is anticipated to provide important insights for the electrification of larger aircraft in the longer term.

Entry into service (EIS) dates are based on historical trends. Table 5 shows that new SA, SMTA, and LTA aircraft generations have entered into service about 20 to 25 years after their preceding generations. This corresponds well with the average age at which airframes are withdrawn from service, noted in Section 8.1 to be 22.5 years. The modelling of future aircraft types does not distinguish between different sub-types (with different seating capacities and/or flight ranges) within each family. Similarly, EIS dates are nominal estimates: some types might arrive in the market slightly earlier, whereas others arrive slightly later. This is assumed not to affect overall modelling. Fleet replacement itself – governed by the aforementioned decommissioning age of 22.5 years – happens gradually, such that the fleet at all times consists of a mix of aircraft of different ages of older and newer types and variants.

For the different classes of aircraft, the remainder of this section discusses applicable technologies, entry into service dates and the estimated fuel efficiency improvement, compared to the upcoming class of aircraft discussed in Section 3.2. It is important to stress the fuel efficiency improvement solely includes an estimated reduction in the energy used by an aircraft. As compatibility with 100% drop-in sustainable aviation fuels is assumed, the potential CO_2 reduction can be higher. That part of the possible emissions reduction is accounted for in Chapter 5[36].

Single aisle (SA)

As seen in Table 5, the latest introduction of families have been the Airbus A320neo in 2016 (start of replacing A319/A320/A321 with EIS 1996/1988/1994) and the Boeing 737MAX in 2018 (start of replacing B737-700/800/900/900ER with EIS 1997/1998/2001/2007). Again taking 20 years to the next family, the introduction of a new SA family generation is therefore modelled to be in 2035.

For this generation advances are modelled both in aircraft configuration and in aircraft engines, leading to an ultra-efficient aircraft configuration with ultra-high bypass engines, possibly open rotor. A conventional tube-wing-tail configuration is assumed that employs major technologies with laminar, high aspect ratio and laminar wing, laminar tail, and lighter (e.g. advanced carbon fibre reinforced) fuselage with integrated modular cabin and passenger/cargo flexibility, and thereby reduced fuel burn and CO_2 emissions. Current UHBR architectures are assumed to be further improved and optimised for a range of conditions through geometry variations, as well as more efficient electricity generation. This would contribute to a fuel efficiency improvement of 30%, as specified in Table 8.

Table 8: Modelled fuel efficiencies for future generation SA, SMTA and LTA aircraft, with respect to upcoming generation

Technology SA/SMTA/LTA	Potential fuel efficiency improvement per flight	Remarks
Major propulsion technology (integrated)	18%	Upcoming UltraFan[37] and further cycle improvements
Major airframe technology	15%	Wing technology: about 9%, based on NLF (Goold, 2018); high aspect ratio wing and combined with (hybrid-)laminar flow technologies and other technologies (Liu, Elham, Horst, & Hepperle, 2018). Tail technology: about 1% (EC, 2019f; Clean Sky JU, n.d.) Fuselage technology: about 6% (Large Passenger Aircraft Platform 2 in Clean Sky JU, 2015)
Total (multiplicative)	**30%[38]**	

[36] Future aircraft in the 'small' class form an exception to this (accounting) rule.

[37] Rolls Royce estimates its upcoming UltraFan, aiming for a bypass ratio of 15, to deliver a 25% fuel burn reduction compared to first-generation Trent-powerplants with demonstration in 2025 (Norris, 2014; Thisdell, 2019; AIN Online, 2019). The fuel burn reduction of the Trent XWB with respect to the original Trent engine is 15%. Hence the benefit of the upcoming Ultrafan is about 10 to 15% with respect to the Trent XWB, powering the Airbus A350.

[38] As an example of the total (multiplicative) computation: here it has been computed as 1 - [(100-18) × (100-15) / (100 × 100) × 100%], representing consecutive reductions.

Small/medium twin aisle (SMTA)

The latest upcoming SMTA aircraft families introduced have been the Airbus A330-800/900 family (in 2020 and 2018) replacing the Airbus A330-200/300 (with EIS in 1998, 1994), as well as the introduction of the Boeing 787-8/9/10 (in 2011, 2014 and 2018). Introduction of the new families is therefore expected between 2031 and 2040, leading to a modelled EIS in 2035.

The assumptions for technology deployment and subsequent 30% fuel efficiency improvement on this generation of SMTA aircraft are identical to the assumptions for the SA model. This is further detailed in Table 8.

Large twin aisle (LTA)

Latest introduction of families have been the Airbus A350 family (in 2015 and 2018) and the Boeing 777X family with the B777-8/9 (expected in 2023 and 2021) replacing the Boeing 777-200ER/-300ER (EIS 1997 and 2004). Entry into service of a future LTA-family is therefore modelled in 2040.

For this generation advances are modelled both in aircraft configuration and in propulsion, leading to an ultra-efficient aircraft configuration with ultra-efficient propulsion, with optimised airframe integration. It is assumed that the engine are compatible with 100% drop-in fuel. More specifically, major fuel efficiency improvements like hybrid-laminar high aspect ratio wing, hybrid-laminar tail, further radical improvements to the UHBR engines, hybridisation of APU functions, and further advanced carbon fibre reinforced fuselage with integrated modular cabin and passenger/cargo flexibility are assumed.

Even though the technology is slightly different (e.g. hybrid-laminar rather than natural laminar flow technology), the same fuel efficiency improvement as for the SA and SMTA models. Besides the technological differences it is taken into account that the EIS of LTA is 5 years later than the EIS for SA/SMTA, which allows for further technology development fully directed towards LTA, taking on the lessons learned from the SA/SMTA development. Overall it is therefore expected that the fuel efficiency improvement of 30% (following Table 8) at aircraft level can also be obtained for LTA.

Regional (R)

Aligned with industry statements made in press and industry reports (Warwick, 2019b; ERA, 2020) it is modelled that hybrid-electric, distributed propulsion can be advanced to enter into service in 2035. This disruptive step in propulsion is assumed to be integrated into a highly efficient aircraft configuration.

More specifically, it is assumed that the hybrid-electric, distributed propulsion is based on parallel hybrid engine architecture. The thermal engines are sized optimally for cruise condition with batteries supplying additional power to cover the peak power loads. This is a common hybrid electric architecture (e.g. Zill, et al., 2020). Additional propulsion units are located at the wing tips. The airframe architecture includes an unswept, high aspect ratio wing, the landing gear is fuselage mounted, and a V-tail is introduced, as in the PHA2-TipProp configuration in Strack, Chiozzotto, Iwanizki, Plohr & Kuhn (2017), which is the most efficient configuration among many configurations studied in this paper.

In terms of fuel efficiency improvement, Strack, Chiozzotto, Iwanizki, Plohr & Kuhn (2017), show a 40% reduction by a turbo-electric turboprop aircraft with electrically driven propellers at the wing tips (a so-called TipProp configuration), a design: range of about 1500 kilometres and a seating capacity of 70 passengers achieves, compared to technology introduced into service in 2000. The reference turboprop aircraft has length of 27 metres, which is similar to the length of the 70-seater aircraft ATR-72. The reduction of fuel efficiency due to airframe improvements is 12%; the reduction of fuel efficiency due to engine improvements is 32%. The latest ATR-72 entered into service in 2011, with improved engine technology with respect to the preceding ATR-72 version equipped with EIS 2000 technology.

Assuming a 5% improvement from 2000 to 2011, the fuel efficiency of the TipProp configuration with respect a modern turboprop aircraft is 37%. Noting the increased fuel efficiency of turboprop aircraft compared to regional jets (ATR, 2018; Babikian, Lukachko, & Waitz, 2002; Ryerson & Hansen, 2010), of which the latter currently have a 45% market share in terms of flights, a total fuel efficiency improvement of 50% is deemed achievable for the TipProp configuration with respect to regional jets, consistent with the Clean Aviation Partnership (2020). Alternatively, if payload capacity and/or range of this configuration are reduced (currently, 94% of the flights operated by aircraft in the regional class is shorter than 1000 kilometres), larger reductions in fuel burn may be realised, for example due to additional benefits of hybrid-electric propulsion. On the other hand, efficiency improvements might be slightly smaller for regional aircraft seating more than 70 passengers. As such, a 50% fuel efficiency improvement is modelled for the entire class.

Table 9: Modelled fuel efficiencies for future generation Regional aircraft, with respect to upcoming generation

Technology Regional	Potential fuel efficiency improvement per flight	Remarks
Major propulsion technology (integrated)	41%	Hybrid-electric turboprop (ATR, 2018; Babikian, Lukachko, & Waitz, 2002; Ryerson & Hansen, 2010) using a TipProp configuration (Strack, Chiozzotto, Iwanizki, Plohr, & Kuhn, 2017)
Major airframe technology	15%	
Total (multiplicative)	**50%**	

Small (S)

These aircraft are modelled to use full electric concepts using propulsion based on hydrogen fuel cells, augmented with advanced batteries. The larger and/or earliest aircraft in this class are assumed to use hybrid-electric technology and bi-fuel concepts, allowing to switch between fuels.

The efficiency improvements anticipated in the regional class (50% lower fuel burn) from 2035 are foreseen to reach possible conventionally powered (i.e. kerosene or drop-in SAF) aircraft in the smaller class five years earlier, in 2030. Nevertheless, it is all but certain that a future generation small aircraft will draw its energy from (fossil or sustainable) kerosene. A wide array of aircraft and propulsion concepts are currently being designed or developed for market entry in the small class in the coming decade (ERA, 2020; McKinsey & Company, 2020), and many of the aircraft and propulsion concepts for small aircraft put less stringent weight-related requirements on the technologies for the smaller aircraft in the category than for larger aircraft. Such small aircraft developments may also become drivers for the regional aircraft development later on.

Due to the impact of energy source on aircraft weight and total energy requirement, it is not possible to compare the fuel (or: energy) efficiency of these alternatively-powered aircraft with current or upcoming models. Because of this, the 99% reduction in CO_2 emissions is modelled, to be achieved regardless of exact technology and fuel source. A figure of 99% is used as it provides an achievable CO_2 reduction potential, even if future small aircraft will be kerosene-based. It is found by combining the 50% lower fuel burn (from the regional class) with 95 to 100% lower life-cycle emissions of SAF in 2050[39] (determined in Table 30 in Section 5.8.2). This introduced a small accounting inconsistency, as the entire improvement is accounted for in the technology-pillar, even though some of this reduction in CO_2 emissions is attributable to alternative energy sources. Given the low contributions of small aircraft to CO_2 emissions (≈ 1 %), it is considered immaterial. For that same reason, the slightly more simplistic modelling approach (compared to regional and larger aircraft) is deemed sufficiently accurate.

[39] As the future small aircraft will be modelled to enter into service in 2030, its fleet materiality in that year will be low. Considering the fact that after 2030, the results are only modelled in the horizon year 2050, the life-cycle emissions of SAF in 2050 are deemed relevant.

Table 10: Modelled reduction of emission for future generation Small aircraft, with respect to upcoming generation

Technology Small	Potential reduction of CO_2 emissions per flight	Remarks
Total	99%	Numerous feasible propulsion technology options (e.g. hybrid-electric, bi-fuel, hydrogen fuel cells and/or advanced batteries). Energy-source independent estimate for *CO_2 emissions* reduction potential, based on conventionally powered aircraft (energy efficiency improvement as for regional class, but entering into service five years prior) and SAF (based on Section 5.8.2).

3.3.3 Hydrogen-powered aircraft

In addition to the kerosene-powered aircraft modelled in Section 3.3.2, possibly operated with substantial amounts of SAF as discussed in Chapter 5, hydrogen-powered aircraft form another pathway to reducing CO_2 emissions. As these aircraft do not combust hydrocarbons, they do not emit CO_2 at all.

This section goes into further detail. Section 3.3.3.1 defines the aircraft modelling parameters and discusses energy demand. The associated supply of hydrogen is analysed in Section 3.3.3.2. Last, Section 3.3.3.3 discusses cost implications – of both technology as well as energy supply.

3.3.3.1 Aircraft modelling

Fitting with renewed interest form both the aeronautical community as well as the energy industry, and largely based on the aforementioned study into hydrogen-powered aviation conducted by McKinsey & Company (2020), a single aisle (hybrid-) hydrogen-powered aircraft, capable of transporting 165 passengers over a range of 2000 kilometres[40], is modelled for entry into service by 2035. This timeframe is consistent with the recently published Sustainable and Smart Mobility Strategy (2020i).

In the modelling, its operational use is limited to intra-European flights below 2000 kilometres. Besides respecting the range limitations of the aircraft, this also acknowledges that hydrogen availability and supporting infrastructure might not be available outside the EU+ to the extent it is estimated to be inside the EU+.

> **HYDROGEN-POWERED AVIATION IN OTHER CLASSES**
> In addition to the potential for hydrogen-powered aircraft in the single aisle class, McKinsey & Company (2020) note possibilities in other market segments – ranging from smaller commuter aircraft to large twin-aisle aircraft. For numerous reasons, these are not modelled in this study[41].
>
> For the larger aircraft classes, modelling by McKinsey & Company shows increased energy consumption and a higher cost per available seat kilometre (compared to reference aircraft powered by sustainable aviation fuel). Both are trends in the wrong direction. In addition, using hydrogen-powered aircraft for long-haul routes requires hydrogen availability and associated infrastructure around the world. Non-European studies that foresee the introduction of hydrogen in aviation substantially later (after 2050) show this global availability might not be realistic (Bruce, et al., 2020).

[40] In September 2020, Airbus (2020c) revealed three zero-emission concept aircraft that use hydrogen as an energy source. This set includes a turbofan design capable of transporting 120 to 200 passengers over a range of more than 2000 nautical miles (over 3500 kilometres). As detailed information about this concept, to the extent documented by McKinsey & Company (2020) is not publicly available, the latter concept is used as basis for the modelling performed in this study.
[41] Notwithstanding the facts presented and reiterating the substantial amount of uncertainty associated to estimating (especially longer-term) technology development, the possibility of the introduction of hydrogen-powered aircraft in other classes is acknowledged.

> That reasoning also partially applies to the aircraft in the smaller classes, often used to connect smaller airports, towns and cities. Investments in infrastructure and fuel supply are likely to weigh heavier on smaller airports. Furthermore, due to the lower share of CO_2 emissions these aircraft contribute to (as shown in Section 3.1) and other decarbonization opportunities (e.g. hybrid-electric propulsion), the introduction of a hydrogen-powered aircraft is considered here most likely for single-aisle aircraft.

Energy demand

The total demand for energy – in the form of liquid hydrogen – is computed by evaluating the energy efficiency improvement compared to upcoming aircraft in the SA-class. For a 165-passenger mission of 2000 kilometres, McKinsey & Company (2020) anticipate an energy demand of approximately 48 MWh[42]. For an upcoming SA-aircraft, which is used as reference for the future generation, the energy demand on a similar mission is estimated at about 75 MWh, yielding a difference of approximately 35%. This is slightly higher (7%, multiplicative) than estimates by McKinsey & Company (2020), who note a 4% reduction in energy demand. This difference is partially explained by possible uncertainties in the data retrieved from that study (notably with respect to the reference aircraft) and the slightly reduced cruise Mach number[43] of the hydrogen-concept proposed by McKinsey & Company.

> **A NOTE ON ENERGY DENSITIES**
> The energy demand comparison in this section is expressed in units of energy (megawatt hour) rather than units of mass (such as kilogrammes or tonnes). This is due to the fact that for each kilogramme, liquid hydrogen has 2.8 times the energy content of a kilogramme of kerosene.

Taking the aforementioned energy efficiency improvement of 35% into account, the total energy demand for flights in the market segment in which the hydrogen-SA aircraft is modelled (intra-EU+ flights below 2000 kilometres) is computed to be 3.7 Mt of liquid hydrogen in 2050.

3.3.3.2 Hydrogen availability

Even though the future hydrogen-SA is modelled to enter into service in 2035, the availability of hydrogen is assessed for both 2030 and 2050 based on multiple sources. This combination of assessments provides information about the likely availability of hydrogen in 2035. Furthermore, this provides input to Chapter 5, in which hydrogen is used as a feedstock for the production of synthetic sustainable aviation fuels through the power-to-liquid process.

> **HYDROGEN PRODUCTION PATHWAYS**
> Most hydrogen today is produced through steam methane reforming. This process is based on fossil feedstocks and therefore not renewable. Efforts to switch to green hydrogen are observed in various States, although development will require further time and effort. Of multiple renewable pathways, electrolysis is most relevant, as it shows the largest potential of industrialisation.
>
> Electrolysis breaks down water into hydrogen and oxygen by electricity. Electrolysers consist of an anode and a cathode separated by an electrolyte. Four main types of electrolysers can be identified: Alkaline Electrolysis (AE), Proton Exchange Membrane Electrolysis (PEM), Anion Exchange Membrane Electrolysis (AEM) and Solid Oxide Electrolysis (SOE). Alkaline electrolysis has low installation costs, is commercially available, and has long life span, but requires high maintenance and is not flexible with variable input power (Khalilpo, 2019). Proton Exchange Membrane Electrolysis is flexible with input power, but has a short life span and is only seeing initial commercial application.

All studies referred to here, produce hydrogen through electrolysis using renewable electricity.

2030

“A hydrogen strategy for a climate-neutral Europe” by the EC sets out a strategic objective for the production of hydrogen in the EU (EC, 2020b) and the study “Opportunities arising from the inclusion of Hydrogen Energy

[42] Based on a tank weight of 4 tonnes, a gravimetry index of 35% and an energy density of LH_2 of 34 kWh per kilogramme (4 × 0.35 × 34 = 47.6 MWh).
[43] McKinsey & Company (2020) foresees a cruise Mach number of 0.72, whereas current aircraft in the SA class generally cruise around Mach 0.78.

Technologies in the National Energy & Climate Plans" (Trinomics, 2020) commissioned by the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) estimates the amount of hydrogen demand based on a low and high scenario analysis. Both do so for 2030.

EC (2020b) sets out a strategic objective to produce 10 Mt (equal to 333 TWh) of renewable hydrogen[44] in the EU by 2030. The EC plans are backed-up by the plans laid out by Hydrogen Europe, an industry initiative, which presented the vision to install 40 GW of electrolyser capacity in the EU and 40 GW in North Africa and Ukraine by 2030[45]. Van Wijk & Chatzimarkakis (2020) foresee an infrastructure connection with North Africa and Ukraine to import around 3 Mt of renewable hydrogen by pipeline[46]. EC (2018c, p. 87) highlights that "hydrogen and e-fuels could actually be globally traded commodities and imported from regions with comparatively cheaper, abundant renewables". At the same time however, the EU aims to increase its energy independence.

The strategic objective by the EC (2020b) foresees that in total 13 Mt of renewable hydrogen is available based on EU production in combination with imports. This hydrogen can be used by industry, transport, power and buildings sectors. Division between sectors is not specified in the EC strategy. On the other hand, Trinomics (2020) estimates renewable hydrogen demand in 2030 will range between 24 TWh_{H2} per year in the low scenario and almost 106 TWh_{H2} per year in a high scenario. This would be equal to a range between 0.7 Mt and 3.2 Mt. Both scenarios assume the hydrogen is produced in the EU: no imports are considered.

The two studies show that there is a substantial difference between the strategic objective set out by the EU (13 Mt) and the estimated demand based on the FCH 2 JU study (1.9 Mt on average). The amount of hydrogen produced in the EU used in the modelling is calculated as the average of these two figures (5.95 Mt). In order to ensure a consistent ambition level with respect to the amount of hydrogen available for import, the aforementioned 3 Mt is scaled by that same factor[47] to arrive at 1.8 Mt. This leads to a total hydrogen availability of 7.8 Mt in 2030.

The amount of hydrogen available for aviation is estimated by first considering the share allocated to transport and then by further specifying the share for aviation. Trinomics (2020) estimates the share for transport will lie between 30 and 43% in 2030 with aviation using between 11 and 35% of this amount. By taking the averages of these ranges the total amount available for aviation would be 8% in 2030, equal to 0.65 Mt.

2050

According to the study "Opportunities arising from the inclusion of Hydrogen Energy Technologies in the National Energy & Climate Plans" commissioned by the FCH 2 JU (Trinomics, 2020), the 1.5 LIFE and 1.5 TECH scenarios assume a hydrogen consumption of 68 to 76 Mt in 2050. According to the ASSET-study "Hydrogen generation in Europe-Overview of costs and key benefits" for the EC (Cihlar, et al., 2020), hydrogen production could range between 20 and 120 Mt in 2050. The higher value would correspond to 500 GW of electrolyser capacity.

Averaging both sources, the amount of renewable hydrogen produced in the EU is estimated at 71 Mt in 2050. The share of imported hydrogen is assumed to remain constant between 2030 and 2050. The amount is therefore scaled up based on the increase in EU production. This would result in 21 Mt of imported hydrogen (23% of total). By 2050, 92 Mt of hydrogen are therefore available based on EU production and imports combined.

[44] This would be achieved by directly connecting renewable electricity to the electrolysers, or by ensuring that certain conditions are met, including the additionality of the renewable electricity used.
[45] The Hydrogen Europe paper differs from the EC vision in the amount of hydrogen produced in the EU based on the installed electrolyser capacity, it assumes that 4.4 Mt (equal to 173 TWh) can be produced based on the 40 GW electrolyser capacity.
[46] Of the 40 GW of capacity installed in North Africa and Ukraine, 32.5 GW would be built for the export market.
[47] 5.95 / 10, or 59.5%.

The 1.5 LIFE and 1.5 TECH scenarios presented by Trinomics (2020) assume that the transport sector will consume between 38% and 42% of the total amount of hydrogen. On average this would result in 40% of the hydrogen being allocated to the transport sector by 2050. Assuming the hydrogen will be equally divided between road, maritime and aviation, it would lead to 13% being delivered to aviation, equal to 12.3 Mt.

3.3.3.3 Cost implications

The cost implications of a hydrogen-powered aircraft materialise in two ways. First, there is the cost of hydrogen itself. Second, there are cost impacts that follow from the characteristics of the hydrogen-SA aircraft as modelled in this study. Based on the combination of these two, the CO_2 abatement cost of the hydrogen-SA aircraft can be computed.

Hydrogen production cost

The expected production costs of renewable hydrogen including liquefaction, based on a number of sources, are shown in Table 11. Costs strongly depend on renewable electricity prices. As the data shows, prices are generally expected to reduce over time.

Producing hydrogen outside of Europe, where renewable energy is available at lower prices, may significantly lower the costs. To produce large amounts of hydrogen for fuel, the renewable electricity should come for additional installations specifically built to supply fuel factories. The prices will vary depending on the type of installation and the geographical location.

Table 11: Renewable liquid hydrogen minimum selling prices based on multiple sources in 2030 and 2050

Year	Source	Scope	Production cost of renewable LH_2 (€/kg)
2030	Trinomics (2020)	EU	5.5
2030	McKinsey & Company (2020)	EU	3.1
2030	McKinsey & Company (2020)	import	2.8
2030	Van Wijk & Chatzimarkakis (2020)	EU + import	2.2
2050	McKinsey & Company (2020)	EU	2.0
2050	McKinsey & Company (2020)	import	1.8
2050	Van Wijk & Chatzimarkakis (2020)	EU + import	1.8
2050	International Energy Agency (2020)	Global	2.7

The minimum selling price of liquid hydrogen is 2050 is estimated based on the production costs given by the three sources in Table 11. Averaging the cost of hydrogen produced in the EU (taking up a share of 85%) and imported from McKinsey & Company (2020), EU-produced and imported hydrogen (from van Wijk & Chatzimarkakis, 2020) and globally-produced hydrogen (International Energy Agency, 2020), an average price of € 2200 per tonne in 2050 is determined[48]. The production process for renewable hydrogen is assumed fully carbon neutral by 2050.

Technology cost

Explicitly associated to the switch to hydrogen technology, McKinsey & Company (2020) foresee a 31% increase in aircraft capital expenditure (cost of the tank structure, fuel distribution and larger fuselage) and 47% increase in maintenance cost (due to the larger fuselage). Longer refuelling times are likely to cause 7% less flight cycles. In addition, the reduced seating capacity (165) compared to the average capacity of SA-aircraft operating flights below

[48] It should be noted that large investments in new infrastructure are needed, such as refuelling trucks, ships or pipeline including on-site liquefaction facilities or on-site production and storage of liquid hydrogen.

2000 kilometres (187, based on year 2050) decreases productivity[49] by approximately 12%. As the aircraft is modelled to be used on shorter flights, the slightly lower cruise speed (Mach 0.72 versus Mach 0.78), is not estimated to have a material effect on productivity. The combined decrease in productivity is 18%.

Using the average cost per available seat kilometre of current single aisle aircraft (Airbus A320 and Boeing 737 Next Generation) reported to the IATA Aircraft Cost Management Group as baseline (IATA, 2019b), Table 12 shows how the aforementioned cost increases for the hydrogen-SA in different steps. First, changes in CAPEX, MRO and (lower) productivity yield an increase of 1.3 cents per ASK, or 26%. Second, including the costs associated to switching the energy carrier from kerosene to LH_2 yield a further increase of 14%, following from the price difference between liquid hydrogen and fossil kerosene (€ 2200 versus € 690 per tonne) and the higher energy density of liquid hydrogen (120 MJ/kg LHV versus 43 MJ/kg)[50]. The multiplicative cost change is then determined to be slightly above 1.6 cents per ASK, equivalent to 31% of reference CASK.

Table 12: Cost per available seat kilometre for hydrogen-SA, excluding and including the influence of energy carrier (2050 LH_2 prices) on fuel and oil cost (based on McKinsey & Company, 2020; IATA, 2019b; van Wijk & Chatzimarkakis, 2020; International Energy Agency, 2020)

CASK-factor	Current CASK (737NG / A320)	Changes due to		Hydrogen-SA CASK, excl. LH_2	Changes due to energy carrier (LH_2)	Hydrogen-SA CASK, incl. LH_2
		CAPEX and MRO	Productivity			
Fuel and Oil	€ 0.0194			€ 0.0194	+ 14 % (€ 0.0027)	€ 0.0221
Aircraft Ownership	€ 0.0092	+ 31% (€0.0029)	+ 18% (€ 0.0022)	€ 0.0143		€ 0.0143
Maintenance and Overhaul	€ 0.0083	+ 47% (€0.0039)	+ 18% (€ 0.0022)	€ 0.0145		€ 0.0145
Flight Deck Crew	€ 0.0057		+ 18% (€ 0.0010)	€ 0.0067		€ 0.0067
Flight Equipment Insurance	€ 0.0001		+ 18% (€ 0.0000)	€ 0.0001		€ 0.0001
Air Navigation Charges	€ 0.0027		+ 18% (€ 0.0005)	€ 0.0032		€ 0.0032
Airport Charges	€ 0.0042		+ 18% (€ 0.0007)	€ 0.0049		€ 0.0049
Station and Ground	€ 0.0031			€ 0.0031		€ 0.0031
Total	**€ 0.0527**			**€ 0.0661**		**€ 0.0688**
Difference				+ € 0.0134 (+ 26%)		+ € 0.0162 (+ 31%)

CO2 abatement cost

Based on the cost difference per ASK (from Table 12) and CO_2 emissions per ASK for the relevant market segment and timeframe (intra-EU+ flights below 2000 kilometres in 2050; 72 gram) the CO_2 abatement cost of hydrogen as used in this study is estimated here to be equal to approximately € 225 per tonne[51].

[49] Productivity refers to the amount of 'product' that is produced by an aircraft per unit of time. This is customarily expressed in seat-kilometres per unit of time, and hence a product of seating capacity and speed.
[50] This means that the energy content of one tonne of kerosene in LH_2 form costs €2200 × 120/43 = €790.
[51] With 72 gCO_2/ASK, 'producing' one tonne of CO_2 requires 1000 / 0.072 = 13,900 ASK. Multiplied with the cost differences yields 13,900 × €0.0162 = €225.

3.3.4 Potential impact overview

Whereas Table 5 presented the potential impact of specific upcoming aircraft types and Table 6 detailed this information at a class-level, Table 13 shows the potential impact of future aircraft. This table combines previously presented information in Section 3.3. The overview shows substantial fuel efficiency improvements and CO_2 emissions reduction to be delivered by aircraft modelled to first enter into service between 2030 and 2040.

> **'Beyond future' aircraft**
> If research and innovation in technology and aircraft development will continue, the second half of this century will see the introduction of even more advanced 'beyond future' types. These will someday replace the aircraft modelled in this section. As this study investigates CO_2 emission reductions in 2030 and 2050, such aircraft types are however not treated in this report: given the 20 to 25 year production cycles identified earlier would mean that such 'beyond future' aircraft would enter into service between 2050 and 2065 and thereby would not be able to affect 2050 CO_2 emissions.
>
> Fleet replacement – through which new technologies are brought into operational use – will of course continue in the years following initial entry into service. As such, new aircraft are delivered each year, realising further fuel efficiency improvements and emission reductions.

As stated in the introduction to Section 3.3.2, this chapter primarily investigates technologically-driven improvements in fuel efficiency (i.e., reductions in energy demand). These are expressed relative to the performance of upcoming aircraft (presented in Section 3.2). The use of SAF, discussed in Chapter 5, can yield further CO_2 emissions reduction. This also means that the potential additional SAF-related emissions saving is accounted for under the SAF-pillar.

The aircraft in the small class as well as the hydrogen-SA form an exception to this rule. As the fuel efficiency improvement is unsure due to its dependency on the technology pathway (in case of the small aircraft, further explained in Section 3.3.2) or the technology necessitates the use of non-fossil fuels (in case of the hydrogen-SA), Table 13 reports the full CO_2 emissions reduction potential. These savings are therefore also accounted for in the aircraft and engine technology pillar.

Table 13: Estimates on future aircraft technologies, EIS, energy efficiency improvement (per flight) and CO_2 emissions reduction (per flight) for impact modelling. Effects of alternative energy sources only included for 'Small' and 'Hydrogen-SA' aircraft. Further CO_2 emissions reduction for other classes, based on the use of drop-in SAF, is treated in Chapter 5.

Class	EIS	Major technologies	Energy efficiency improvement	CO_2 emissions reduction	Remarks
Small (S)	2030	Hybrid-electric and bi-fuel concepts. Possible full electric propulsion concepts based on hydrogen fuel cells and/or advanced batteries.	N.A.	99%	
Regional (R)	2035	Hybrid-electric, distributed propulsion coupled with highly efficient aircraft configuration	50%	50% (excl. reduction due to drop-in SAF)	
SA	2035	Advanced ultra-efficient aircraft configuration and ultra-efficient thermal engines, ultra-high bypass (possibly open rotor)	30%	30% (excl. reduction due to drop-in SAF)	

Class	EIS	Major technologies	Energy efficiency improvement	CO_2 emissions reduction	Remarks
Hydrogen-SA	2035	High-efficient hydrogen(-hybrid)	35%	100%	165 passengers, 2000 km range, 31% higher CASK (excl. LH_2-cost).
SMTA	2035	Advanced ultra-efficient aircraft configuration and ultra-efficient thermal engines, ultra-high bypass (possibly open rotor)	30%	30% (excl. reduction due to drop-in SAF)	
LTA	2040	Advanced ultra-efficient aircraft configuration, ultra-efficient propulsion using drop-in SAF with optimised airframe integration, hybrid APU.	30%	30% (excl. reduction due to drop-in SAF)	

3.4 Drivers and barriers

Following the industry characteristics discussed in Section 1.1 and various remarks on technology development in the previous section, the present treats some of the important drivers and barriers influencing the development and adoption of new aircraft technology.

3.4.1 Drivers

An increased focus on reducing fuel consumption and environmental impacts is an important driver. The fact that fuel-burn reducing technologies generally also yield reductions in operating costs supports this driver from a more business-oriented perspective.

Strong focus on research and innovation

Europe has a strong collaboration network in research and innovation, also towards high technology readiness levels. In various past and current programmes, projects aim to develop innovative technologies for improving performance – notably in terms of fuel efficiency. Technologies developed in Clean Sky and Clean Sky 2, for example, provide a solid basis for maturation, integration and further expansion for focused needs not covered yet. As such programmes reduce the risk of technology development, they increase the speed of research and innovation and help to rapidly get technology to the market. This provides a firm basis for the challenges ahead.

The higher TRL research and development is supported by a more fundamental research infrastructure. Numerous facilities and methods are available across Europe in which new technologies can be assessed and optimised at affordable cost as well as demonstrated – if the technologies reach that stage. This includes low and high fidelity simulation, multidisciplinary analysis and optimisation, ground testing, large-scale integrated ground test demonstrators, and scaled as well as full-scale flight testing.

The recently proposed European Partnership for Clean Aviation encompasses the entire aforementioned infrastructure and orients it towards the development of the aircraft and engine technologies required for decarbonising aviation. Its timeline – delivering the results in 2027 – aligns very well with the anticipated entry-into-service dates of the aircraft modelled in this study. This is a major driver towards quick adoption of the latest available innovations.

Cross-pollination inside and out

The fact that aircraft of different weight and size classes are able to share technologies is a major driver. It both reduces development risk – as investments can be recuperated over a larger number of products – and enables simultaneous innovation on multiple fronts. Even if particular technologies are not directly interchangeable, knowledge gained during development of one such technology supports the development of others.

In addition to cross-links between developments for different aircraft families, aviation can benefit from developments elsewhere. Emerging technologies in other sectors such as sustainable fuels, battery technology, fuel cell technology, and hydrogen technology have large potential for reduction of emissions in these other sectors, with hydrogen even offering zero carbon emission during flight. Driving forces in these sectors are also driving towards their application in aircraft, keeping in mind that the aircraft requirements typically are quite different and more challenging (for example, electric batteries used in road vehicles might be too heavy for direct use in aircraft propulsion). It undeniably stimulates R&D in these areas.

Potential first mover advantage

Tightly linked to the Partnership for Clean Aviation mentioned before, Europe and its aviation industry are seen to be well-equipped to take the lead in the development of more efficient aircraft. When the focus on decarbonisation increases in other parts of the world, this leading position presents a major competitive advantage for European manufacturers and supporting value chains.

Ambitious European hydrogen strategy

The ambitious European hydrogen strategy is a key factor enabling the introduction of hydrogen-powered aircraft. The expected cost reduction in renewable electricity prices and electrolyser technology will enable the upscaling of the hydrogen economy and make renewable hydrogen cost-competitive with fossil-based energy sources. The application of large amounts of hydrogen in all sectors of the economy will enable further cost reductions in terms of infrastructure and standardization. For aviation, the CO_2 abatement costs of hydrogen are estimated to be cost competitive with other technologies. Additionally, combusting hydrogen rather than kerosene reduces the emissions of sulphates, particulate matter and nitrogen oxides leading to co-benefits in terms of improving air quality around airports and reducing non-CO_2 effects.

3.4.2 Barriers

The drivers mentioned in Section 3.4.1 are factors that stimulate the development and market penetration of new technology; the challenges described here make this more difficult. Although these are split into a number of groups, they are primarily caused by one and the same aspect: the high levels of complexity of both individual products as well as of the aviation system at large.

Interdependencies

A primary consequence (if not inherent characteristic) of this complexity are numerous interdependencies. Design improvements yielding benefits in terms of fuel efficiency and CO_2 emissions might have adverse effects elsewhere if these are not properly mitigated. Or put differently: additional efforts are required to improve fuel efficiency while at the same time meeting design requirements with respect to other performance characteristics (e.g., range, noise, NO_X), safety, total cost of ownership, crew working environment and passenger experience. For hydrogen, the effect of hydrogen combustion on non-CO_2 emissions and their related climate impact (not considered in this study) are relevant items of further research, in addition to improving understanding of the effects of its implementation on aircraft design and operation, and airport infrastructure.

In addition to the challenge of meeting possibly conflicting goals in the design and development of an aircraft, the resulting product and infrastructure are heavily integrated. Whereas hydrogen-based propulsion allows achieving significant reductions in aircraft emissions, it not only requires a significant aircraft redesign but also needs changes to airport infrastructure and maintenance equipment. Amplified by the fact that the previous sixty years were spent on optimising the air transport system as it exists today, there is substantial lock-in.

High levels of risk and cost

Combining the dependency on and impact of external developments with the previously discussed capital intensity and long time horizon of the industry (Section 1.1) rapid large-scale innovation requires excellent mastering of the development risks. Funds, required for either technology R&D, product development, product acquisition or infrastructure building, can only be committed gradually with reduction of uncertainties in external trend estimates spanning years or decades into the future. The fact that it takes many years for aircraft programmes to break even further contributes to relatively long periods between multiple generations of aircraft – as new investments may be limited until a previous one has been largely recouped.

Certification uncertainties

Linked to the problem of determining the suitability of particular technologies is the question of certifiability. There is a long tradition of certification of aircraft with new technologies, which has led to very low safety risk. Both parties have to learn about the new technologies in parallel: aircraft and engine manufactures (and their supply chains) aim to develop certifiable designs, whereas certification authorities develop certification rules and means of compliance that may depend on the design choices of the aircraft and engine manufacturers. This issue is also noted by Bruce and Spinardi (2018), who state that knowledge lock-in is one of the key barriers to innovation in aircraft design. Certification is a costly and lengthy process that can only be changed without compromising safety.

Certification is even more challenging with the introduction of new, disruptive technologies such as (hybrid)-electric propulsion and hydrogen-powered aircraft. The first actions to overcome the potential barrier have already been taken with the establishment of EUROCAE working groups WG80 “Hydrogen and Fuel Cells” and WG113 “Hybrid-Electric Propulsion”. This way, factors currently acting as a barrier towards technology uptake, such as uncertainty with respect to certification, can be turned into a driver – if certification standards are in place, technology development can become more focused and more effective.

3.5 Policies and actions

The previous sections discussed the market implementation of numerous readily available or upcoming aircraft types, as well as the development of a next generation of aircraft with the potential of making significant contributions towards decarbonising aviation. However, as stressed by especially the challenges listed in Section 3.4.2, these will not simply manifest themselves. Policies (Section 3.5.1) from governments and actions (Section 3.5.2) from sector parties alike are required to make the potential identified a reality.

The sections both treat upcoming (EIS up to 2025) and future (EIS beyond 2025) aircraft. Given the fact that the upcoming aircraft treated in Section 3.2 are – or will soon be – available for purchase, their fate is mostly in the hands of airplane operators. On the other hand, R&D-stimuli can play a decisive role in the development and maturation of future technology. As such, the policies are predominantly geared towards future technology, whereas the actions mostly concern upcoming aircraft.

3.5.1 Policies

Research and development and supporting stimulus programmes

With new aircraft programmes ahead in the 2030s, Europe now has the opportunity to position itself as the global leader to reduce the impact of aviation on the climate change with competitive products.

To achieve the predicted impact, coordinated and collaborative European policy is needed to have technology ready for adoption in aircraft development programmes five years before the modelled entry-into-service. As Bruce and Spinardi (2018, p. 43) write, “we need policy initiatives targeted towards the knowledge practices of specific sectors. In the case of aviation, funding basic R&D seems futile unless it is accompanied by support for operational implementation that addresses the risk-adverse nature of the industry by building a knowledge base with regard to commercial viability and reliability”, pointing to examples of military sponsorship of carbon fibre application or “specific environmental and efficiency-orientated programmes”. In the civil European context, this suggests to have stimulus programmes for environment and efficiency, specifically oriented on aviation.

A stimulus programme with a clear focus towards achieving this technology readiness is proposed in the Strategic Research and Innovation Agenda by the proposed European Partnership on Clean Aviation (Clean Aviation Partnership, 2020). Three key thrusts for R&I efforts are identified, all addressing innovation in aircraft architectures and engines:

- Hybrid electric and full electric architectures
- Ultra-efficient aircraft architectures to address the short, medium and long range needs
- Disruptive technologies to enable hydrogen-powered aircraft

The aircraft categories selected for demonstration in the programme are the regional aircraft and the short-medium range aircraft with key technologies and architectures and EIS as modelled in Table 13. For other aircraft segments (small aircraft and long range aircraft), the impact of Clean Aviation is expected via scaling and transfer of technology.

Fitting with the barriers identified in Section 3.3.2, policies should aim to reducing uncertainty and risk. Uncertainty stimulates risk-averse behaviour, whereas an innovative and entrepreneurial mindset should be stimulated and nurtured.

Supporting the disruptive developments in Clean Aviation, a clear policy is needed with respect to the certification of the disruptive technologies that are investigated to overcome the barrier of certification uncertainty. Virtual certification, exploring digital methods in combination with physical testing, can reduce the cost and time for development, validation, and certification, while maintaining or improving the safety (Clean Aviation Partnership, 2020, Section 2.8).

Research and Technology Infrastructures are essential to test and validate new technologies and platforms. Recently, a EU funded study found that a large increase of investments into RIs is required for the EU to remain competitive with other countries such as USA and China (RINGO, 2020). Additional funding is also required to be used for enhanced collaboration and providing access to existing facilities.

While Clean Aviation is focusing on the technologies for the low-emission aircraft concepts, another stimulus programme, a Collaborative Research programme will have to address the following (Clean Aviation Partnership, 2020, Annex):

- Breakthrough technologies towards zero-emission aiming at potential technologies for the next aircraft generation and disruptive technologies for long term products (EIS from 2035)
- Transverse technology enablers to have the means to accelerate an affordable decarbonisation by leveraging all steps of the product lifecycle from early trade-offs up to certified operational aircraft joining the fleet.

Stimulus programmes, which might receive partial or additional funding from proceeds of the EU-ETS, should cover the entire innovation chain, having a tailor made approach to each phase of the chain. One must fund new, disruptive, low-TRL ideas as well as applied and more industrial research. The right framework conditions must be in place: funding intensity should be appropriate, and the right parties, facilities and expertise should be involved. In an innovation funnel approach, in the beginning a larger number of smaller projects should be funded to investigate potential solutions. Selecting the most appropriate solutions, the number of projects will reduce. The depth of the research and the corresponding funding intensity per project will increase. Especially the development of first-of-a-kind innovative hydrogen technologies is relevant. The EC indeed indicated such efforts might be supported by the EU-ETS Innovation Fund (EC, 2020e).

While the medium and long range aircraft segments provide the bulk of improvement potential identified in this report, it is important that research activities related to electrification are maintained and where possible, enhanced. This includes, amongst others, the understanding of implications of electrification on airport infrastructure (e.g. in terms of charging and/or battery swapping capabilities). In a similar way, the large-scale future introduction of hydrogen for aircraft propulsion will also likely require major infrastructural changes at airports. It is important to understand these implications – not in the least from a more holistic sustainability perspective, and include them into the above mentioned stimulus programmes.

In addition to policies focused on technology development, policies supportive of SAF need to be put in place in a coordinated manner. Coherency between SAF and propulsion developments and investments need to be maintained, including enabling a 100% blending limit for drop-in SAF (discussed in Section 5.10.2) and the introduction of hydrogen.

There are relevant potential connections with other preparations for Horizon Europe to be made for better coordination and exploitation of results (spin-in/spin-off). For example, the Fuel Cell and Hydrogen Joint Undertaking may clearly link to the hydrogen thrust of Clean Aviation. The Circular Economy Action Plan, one of the main blocks of the European Green Deal, is also a relevant link. Whereas Clean Aviation addresses the emissions due to the operations of aircraft, also opportunities to further improve the ecological footprint of the aircraft lifecycle from production to recycling should be explored. This is just one of the potential links with the proposed Made In Europe partnership. Furthermore, coordination with national and regional programmes, as already initiated in Clean Sky 2, is needed for complementing the strong European R&D stimulus programmes.

Technology uptake and operational implementation

As the potential improvements of new technologies will only contribute to reducing CO_2 emissions when they are fitted on aircraft which enter the market, it is the crucial responsibility of industry actors to develop these products and implement them into their fleets. Although these are and should remain business decisions, various government policies can support technology uptake.

This report does not assume an increased rate of fleet renewal, but adheres to the historical average of 22.5 years. Nevertheless, to possibly reduce this, or ensure fleet renewal is not slowed, regulatory factors can push deployment of technology, or reduce business case uncertainty associated with the introduction of new aircraft.

This can take various forms, driven by both government policy as well as industry actions (treated in Section 3.5.2). In the former category, options include but are not limited to opportunities to enable emission-based airport slot assignment, sustainability requirements for public service obligation routes, and CO_2 emissions standards targeting engine and aircraft manufacturers. The 2016 ICAO CO_2 standard for subsonic aircraft, which applies to new aircraft types from 2020 onwards, should be rapidly adopted in national or European regulations. Recent research shows “the CO_2 standard at its current stringency is unlikely to promote additional fuel burn reductions beyond what industry has already accomplished” (Zheng & Rutherford, 2020, p. 15), suggesting that the standard furthermore needs to be made more stringent in order to be consistent with a net zero 2050 pathway. Extending this standard to in-service aircraft is expected to be effective in phasing out the most inefficient aircraft in the current fleet, but is a rather extreme measure. Incentives to ‘early retire’ older in-service aircraft and replace these with newer, more fuel-efficient aircraft, can also be used[52].

Further research and analysis is required to determine which (combination) best achieves the intended goal, ensuring the implemented policies cannot be circumvented. In addition to the more rapid uptake of entirely new technologies, such regulatory factors can further stimulate the development of retrofits and product updates to in-service aircraft. This has yielded success in the past regarding noise (e.g., the development and installation of hush kits).

Besides these stimuli, policies should be put in place to standardise and promote the availability of new infrastructure to support more disruptive types of aircraft. As further elaborated in Section 4.6, this includes charging facilities at airports using renewable electricity as well as infrastructure for storage and distribution of hydrogen. Again, this should go hand-in-hand with technology development. This way, progress in terms of infrastructure development will reduce market uncertainty required for the necessary investments in technology, and vice versa.

Last, especially as development and production processes change or new technologies and concepts are incorporated into commercial products, up-skilling and re-skilling of the European workforce is likely to be required. Governments can play an important role in supporting this.

3.5.2 Actions

In addition to supporting policies from government and regulators, there are numerous actions to be taken by the industry itself.

A step up in R&D and stimulus programmes

Aligned with the European policies for stimulus programmes, the industry should invest in these stimulus programmes. In Clean Aviation, this will be as partner in the proposed Partnership for Clean Aviation; for the Collaborative Research programme the industry participation should contribute to the exploitability of the project results. Given the focus on technology development of these programmes, engine and aircraft manufacturers and their supply chains are in the position to take a key role. Airport operators can fulfil an important role in ensuring the development of possibly different infrastructure and handling that suit the needs of future aircraft.

[52] As explained at the end of Section 3.5.2, such a measure is not included in the modelling performed.

In Clean Aviation, the industry should take the lead in the technical execution of the work to achieve the predicted impact on aircraft level, taking into account that these impacts only materialise when the technology is introduced in aircraft that enter the market. The industry should therefore keep sufficient focus in the Clean Aviation programme towards achieving the technology readiness for adoption in aircraft development programmes.

Key attention should also go out to the development of the (technology required for) hydrogen-powered aircraft foreseen to enter into service from 2035 on select intra-EU+ flights. Although some test flights have been made using hydrogen as aircraft propellant in the past, operational application in a commercial aircraft would be a world's first. Aircraft technology research topics include safe and efficient storage of liquid hydrogen and distribution throughout the aircraft, fuel cell systems and hydrogen turbines. In terms of aviation infrastructure, refuelling systems need to developed and operational implementation has to be thought through.

Research establishments and academia should take the lead in providing innovative technological solutions as well in the stimulus programmes, based on their extensive knowledge and proven innovation capabilities. This contributes to the progress through the lower TRL level. In addition, they should contribute with methods and facilities for reaching the highest TRL levels, for which the methods and facilities need to be innovated to the level needed for the disruptive aircraft and engine technologies and configurations.

Progress in TRL levels should be shown on demonstrators showing the appropriate industrial level of integration. Ground demonstrators will be developed at various scales, sizes, and levels of representativeness, including wind tunnel tests. In-flight demonstrator should be developed as well as scaled flight tests, flying test beds, and flight demonstrators. Virtual demonstrators, combined with physical demonstrators, should be exploited as well.

New business models should be investigated to the earliest affordable introduction of emission-reducing technologies. This also includes opportunities for product enhancements and retrofits based on past technology development in Horizon 2020 (including Clean Sky 2) and Clean Aviation. New business models should also be investigated in view of potential disruptive changes to the traffic scenario due to the increase of traffic demand, such as more direct connections with smaller aircraft or carrying out the same flight with larger aircraft.

Besides policies that coordinate efforts in technology and (drop-in and non-drop-in) SAF development, industry actions should also keep an aligned connection. Specifically, aircraft and engine manufacturers should guarantee their products can safely and efficiently support blending levels of up to 100%.

Technology uptake and operational implementation

Following lower-TRL research and development efforts, industry should primarily ensure the latest available technology is transferred from testing facilities to the operational environment. As highlighted in Section 3.4.1, the timeline proposed in the Clean Aviation programme aligns very well with market uptake in the timeframe adhered to in this study. In order to speed up the product development cycle, industry should remain focused on the further maturation of technologies as high-fidelity simulation and scaled flight testing. With the involvement of the authorities, regulations can be adopted towards the use of such technologies, in order to contribute to accelerated certification, without compromising safety.

In addition to bringing to market new technologies, aircraft and engine manufacturers might re-evaluate results from previous applied R&D-projects, such as Clean Sky and Clean Sky 2. Given the increased climate ambition, higher societal awareness and growing cost of carbon abatement, the business case for commercialisation might today be different from when innovations were shelved. This not only holds for technology developed earlier, but also for newer innovations – that should be made available for retrofitting or other forms of performance improvement programmes for in-production aircraft. This way, relevant developments from partially publicly-funded programmes can also deliver benefits for European travellers and citizens.

For European operators and manufacturers in concert, it might be worthwhile to explore opportunities of developing derivative designs specifically suited for the European market. The hydrogen-powered single aisle aircraft anticipated in this report and designed for a range of 2,000 kilometre is a key example of this. Although the performance of current aircraft used on intra-European routes makes it possible to deploy these aircraft flexibly and allows manufacturers to sell them in larger quantities, it also adds weight and thereby reduces efficiency.

Looking further ahead, and aligning with policy recommendations in this area discussed in Section 3.5.1, manufacturers should contribute to standards for, for example, connectors for electric charging, the design of interchangeable battery packs and hydrogen-refuelling infrastructure. Airport operators should furthermore ensure the availability of relevant infrastructure for these novel concepts, once these requirements have been identified – requiring joint efforts by airports, operators, aircraft manufacturers and other parties involved in the ground handling process. In a shorter term, they can – together with regulators – explore the possibilities of using locally CO_2 modulated airport landing charges[53] in order to financially incentivise operators to use aircraft types with lower CO_2 emissions while maintaining level playing field and avoid traffic displacement to airports with different policies.

Fleet renewal

Once new technologies are incorporated into aircraft products, operators are the ones to bring these types into service. Based on historically observed trends, this study models replacement of individual aircraft takes place 22.5 years after they were delivered to their first customer. In order to realise the contribution that improvements in aircraft and engine technology are projected to make to decarbonising European aviation, this fleet renewal rate should be maintained.

> EARLY FLEET RENEWAL
>
> Numerous parties have pointed to the COVID-19 crisis as an opportunity for retiring older airframes form service early, as capacity is strongly reduced (Aviation Round Table, 2020; Saeed, 2020). Indeed, various operators around the world have done so (Pallini, 2020; ICF & Petchenik, 2020; Falcus, 2020; Broderick, Massy-Beresford, Schofield, Flottau, & Goldstein, 2020). By reducing fleets to the most modern and most fuel-efficient aircraft, fuel cost and CO_2 emissions can be quickly reduced.
>
> Notwithstanding this possibility of realising emissions reductions in the short term, this study does not specifically address the effect of such a measure. The reason for this follows from choices made concerning the project scope, which evaluates emission reductions in 2030 and 2050, and not the intermediate years. Given the average airframe retirement age of 22.5 years, 2030 estimates of CO_2 emissions would only be affected if airframes that are younger than 12.5 years in 2020 would be 'early retired'. Put differently: removing currently 15-year old airframes from service in 2021 would in the modelling used in this report not affect the CO_2 emissions estimate for 2030, as by then, these airframes would have reached 24 years, and be retired anyway. Although there might be some airframes currently below 12.5 years for which immediate withdrawal from service might be an option, it was not considered in this report.

[53] Challenges of this have been recently reviewed by ACI Europe (2020b)

4 Improvements in ATM and aircraft operations

Improvements in ATM and aircraft operations are estimated to be able to make an important contribution to reducing aviation's CO_2 emissions in the short to medium term. Fitting with the highly complex and interdependent environment of air traffic operations, improvements are clustered in three areas: airline operations, airspace and air traffic management, and ground operations at airports.

Specifically, improved flight planning, weight reduction and improved airframe condition and maintenance are modelled to reduce fuel burn for aircraft operators by approximately 3%. In addition to better flight efficiency, the realisation of the Single European Sky is anticipated to yield the largest benefits. Based on recent literature, an improvement potential of 3.5% (departing intercontinental flights from the EU+ region) to 7.1% (flights within the EU+ region) is modelled. Improvements to ATM outside Europe are estimated to add additional savings of 2.1% for flights that depart to a non-European destination. In a slightly longer term, wake energy retrieval is anticipated to be able to contribute a 3% reduction, applicable to 50% of flights. Lowering emissions from aircraft ground movement and APU usage through the introduction of electrical operational towing and using electrical ground power, has the potential of realising CO_2 cuts by 1.5% to 3% per flight – depending on the aircraft type and mission.

In order to achieve these reductions, it is crucial for actors – both governments and industry – to work in concert. As it is the largest potential gain, realisation of a network-centric and digital Single European Sky is considered essential. Further policies and actions are required to realise and implement continued development and uptake of communication, navigation and surveillance equipment with improved capabilities. At airport-level, efforts should focus on rapidly decarbonising ground operations by reducing APU usage and taxi emissions, and in general preparing for a more-electric future. This will not only reduce the climate impact of aviation, but also has the potential of delivering important co-benefits in terms of lowering noise and reducing other emissions.

4.1 Introduction

The operational environment of air transport is a (highly) regulated and complex one, in which a large number of actors are collectively responsible for a safe and efficient air transport. Within this environment, airlines, air navigation service providers (ANSPs), airports, ground handling agents, aircraft manufacturers (OEMs) and other parties influence air transport operations and the efficiency of the operational process. Some relationships are mostly one way (such as an OEM prescribing maintenance intervals or a minimum equipment list), whereas others are of a much more collaborative nature (such as the way airlines and ANSPs plan and conduct a flight).

The remainder of this chapter addresses numerous operational improvements that have the potential to reduce CO_2 emissions. These reductions will generally also make a positive contribution towards lowering other emissions, such as NO_X and soot[54]. Despite the strong interdependencies between actors involved, the analysis presented in this section divides potential improvements into three categories: airline operations (Section 4.2), airspace and air traffic management (Section 4.3) and ground operations at airports (Section 4.4). At the end of each of these sections, the potential impact of all measures in that category are summarised.

At the end of the chapter, Section 4.5 discusses drivers and barriers influencing these improvements, whereas Section 4.6 elaborates on policies and actions that can be used to strengthen drivers and circumvent barriers to implementation, and thereby contribute to the realisation of the improvements considered.

4.2 Airline operations

The improvements grouped in the category airline operations concern the way in which aircraft are used by airlines. Even though more and more airlines report on their efforts of reducing CO_2 emissions, Becken & Pant (2020) note that there “surprisingly” are still many that do not, and that even “for those that do, a very broad range of reduction opportunities could be identified”. Focussed on three groups of measures, this section discusses flight planning and execution (Section 4.2.1), weight reduction (4.2.2) and airframe condition and maintenance (4.2.3). The results are summarised in Section 4.2.4.

As load factor growth is also part of the reference scenario, it is not taken into account as potential environmental improvement.

4.2.1 Flight planning and execution

The core business of an airline is obviously carrying out flights, which includes flight planning and subsequent execution. Based on decisions made in the preceding network and schedule planning stages, in which flight frequencies and aircraft types are assigned to city-pairs to be connected, actual flight planning only takes place a few hours before the associated departure. It is concerned with choosing the best flight trajectory, considering all relevant factors – such as payload, weather conditions, air traffic control tariffs, fuel prices and the actual traffic situation, including restrictions. For most airlines, this is a largely computer-automated (or at least: computer-supported) process in which manual input is steadily decreasing. Nevertheless, airlines do adjust optimisation algorithms and optimisation priorities to their own needs. A full-service carrier with substantial transfer traffic is generally operating from a (large) hub, and will place most emphasis on punctuality and slot availability (to prevent network disturbances downstream, which are often costly to recover), whereas a low-cost airline is likely to focus primarily on route, fuel efficiency and cost. All things equal, however, airlines will aim most economical flights – which might result in less fuel-efficient routing.

As flight planning and execution are the primary drivers of operating cost, it is in the best business interest of airlines to optimise those activities. Despite that fact, improvement potential is seen. Using newer flight planning software, various airlines have reported fuel savings of 2.6 to 3% (GreenAir Communications, 2018; Honeywell, 2019); improved flight management systems (FMS) envisioned to enter the market in 2024 and also available for implementation in

[54] Per Section 1.4.2, these emissions have not been studied in detail.

aircraft flying today would yield potential benefits of 3 to 4% (Sheppard, 2019; Thisdell, 2020). In a more experimental setting, Gosnell, List and Metcalfe (2016) investigated the potentially beneficial effects of information provision and incentivising airline captains on reducing fuel burn. Based on a field experiment involving 40,000 flights, they estimate a CO_2 reduction potential of 838 to 2,200 tonnes in a period of 8 months, computed for this study to be equivalent to up to 0.2% of the estimated total emissions of the test flights. Lastly, EUROCONTROL (2019b) noted that in 2018, filed flight plan distances were on average 0.4% longer than the "shortest constrained route" made available to airlines. Nevertheless, actually flown trajectories were 1.3% shorter than the shortest constrained route (for example using more efficient re-routing mid-flight, instigated by either the pilot or air traffic controller), severely limiting the improvement potential[55].

Summarising the more straightforward improvements discussed in the previous paragraphs while considering that some of these improvements are not mutually compatible[56], a generic improvement potential of 2% is assumed, to be realised over a five-year period starting in 2020 and delivered by improved flight planning, information provision and pilot awareness. To correct for improvements that have already been realised, the improvement is applied to 75% of the flights. From 2025, an additional 1% is assumed following FMS-updates[57], to be realised over the course of ten years. This transition period is somewhat longer as hardware changes are necessary.

4.2.2 Weight reduction

In addition to the way a flight is planned and executed, airlines have some control over the configuration of the aircraft used and thereby over the weight of an aircraft. As every kilogramme requires additional fuel to be transported, weight reductions can bring relevant savings in fuel consumption and CO_2 emissions. Note that weight reduction of the aircraft (structure) itself, for example through the extended use of composite materials, was already covered in Chapter 3 and is therefore not considered here.

Over the last few years, many airlines have replaced paper cockpit manuals by electronic systems, annually saving between 200 to 12,000 tonnes of CO_2. Similarly, Finnair expects that lower weight cargo containers reduce their carbon emissions by 2,500 tonnes each year (ATAG, 2015). Replacing paper newspapers with a mobile app has allowed KLM to save 750 tonnes of CO_2 per year (KLM, 2017). Future improvement potential exists for example in replacing current (and relatively heavy[58]) in-flight entertainment systems with seat-back screens by systems that allow passengers to utilise their own devices carried on board anyway, lighter cabin trolleys, lighter crew equipment, lower-weight seats[59], carbon brakes, 'rightsizing' water and supplies, helped by pre-ordering of meals and retail purchases (Gubisch, 2011; Reals, 2014; Schäfer, Evans, Reynolds, & Dray, 2015; Becken & Pant, 2020; Cirium, 2020). Although some of these changes require OEM or regulatory approval, they can be applied to aircraft already in operation (for example during larger maintenance work) and thereby realise savings earlier than the introduction of an entirely new aircraft would. Noting that the full potential might not be reached due to regulatory or cost constraints, and realising that not all weight savings are applicable to all aircraft (many short-haul aircraft currently already fly without seat-

[55] Some improvement potential still remains, however, as the amount of fuel taken on board an aircraft is determined by the filed flight plan. If that flight plan distance can be reduced (by either 0.4% or further, if even shorter shortest constrained routes would be made available by ANSPs), fuel uptake is limited. Even though that fuel might not be used, this can save other fuel that is used for transporting the redundant fuel (cost of weight, also discussed in Section 4.2.2). Last, as further discussed in Section 4.3.1, it is emphasised that the shortest constrained route might not be the most fuel efficient one due to e.g. weather (wind) effects.
[56] With better flight planning, the improvement potential of better flight management systems is likely to be reduced, just as is the case vice versa.
[57] Total benefits are estimated at 3 to 4%, and if 2% of improvement is already realised earlier on, 1 to 2% remains. A conservative value of 1% is assumed here.
[58] The Canadian airline WestJet indicated saving approximately 550 kilogrammes per aircraft by removing seat-back screens (The Economist, 2012). Based on Bakx (2015), these numbers are likely to correspond to Boeing 737 aircraft, of which WestJet operates multiple versions (Airfleets, 2020). Assuming typical 2-class configurations and averaging seat count based on number of aircraft in the fleet (13 × 108-seat 737-600, 52 × 128-seat 737-700, 39 × 160-seat 737-800) yields an average of 137.5 seats per aircraft. This translates into a weight saving of 4 kilogrammes per seat. Ferro (2014), citing Bachman (2012), notes a weight of 13 pounds or 5.9 kilogrammes.
[59] Gubish (2011), Reals (2014) and Schäfer, Evans, Reynolds & Dray (2015) cite various industry parties which estimate weight savings of 15 to 30% per seat, reducing the weight of seats from approximately 16 to 12 kilogrammes for long-haul aircraft and from 12 to 5 kilogrammes for short-haul aircraft.

back screens, for example), a weight saving potential of 10 kilogrammes per seat is assumed. This corresponds well with the average cabin weight reduction potential estimated by Schäfer, Evans, Reynolds & Dray (2015).

Besides equipment, weight savings can be realised by reducing the amount of fuel taken on board. Although regulations require particular amounts of reserve and additional fuel for reasons of safety, some aircraft carry more fuel than necessary to conduct the flight. Reducing this is assumed to unlock a potential saving of 0.25%. More significantly, EUROCONTROL (2019a) estimated 15% of ECAC flights perform tankering. Bringing along some fuel for the next flight, airlines reduce operating cost when flying to airports where fuel prices are substantially higher – sometimes up to 55%. While saving 265 million Euros annually, CO_2 emissions are at the same time increased by 901,000 tonnes, equivalent to roughly 0.5%.

Summarising the potential improvements discussed above, a carbon emissions reduction of 0.75% is assumed, in addition to a weight reduction of 10 kilogrammes per seat, applicable to 75% of the flights in order to take into account airlines already having made above-average efforts. This translates into emissions savings by assuming a 3.5% hourly cost-of-weight factor (ICAO, 2014b)[60]. Both (one-time) efficiency improvements are assumed with respect to the baseline year and are modelled to materialise between 2020 and 2030. Weight reductions after 2030 are realised through fleet replacement and as such are part of Chapter 3. Similarly, weight reductions following from advances in the field of condition-based or predictive maintenance are included as improvements in technology.

4.2.3 Aircraft condition monitoring and maintenance

Improving the airframe condition also has beneficial effects on fuel consumption. Cleaning the engines more often, for example, is estimated to save between 0.5 and 1.2% of CO_2 emissions (Schäfer, Evans, Reynolds, & Dray, 2015; ATAG, 2015) – although water consumption is likely to increase. Reduced exterior skin quality through dents or dirt decreases the aerodynamic efficiency and thereby increases fuel consumption, as does improper control surface rigging. The International Civil Aviation Organisation notes that "over a period of 5 years, engine and airframe deterioration may increase the drag of the aircraft by up to 2 per cent" (ICAO, 2014b, p. x). Noting the "up to" clauses in the previous statements, reality is likely to be much less dire. As such, and largely consistent with similar works published previously (Sustainable Aviation UK, 2016; Sustainable Aviation UK, 2012), a fuel efficiency improvement of 0.2% is assumed, delivered between 2020 and 2050.

4.2.4 Potential impact overview

Table 14 provides an overview of potential impacts of the aircraft operational improvements discussed in this section. Weight savings listed in the column 'potential CO_2 emissions reduction', for example as a result of lighter cabin equipment or reduced fuel load, are translated into fuel savings on a flight-by-flight basis using a cost-of-weight computation (further explained in Section 4.2.2, specifically footnote 60 on page 56).

[60] This means that for transporting 10 fewer kilogrammes, 0.035 × 10 = 0.35 kilogrammes of fuel are saved per block hour. For a single aisle aircraft with 200 seats operating a flight of 4 block hours, the fuel reduction would add up to 280 kilogrammes, equivalent to almost 900 kilogrammes of CO_2. For 1000 flights per year (a little under three flights per day), this entails a CO_2 saving of 900 tonnes.

Table 14: Potential CO_2 emissions reductions to be delivered by airline operational improvements per flight

Measure	Potential CO_2 emissions reduction	Starting year	Delivered by	Remarks
Improved flight planning	2% × 0.75 = 1.5%	2020	2025	
Flight management system updates	1%	2025	2035	
Weight reduction	10 kg / seat, 75% of flights	2020	2030	Modelled using 3.5% cost of weight
Airframe condition and maintenance	0.2%	2020	2050	

4.3 Airspace and air traffic management

Airspace is part of the infrastructure in which aviation activity takes place. Air traffic management (ATM) – often subdivided into air traffic services, air traffic flow management and airspace management – aims to ensure safe and efficient flights, to balance demand for flights and airspace capacity available and to provide aeronautical information to airspace users. The improvements grouped in this category therefore mainly concern the design and use of airspace in which airlines conduct their flights. Traffic management at the airport itself (from the gate to the runway and vice versa) is partially included. Improvements that for example prevent aircraft to wait in a queue with running engines are part of this section; opportunities with regard to electric taxi or operational towing are dealt with in Section 4.4.

The section is subdivided as follows. Section 4.3.1 first discusses the Single European Sky and SESAR. Then, Section 4.3.2 pays attention to non-European ATM efficiency improvements and Section 4.3.3 specifically discusses improved flight efficiency over the North-Atlantic. Wake energy retrieval, an innovative concept also known as extended formation flight, is treated in Section 4.3.4. It is included in the present section rather than in the previous one to emphasise the airspace and ATM-related actions required to ensure its implementation. Again, Section 4.3.5 concludes this section and summarises CO_2 emissions reduction potential.

4.3.1 Single European Sky and SESAR

A major improvement potential in Europe in terms of air traffic management is the realisation of the Single European Sky (SES). As this programme encompasses changes to European ATM at system-level, it has a potential impact on the entire flight – from gate to gate. The dedicated underlying research programme SES ATM Research (SESAR) is regarded as a crucial enabler for realising the contribution the SES can make to lowering CO_2 reductions.

Background

Agreed upon in the International Convention on Civil Aviation (colloquially known as the Chicago Convention), states have “complete and exclusive sovereignty over the airspace above its territory” (ICAO, 2006). As such, it is no surprise that airspace and air traffic management have historically been national affairs. As air traffic is however inherently international, aviation growth signified the limitations of the national perspective on air traffic management. Among other things, this resulted in heavy delays at the end of the 1990s, with up to 20% of flights seeing average delays of 25 minutes (EC, 2000). In order to solve these problems, the SES was conceived, following a report of the high level group on SES noting that “airspace is a common resource and should be treated as a single European sky” (EC, 2000, p. 35). The European Commission formally launched the programme in 2004 and set a number of High-Level Goals for 2020: increasing capacity (× 3), reducing delays, improving safety (× 10), reducing environmental impact (- 10%) and reducing cost (- 50%) (SESAR JU, 2019f). The aforementioned SESAR programme was set up in 2007 as “the mechanism which coordinates and concentrates all EU research and development (R&D) activities in ATM” (SESAR JU, 2019c). In 2014, the SESAR Deployment Manager was created to coordinate synchronised deployment of SESAR solutions to maximise their benefit to the network. The European Air Traffic Management Master Plan (EU ATM MP), then, “defines the development and deployment priorities needed to deliver” the vision as set out by SESAR (SESAR JU, 2019d, p. V). Implementing Regulations on common projects (such as Regulation 716/2014) help to more concretely operationalise the high-level Master Plan vision.

Regulatory and administrative outline

In SES, as it was envisioned in the beginning of the century, a major objective was to defragment European airspace and increase collaboration between ANSPs. In order to achieve this goal, so-called functional airspace blocks (FABs) were introduced. These would allow airspace to be managed based on operational requirements rather than state boundaries, enable economies of scale, and increase air navigation service provision across country borders. This would also increase competition, drive down costs, stimulate innovation and reduce environmental impact. The SES II regulation, approved in 2009, then introduced a performance scheme, setting binding performance targets on safety, environment (horizontal en-route flight efficiency), capacity (delays) and cost-efficiency (EC, 2019a). This compels ANSPs to deliver increased service at lower cost, even in case market mechanisms (which would otherwise yield such an incentive for service improvement and cost reduction) are limited or lacking and in an industry where “monopolistic service provision” often applies (ECA, 2017, p. 8). SES II also introduced the Network Manager (NM; a function currently fulfilled by EUROCONTROL) to “co-ordinate certain actions at network level” and refocussed the FABs towards service provision rather than airspace design (EC, 2020h). In 2013, the European Commission proposed an update to the SES II framework, called SES II+, aimed to accelerate the implementation of the SES vision (EC, 2013b; EC, 2013a). Among other aspects, it aims to strengthen the performance scheme, increase the flexibility and performance-focus of FABs and reinforce the role of the NM. Despite the fact that seven years have passed since it was proposed, SES II+ has not been agreed on. To pick up the work again the European Commission has published a revised proposal for SESII+ based on a recent staff working document (EC, 2020a).

This historical background may form the basis for concrete and tangible solutions that in turn realise the various goals. A prime operational shift that builds upon these wider trends in ATM harmonisation and collaboration efforts is 4D (space and time) trajectory management or Trajectory Based Operations (TBO). By sharing information about the current and future positions of aircraft, TBO continues the paradigm shift which in the past realised the step from procedural (estimating positions based on flight plans) to radar-based (‘measuring’ positions) navigation and surveillance (Da Silva, 2012). Because it improves predictability of aircraft trajectories, potential problems or possibilities for efficiency improvements can be identified further in advance and acted upon. Rather than having to put an aircraft in a (fuel- and emission-intensive) holding pattern when it arrives at an airport earlier than expected, this longer planning horizon allows for solving this problem by a slight reduction of cruise speed[61]. Furthermore, the fact that flight trajectories are dynamically negotiated between airspace users and ANSPs enables trajectories to be optimised from the system perspective rather than that of the individual airspace user. This can improve ATM performance in a wide range of areas – from capacity and safety as well as from an environmental point of view. In order to further increase predictability, better data sharing and interoperability are key.

Solutions and improvements

Whereas the previous paragraphs treated largely conceptual aspects, the current illustrates a number of concrete solutions these can deliver. A clear example is Free Route Airspace (FRA), in which airline crews enjoy more freedom in selecting a particular – more fuel-efficient – trajectory. Implementation of FRA depends not only on ATM, but also on political will by governments to make the necessary compromises regarding organisation of airspace. Flexible Use of Airspace (FUA, now Advanced Flexible Use of Airspace or AFUA (EUROCONTROL, n.d.)), in which airspace is no longer designated as either military or civil but is allocated based on current operational requirements. The potential

[61] Cross-border arrival management, implemented in various airports in Europe, is a SESAR solution that helps achieve this.

environmental benefits of both are clear, as they allow shorter and/or wind optimal routes. A third example – extended arrival management and cross-border arrival management (Extended AMAN and XMAN) – mainly indicates the benefits of collaboration with other ANSPs in increasing the arrival management planning horizon, such that potential inefficiencies during approach can be resolved in the cruise part of the flight. This way, aircraft can be instructed to fly slightly slower to prevent arriving early and having to wait in a (fuel inefficient) holding pattern. Even though this does not change airspace boundaries, it reduces fragmentation from a service-provision point of view. Better and more comprehensive information sharing and interoperability between parties (through system-wide information management or SWIM) and collaborative decision making (CDM) can further reduce the time aircraft spend waiting in queues – burning fuel in the process – and thereby also contributes to environmental objectives in terms of operations and ATM. Last, numerous innovations aim to improve surface navigation accuracy in low-visibility conditions, benefit both safety and environment.

Current status

Even though the SES vision was to be fully implemented by 2020, these objectives have regrettably not been met. Recent reviews stress current airspace inefficiencies are unacceptable (Wise Persons Group on the Future of the Single European Sky, 2019) and note that only “lacklustre quantitative results” (ECA, 2017, p. 43, talking about the performance scheme) have been achieved.

According to the 2020 EU ATM Master Plan, 37% of SESAR solutions have been delivered (of which 70% have a regulated or non-regulated deployment decision and 30% are awaiting such a decision), 31% are under development, and 32% are expected to be covered in future R&D (SESAR JU, 2019d, p. 94; SESAR JU, 2019g). That means that of all SESAR solutions, approximately 26% have been deployed[62]. Substantial differences, however, exist between the implementation progress of individual solutions, with some (such as direct routing and continuous descent operations) reported to be implemented by over 80% airports or States and others (e.g. time-based separation) not having passed 10% (SESAR, 2019).

A number of recent reports, such as by the European Court of Auditors (2017), a Wise Persons Group established by the Directorate-General of Mobility and Transport (DG MOVE) to make recommendations for the future of SES (2019) and the Industry Consultation Body SES Vision 2035 (ICB, 2019), reviewed the current status of SES and indicated reasons why 2020 implementation objectives are not met. Relevant outcomes and recommendations of those studies are addressed in greater detail in Sections 4.5 and 4.6, but two aspects are already briefly discussed here:

- Despite “substantial efforts undertaken for their implementation”, objectives of reducing defragmentation through the use of FABs have not been met (ECA, 2017, p. 30; Integra A/S; ECORYS Nederland BV; Winsland Consulting & Combitech, 2017). Initially envisioned as a way to provide “integrated management”, “FABs were gradually transformed” into “enhanced” “cooperation mechanisms” (ECA, 2017, pp. 28-29; EP & CEU, 2009). As indicated in the title of the ECA review (“Single European Sky: a changed culture but not a single sky”), the SES work so far has instilled a more efficiency-focussed culture in ATM, but has not managed to create a single European sky. Whereas national sovereignty interests might stand in the way of treating airspace as a “common resource” (EC, 2000, p. 35), cooperation within sovereignty boundaries has not resolved interoperability issues to the maximum extent possible[63].

[62] The SESAR Deployment Manager (SESAR DM, 2020) states that 155 out of 343 projects (approximately 45%) are in operation bringing benefits to passengers. Deployment is completed or in progress of 75% of the Pilot Common Project (PCP).

[63] EUROCONTROL’s 2016 ATM Cost-Effectiveness benchmark, for example, notes that throughout Europe, flight data processing systems from at least 10 different suppliers are used. ‘At least’ is used, because bespoke systems are not individually indicated, making it impossible to access whether each bespoke FIR is a separate system, or whether multiple FIRs share the same bespoke system. The former seems most likely.

- Aspirational goals rather than targets were set, which were based on projections of demand growth[64] and associated capacity requirement and benefits of economies of scale that did not come true (ECA, 2017). Furthermore, the original goals – in addition to addressing safety – seemed to prioritise capacity, efficiency and cost over environment – which is quite different from the realities of today (Wise Persons Group on the Future of the Single European Sky, 2019), where environmental aspects are deemed much more important than before[65]. This was also acknowledged recently by the Commission, noting “a decreased emphasis on cost reduction and an increased emphasis on delays and the environment” in its Staff Working Document on SES2+ (EC, 2020a, p. 4).

Interdependencies

The different topics addressed in the SES goals and the previously discussed shift in priorities of those goals also draw attention to the complexity of the air traffic management system – aiming to cater to a wide array of often conflicting and varying demands from a large number of stakeholders – and the interdependencies that cause that complexity, further discussed in e.g. Sustainable Aviation (2017) and EUROCONTROL (2018c). Although not limited to it, this complexity is especially seen in the airport vicinity. While a particular departure procedure may have a beneficial effect on the noise exposure to surrounding communities[66], that same departure procedure might not be most fuel efficient – or vice versa. The same is true for flying approach routes in which aircraft navigate around populated areas, but which come at a price of increased flight distance and fuel consumption, or having to choose between continuous climb versus descent operations. Trade-offs between CO_2 and other emissions (such as NO_X) affecting local air quality further complicate the matter, as well as the lack of (quantified) knowledge about the effects of various interdependencies (BLUE MED, G.A.R.S, Universita di Bologna, & FABEC, 2020).

Whereas noise is of limited concern during cruise flight, other interdependencies play a role. Guaranteeing separation limits in highly demanded airspace results in congestion and capacity shortages, which in turn might require aircraft to be distributed over a wider set of routes – reducing horizontal flight efficiency and increasing CO_2 emissions. Similarly, increasing the number of air traffic control operators available might alleviate queues, enable closer flight monitoring and suggestions to reduce environmental impact, but on the other hand increases cost.

Lastly, and although climate effects beyond CO_2 emissions are not considered in this research (as indicated in Section 1.4), opting to fly a longer route can have a (net) beneficial effect on global warming, as it might make optimal use of strong tailwinds (reducing fuel consumption) or circumvent climate sensitive areas of atmosphere (where contrails, which have a warming effect, more easily form) (Grewe, et al., 2017). Especially in terms of non-CO_2 effects, such as contrail cirrus and NO_X emissions, numerous research efforts and projects are underway that examine the feasibility of tactically rerouting aircraft around regions where persistent contrails are likely to form and produce long lived cirrus cloud. This can help minimise the climate impact of these flights. Despite this potential, interdependencies with other performance indicators (such as noise and cost) must be taken into account in such assessments.

In some cases, the specific trade-off examples discussed in the previous paragraphs can be readily generalised to the SES Performance Scheme (EC, 2019a) of safety, environment, capacity and cost-efficiency. This is for instance the case in the example of congested airspace, resulting in interdependencies between safety, capacity and environment.

[64] A cost/benefit-analysis for SES from 2005 assumed 2.9% annual growth rates from 2005 to 2035, whereas growth rates of only 1.1% per year were realised between 2005 and 2016 (ECA, 2017). The current study predicts a year-on-year growth from 2005 to 2035 equal to about 1.5%.

[65] “From the very beginning the [Wise Persons] Group was clear that safety, security and environmental elements have the highest priority, whatever recommendations it makes to increase the capacity and improve the efficiency, including the cost efficiency, of the ATM system. These elements must also have priority when the recommendations are implemented.” (Wise Persons Group on the Future of the Single European Sky, 2019, p. 4)

[66] Which might, due to the reduction of noise, also reduce adverse health effects.

Potential impact

As emissions are not reported for different flight phases, data indicating the impact of specific parts of the SES framework is difficult to acquire. Similarly, fuel or emission estimates on the level of all individual SESAR solutions is not publicly available. As such, the impact estimate shown in this section considers the effect of ATM-related improvements[67] on a gate-to-gate level. Nevertheless, a breakdown is used to split these potential impact estimates over airport, climb/descent and cruise in order to account for the aforementioned interdependencies. It is emphasised that opportunities such as e-taxi – that are mostly concerned with *how* ground operations are carried out – are not part of the current section.

In 2005, the Commission envisaged SES would deliver a 10% reduction in CO_2 emissions by 2020, compared to levels observed in 2005 (SESAR JU, 2019f; IATA; AEA & ERA, 2013), although this did not form any base for the SES legal framework. In recent communications by the European Commission on the European Green Deal, the environmental impact of an improved ATM system in the EU is now represented as "up to 10%" (EC, 2019h) – a likely consequence of the fact that the European Commission has acknowledged that the initial goals were "to be seen as aspirations rather than targets" (ECA, 2017, p. 18).

The 2020 European ATM Master Plan[68], based on the same flight forecast as the current study[69], does list targets: a reduction of gate-to-gate emissions by 5 to 10% compared to 2012 should be realised by 2035. This is for an average flight consuming 5,280 kilogrammes of fuel. This saving is equivalent to a reduction in fuel consumption of 250 to 500 kilogrammes and an associated reduction in CO_2 emissions of 0.8 to 1.6 tonnes[70] (SESAR JU, 2019d, p. 37).

Another study from the SESAR Joint Undertaking, on the potential benefits of a Single European Airspace System, indicates a potential of "between 240 and 450 kg of CO_2 saved on an average flight due to optimisation of trajectories" (SESAR JU, 2019a, p. 67) to be obtained by 2035 compared to 2019 – equivalent to a total reduction in CO_2 of 30 to 60 million tonnes. These reductions in CO_2 emissions would follow from a reduction in flight distance between 7 to 13 nautical miles in 2035. Although the Single European Airspace System is different from the SES legal framework (it is described as ''an evolution of the European airspace architecture'', SESAR JU, 2019a, p. 3), its focus on collaboration, harmonisation and data sharing demonstrate it being consistent with SES ideas.

Besides estimates from the SESAR Joint Undertaking, various other parties have published similar data. EUROCONTROL (2019b, p. 11) shows 2018 excess gate-to-gate emissions at approximately 6.1%, predominantly caused by horizontal en-route flight inefficiency, horizontal arrival flight inefficiency, and vertical cruise flight inefficiency. Noting that inefficiencies cannot and should not be reduced to zero[71], EUROCONTROL (2019b) cites the 2015 European ATM Master Plan in the ambition of reducing these excess emissions to 2.3% by 2035 – a reduction of 3.8 ppt (percentage point). A note preceding the policy debate on the future of the SES[72], too, states the number of "around 6%", but describes those as "avoidable emissions" (Presidency of the Council of the European Union, 2019). Although no timelines are mentioned in that document, it is assumed this 6% too holds for 2035 with respect to 2018.

Estimates provided by industry experts interviewed for the current study are somewhat more extreme – on both ends of the scale. One representative expected essentially no environmental benefits from ATM, stating that airspace users should be happy if performance remains at the current level as air traffic continues to grow. Indeed, these worries are

[67] Thereby excluding the impact of reduced engine taxi, operational towing or e-taxi, discussed in Section 4.4.
[68] The fuel consumption reductions reported in the 2020 EU ATM Master Plan comprises "additional ATM-related gate-to-gate fuel burn per flight", on top of "the ability of accommodate traffic increases safely and simultaneously and ensuring the achievement of punctuality objectives of airspace users" (SESAR JU, 2019e, p. 14)
[69] EUROCONTROL Challenges of Growth 2018, 'Regulation and Growth'-scenario. Further details can be found in Chapter 0.
[70] Although computed values differ slightly (5 to 10% of 5.280 equals 264 to 528 kilogrammes of fuel, equivalent to 832 to 1664 kilogrammes of CO_2 emissions), the rounded values used in the cited documents are used.
[71] Some elements that strongly contribute to aviation safety, such as separation minima and navigation around adverse weather, reduce flight inefficiency. This is due to the fact that these conditions are not reflected in the KPIs.
[72] Part of the 3734th Council meeting on Transport, Telecommunications and Energy, Brussels, December 2-4, 2019.

shared by numerous parties. EUROCONTROL (2019c, p. 7), for example, notes it “may be challenging in itself to maintain efficiencies as traffic grows” and Sustainable Aviation (2020a, p. 49) states “increased traffic growth can erode or nullify ATM efficiency gains”. Increased concerns about interdependencies – most notably noise – has furthermore made the UK ANSP NATS re-phase their emission reduction commitments (Sustainable Aviation, 2020a, p. 48), also indicating the difficulty of meeting emission reduction targets. On the other end of the spectrum, another representative estimated SES would deliver fuel consumption reductions of 12 to 14%, due to for example more direct routings, reduced altitude restrictions and increased continuous climb and descent operations. The wide range in industry estimates clearly illustrates the uncertainty associated with the SES benefit pool. The differences might, however, also be caused by some stakeholders promoting their goals over those of the network whereas others do not.

The impact assessments are combined as follows. Starting with the total impact potential of 5 to 10% listed in the 2020 EU ATM Master Plan, this is reduced to 3.7 to 7.4% by taking into account that 26% of SESAR solutions has been deployed[73], yielding a single value of 5.6% reduction potential by 2035 with respect to 2018. Following the most ambitious of the two rollout timelines published[74], realisation of the full SESAR vision by 2040 is expected viable – if necessary actions and policy measures are taken (SESAR JU, 2019d). As that vision goes beyond the environmental performance improvements discussed here, these are expected to be realised by 2035.

Then, this is combined with the estimates of excess gate-to-gate emissions. According to EUROCONTROL and the European Council, this varies between 3.8% and 6.1% (for 2035 with respect to 2018). The benefit pool noted by FAA and EUROCONTROL (2019), expressed in relative terms[75], is 6.4%. The fact that this is a higher value is consistent with its classification as a theoretical maximum[76], which cannot be completely achieved due to safety concerns introducing some inefficiencies. Regardless of that theoretical status, it indicates the validity of the two earlier values. As neither one was determined to be more accurate or more truthful, these figures are combined to yield an average of 5.0%. Combining this with the 5.6% found previously – again using an averaging operation – results in a figure of 5.3%[77].

As not all flights are part of the scope of the present study (further detailed in Section 1.4, more specifically in Section 1.4.3), the potential improvement of 5.3% is split up over various flight phases[78]. Information for that exercise comes from two sources: the SESAR Joint Undertaking website (2019) and the 2020 European ATM Master Plan (SESAR JU, 2019d) and its Companion Document (SESAR JU, 2019e). Furthermore, following interdependencies between noise and CO_2 in the TMA, it is assumed that only 75%[79] of the potential in the TMA (excluding the holding phase) can be realised. Table 15 summarises the results and shows:

- For the EU ATM MP2020 estimate, what share is delivered by what elements. For example, airport operations (12.6% improvement potential) is composed of taxi-in (4.4%) and taxi-out (8.2%). These individual components hence make up 4.4 / 12.6 = 35% and 8.2 / 12.6 = 65% of the total improvement in terms of airport operations.

[73] Lacking emission impact estimates at solution level, as indicated, this assumes that each solution contributes an equal amount of the CO_2 emission reduction potential.
[74] A less ambitious rollout option sees full SESAR implementation by 2050. Given the ambition level displayed in the European Green Deal as well as in this study, the 2040-timeline is deemed realistic.
[75] The benefit pool is estimated to be a fuel burn reduction of 259 kilogrammes for a 450 nm flight operated by a standard aircraft (Airbus A320). In the model used for this study, flights operated using A320-family aircraft on distances between 350 and 550 nm consume an average of 4032 kilogrammes (over an average flight distance of 447 nm). 259 / 4032 × 100% = 6.42%.
[76] Nevertheless, Ryerson, Hansen and Bonn (2014, p. 297) argue that an earlier version of the FAA/EUROCONTROL-report “may be too conservative”, seeing a “substantially greater” benefit pool associated with improved terminal efficiency in their research results than reported by the FAA and EUROCONTROL. On the other hand, the Ryerson-study is limited to the US. As such, its argument of conservatism need not apply to the European situation.
[77] Figures relating to the environmental efficiency of current air traffic presented in the recent SES2+ Staff Working Document (EC, 2020a) have not been used in this study, as it refers to the EUROCONTROL-analyses also referred to in the SWD. In addition, the “several % points of additional emissions” referred to in the SWD are linked to “the congestion and necessary re-routing of many flights” in recent years. Interpreting this as a reference to the 2019 capacity crunch, these additional emissions would not be part of this study anyway, as it uses 2018 as a baseline.
[78] The total CO_2 emissions reduction potential identified by both sources varied from the number derived from literature in this report. Lacking more detailed information, it is assumed here that the relative contributions of different flight phases do not change with a higher or lower overall improvement potential.
[79] Rather than choosing 0 or 50%, a value of 75% is selected because of the fact that there are also synergistic effects – measures that reduce both CO_2 emissions as well as noise. Continuous descent operations (or rather: optimised descent profiles) are a prime example.

- An average value combining the two sources. Contributions from the more detailed elements listed in the ATM Master Plan are computed by splitting the average according to the ratio determined using the Master Plan. For example, given an averaged potential improvement of 13.8% for airport operations, 65% × 13.8% = 9.0% is contributed by taxi-out and 35% × 13.8% = 4.8% is delivered by taxi-in.
- The potential improvement per flight phase. This is found by multiplying the average share of the total SES(AR) improvement potential by the total SES(AR) improvement potential, determined previously as 5.3%.
- The applicability of the different potential improvements to different types of flight considered within the scope of the present study. For intercontinental flights (i.e., extra-EU+), it is assumed that 50% of the en-route distance travelled is within airspace covered in the SES programme.

Table 15: Breakdown of the total quantified SES(AR) improvement potential of 5.3% over different flight phases (SESAR JU, 2019b; SESAR JU, 2019d; SESAR JU, 2019e)

Flight phase	Share of quantified potential SES(AR) improvement			Potential CO_2 reduction	Applicability
	Website	EU ATM MP2020[80]	Average		
Airport operations	75 / 500 = 15%	23 / 182 = 12.6%	13.8%	0.73%	
Taxi-out		15 / 182 = 8.2% (65%)	9.0%	0.48%	All
Taxi-in		8 / 182 = 4.4% (35%)	4.8%	0.25%	Intra-EU+
Climb/descent (TMA)	325 / 500 = 65%	67 / 182 = 36.8%	50.9%	2.70%	
Climb		2 / 182 = 1.1% (3%)	1.5%	0.08%	All, 75%
Descent		21 / 182 = 11.5% (31%)	16.0%	0.85%	Intra-EU+, 75%
Holding		44 / 182 = 24.2% (66%)	33.4%	1.77%	Intra-EU+
En-route	100 / 500 = 20%	92 / 182 = 50.6%	35.3%	1.87%	
Horizontal efficiency		55 / 182 = 30.2% (60%)	21.1%	1.12%	100% intra-EU+; 50% extra-EU+, dep. only
Vertical efficiency		37 / 182 = 20.4% (40%)	14.2%	0.75%	100% intra-EU+; 50% extra-EU+, dep. only

Table 15 shows the total quantified improvement potential of 5.1%[81] is fully applicable to intra-EU+ flights. For departing extra-EU+ flights, this value is reduced to 1.5%[82]. An additional improvement potential of 3.6%[83] for arriving extra-EU+ flights is noted, but (given the selected scope, as documented in Section 1.4.3) not modelled. Similarly, an additional en-route improvement potential of 1.9% is noted – but again not modelled – for flights that either not depart from or not arrive at a European airport.

> **EFFECTS OF TRAFFIC GROWTH ON ACHIEVABLE EFFICIENCY**
> Even though concerns to that extent are shared by various stakeholders, no discounts are applied to compensate for the potentially negative impacts of traffic growth on efficiency. This is because no sources could be found that quantify that impact. Furthermore, it is noted that original SES goals targeted simultaneous efficiency improvement and a three-fold capacity increase. When the SES programme was launched in 2004, there were approximately 9 million IFR movements (EUROCONTROL, 2018b), leading to a goal of 27 million movements after SES implementation. In the present report, a 1.4% annual growth in the number of flights is anticipated (Figure 5) relative to 2018. Given 11 million flights in 2018 (EUROCONTROL, 2019b), this yields approximately 13.6 and 17 million flights in 2035 and 2050[84], respectively. For 2035, this is below the ambition value of 15.7 million flights expressed in the 2020 European ATM Master Plan (SESAR JU, 2019d),

[80] The cited document states breaking down 173 kilogrammes of additional fuel burn, but component values add up to 182 kgs. This is a consequence of the fact that in the 173 kilogrammes estimate, discounts are applied for arrivals and/or departures outside the ECAC area (SESAR JU, 2019e, p. 17). As such, factors are based on the 182 kilogramme total.
[81] Summing the contributions from airport operations, climb/descent and en-route: 0.73% + (0.08% × 75% + 0.85% × 75% + 1.77%) + 1.87% = 5.1%.
[82] Again, summing the contributions from airport operations, climb/descent and en-route: 0.48% + (0.08% × 75%) + (1.87% × 50%) = 1.5%.
[83] Computed by taking the difference from 5.1% and 1.5%.
[84] This number is different from the figure reported in Section 2.3.1 (12.4 million in 2050), as that is limited to flights departing EU airports.

> which is presented in concert with environmental improvements. Also, the aforementioned Master Plan takes into account the growth projections from EUROCONTROL (2018b) that underlie the present study (SESAR JU, 2019e, p. 8).

Further CO_2 emissions reduction potential

A number of recent analyses and reports suggests that the CO_2 reduction potential derived and quantified in the foregoing pages does not capture the full decarbonisation potential that exists. EUROCONTROL (Vranjkovic & Brain, 2020), for example, suggests that "further inefficiencies exist" which might only be demonstrated by "indicators that are directly based on CO_2 emissions".

A more detailed EUROCONTROL study (2020a) utilising a different metric for assessing fuel inefficiency also shows significantly higher reduction potential than the excess gate-to-gate emissions noted in other publications (such as the PRR; EUROCONTROL, 2019b). Rather than distance-based current regulatory metrics as KEP (based on last filed flight plan) and KEA (based on actual route), EUROCONTROL used the 10th percentile fuel-burn observed for each combination of airport pair and aircraft type as benchmark for determining the excess fuel burn (and subsequent CO_2 emissions) of the remaining 90% of flights. Contrary to distance-based metrics, this new metric is likely to capture – at least to some extent – favourable operating conditions, such as beneficial tailwinds or avoidance of headwinds, even though distances flown may be longer. Indeed, and as noted in Section 4.2.1, the shortest route may not be the most fuel- and thereby CO_2-efficient route. ICAO (2014a) lists numerous examples and this concept is also applied on flights between Europe and North-America, the Middle East and Australia, and in Asia where airlines and ANSPs work together to plan their daily operations taking account of forecast metrological conditions. Such route optimisation can also have a beneficial effect on non-CO_2 effects, such as contrail cirrus.

Last, it could not be definitively determined to what extent the improvement potential quantified earlier might be constrained by inefficiencies that are accepted as given in the 'optimum reference' of studies referred to, whereas such inefficiencies might actually be (partially or fully) resolved by the EU wide implementation of solutions developed in SESAR – creating a truly seamless and digital single European sky.

Detailed system-level assessments on the impact of optimising for CO_2 emissions are presently unknown to the authors of this study. The further inefficiencies discussed are estimated to lie between 0 and 4% by Vranjkovic & Brain (2020). Due to the significant uncertainty, and as Vranjkovic & Brain (2020) also refer to new concepts (such as wake energy retrieval, discussed in Section 4.3.4) as a way to reducing these excess emissions, the potential is modelled in this study as 2%, applicable to all flights within the scope. That means that the total SES(AR) CO_2 emissions reduction potential grows to 7.1% for intra-EU+ flights and to 3.5% for departing extra-EU+ flights. Due to the uncertainties associated to the additional 2% improvement potential, that impact is modelled five years later (delivery between 2025 and 2040) than the previously identified 1.5 to 5.1%.

4.3.2 Non-European ATM efficiency improvement

In addition to the ATM modernisation and efficiency improvements underway in Europe as part of the Single European Sky initiative (discussed in greater detail in Section 4.3.1), similar goals are pursued elsewhere around the world. Even though European policymakers can only aim to indirectly influence such efforts, notable improvements are anticipated that do directly influence the fuel consumption and associated CO_2 emissions of flights departing European airports[85].

[85] Further elaborated in Section 1.4.3, all emissions of flights departing from EU+ airports are considered in the scope of this study.

Potential impact

The size of the anticipated improvement is based on studies conducted previously. CANSO (2012)[86] set global ATM efficiency goals for 2020 (between 93 and 95%) and 2050 (95 – 98%), compared to a baseline in 2005 (92 – 94%). The 2020-goal aligns well with estimates on the current EU+ ATM efficiency (approximately 6%; further discussed in Section 4.3.1). Efficiency numbers from 2017, analysed and presented in the 2019 ICAO Environmental Report are slightly higher (between 94 and 98%, 95% when averaged based on 2018 traffic volumes from ICAO, 2018b), but only include horizontal en-route flight efficiency (Brain & Voorbach, 2019). In contrast, the CANSO-study investigated the complete trip as well as vertical flight efficiency, and thereby is found to provide a more realistic assessment of the available improvement potential. The total non-European ATM efficiency improvement is therefore estimated at 3%.

This is slightly above the 2.5% mentioned by the 2016-version of the Sustainable Aviation UK roadmap (Sustainable Aviation UK, 2016), but in the lower half of the range presented in the 2020-version (being 0 to 8%; Sustainable Aviation, 2020a). Given the fact that ICAO CAEP has set a 92 to 96% efficiency goal for 2026 (Brain & Voorbach, 2019) and SES(AR) implementation is foreseen by 2035, the 2050-timeline anticipated by CANSO (2012) and Sustainable Aviation (2020a) are shortened by ten years. This means the CO_2 reduction potential is to be delivered by 2040.

In order to avoid double-counting with the anticipated CO_2 reductions delivered by SES(AR), the improvement potential identified here is only applied to flights that depart to a non-EU+ destination. Nevertheless, it is additional to the 1.5% identified in Section 4.3.1. Based on the previously computed 3.6% of noted but unmodelled emissions reduction potential in Section 4.3.1 (below Table 15), the value of 3% is reduced to 2.1%[87]. This corrects for the fact that even for flights to non-EU+ destination, a SES(AR)-based savings potential due to improvements during taxi-out, climb-out and 50% of the cruise phase (per Table 15) was identified. Also, consistent with Section 4.3.1, this correction takes into account that only 75% of the CO_2 emissions reduction potential in the TMA can be realised due to interdependencies between noise and CO_2.

4.3.3 Improved North-Atlantic flight efficiency

A large portion of aircraft flying between Europe and (North-)America currently cross the Atlantic Ocean using the so-called North-Atlantic Tracks (officially the North-Atlantic Organised Track System, abbreviated to NAT-OTS). Lacking the means to accurately track the position of aircraft in this area, these routes were designed in the 1960s to enable safe oceanic crossings.

Overview

The working principle behind NAT-OTS is straightforward. The system consists of a number of fixed routes, which change twice a day depending on weather conditions. These routes are designed to exploit beneficial tailwinds flying East and prevent adverse headwinds flying West. Based on airline preferences indicated earlier, the final routes are published in advance in order to allow airlines to file their flight plan. Oceanic controllers then assign a particular track (and altitude) to a flight, thereby effectively defining a tunnel through which the flight has to be operated. Given the fact that speeds are also fixed, the position of aircraft can be predicted during the crossing. If an aircraft is detected at a particular waypoint (either at the start of the tracks or at an intermediate checkpoint), multiplication of time and velocity allows computing the distance travelled – and thereby determining the current location.

[86] Even though this report is based on older data, more recent updates could not be found. Also, the CANSO-report is still referred to in other much more recent reports (ATAG, 2020b).
[87] 3% × (3.6 / 5.1) = 3% × 0.71 = 2.1%.

Developments and improvement potential

Since its inception, the NAT-OTS has seen numerous improvements. Fairly recently, vertical as well as lateral separation minima were reduced (RVSM and RLAT), increasing capacity of the tracks. This allows more flights to use their preferred – fuel-burn optimised – track.

A more significant change – and according to some “the beginning of the end of the OTS”[88] – is formed by the introduction of Automatic Dependent Surveillance - Broadcast (ADS-B) coverage over the North-Atlantic, enabled by using space-based receivers which relay their signals to ANSPs on both sides of the Atlantic. ADS-B equipment will be mandatory for aircraft used in United States, European and Canadian airspace from January 2020, December 2020 and February 2021 onwards, respectively (Learmount, 2019a; United States Government Publishing Office, 2011; FAA, 2020; EC, 2014; Learmount, 2019b; SESAR DM, 2020). This requirement means the advantages of this technology over the North-Atlantic airspace can be fully exploited, as the ATM system no longer needs to support older equipment. In addition to further reductions in separation minima and associated capacity advantages from November 2020 onwards, ADS-B is expected to enable aircraft to fly optimal – rather than fixed – speeds (Learmount, 2019a; Osborne, 2019), possibly allowing for further improvements.

Potential impact

According to NATS-estimates, increased use of ADS-B over the North-Atlantic is expected to result in a fuel saving of 400 to 650 kilogrammes per crossing (Learmount, 2019a; Osborne, 2019), equivalent to approximately 1,250 to 2,050 kilogrammes of CO_2. In an earlier study, Sridhar et al. (2015)[89] computed a savings potential of 3 to 5%, equivalent to 420 to 970 kilogrammes of fuel for a Boeing 767-300[90]. For the same routes, the model used in the present study (described in Section 2.1) shows the absolute fuel burn reduction is equivalent to 1.1 to 2.6%. As it cannot be established what model offers the best approximation, an averaged range of 2 to 3.8% is used. Combining these numbers, a savings potential of 2.9% is estimated. As not all traffic uses the OTS, the savings potential is applied to 45% of flights over the period 2020 to 2027[91].

4.3.4 Wake energy retrieval

A more disruptive improvement potential under renewed attention is wake-energy retrieval, also known as cooperative trajectories or extended formation flight (Warwick, 2020; Flanzer, Bieniawski, & Brown, 2020). In this operational concept, aircraft fly closer together than usual (reducing separation to approximately one nautical mile). Most relevant to long-haul operations, academic studies estimate formation-level reductions in fuel burn between 2 and 12%, depending on cruise Mach number (Bergmans & den Boer, 2012; Voskuijl, 2017). Recently, this idea has also received increased attention from the industry. Boeing showed a 10% fuel burn benefit (5% at formation level) in flight tests in 2018 with two Boeing 777 Freighter aircraft (Norris, 2019), and Airbus announced similar plans, targeting 5 to 10% better fuel economy and expecting entry into service in the first half of this decade (Airbus, 2019a; 2019d). Flanzer, Bieniawski & Brown (2020) estimate that the potential is 3% for each aircraft part of a formation – taking into account that wake-energy retrieval will only be possible in the cruise phase of the flight and splitting the savings equally over both aircraft. Dahlmann et al. (2020) observed a larger reduction potential and noted especially

[88] Osborne (2019), citing Andy Smith of UK ANSP NATS.
[89] Sridhar et al. (2015, p. 1) have examined “the benefits of a wind-optimal trajectory concept with a strategic de-confliction component compared to the current flight planning using the North Atlantic Tracks”, enabled by the “availability of Automated Dependent Surveillance-Broadcast”.
[90] The difference between these figures and the NATS-estimate are most likely caused by fleet renewal over the years between the assessments (Sridhar et al. use data from 2012; the NATS-estimates were made in 2019) and a limitation in city pair coverage (Sridhar et al. have only considered transatlantic flights between the United States and Europe).
[91] EUROCONTROL (2017) estimated in August 2017 that 50% of flights used the OTS; Osborne (2019) estimated in September 2019 that this number had reduced to 38%, a reduction of 12% in 25 months, approximately equivalent to a reduction of 0.5% per month. Taking 50% in August 2017, this rate yields an estimated OTS use of 48% in January 2018 (the reference year used in this study) and 42% in December 2018 – averaging 45%. At the current rate, this will reach zero in 90 months or 7.5 years from January 2019.

significant non-CO_2 effects. This study follows Flanzer, Bieniawski & Brown (2020) and models a 3% fuel efficiency savings for flights using wake-energy retrieval.

Notwithstanding the potential, the concept is not yet mature and requires substantial work – not only from an air traffic management perspective, but also from the side of manufacturers and operators. Many questions on operational application for example still exist: how can safety be guaranteed, how will the costs and benefits be shared, what routes are suitable, how will airline schedules be affected?

Following airline operational flight tests in the next few years (Sustainable Aviation, 2020a), implementation is estimated to be able to start from 2025 on flights between Europe and North-America (Dumont, 2020). Full adoption is anticipated in 2032. From 2030 to 2040, the scope is expanded to include other routes such that by 2040, these benefits are obtained for 50% of flights. It is assumed that cost savings associated to realising reductions in fuel burn offset any expenditures following these improvement programmes (Flanzer, Bieniawski, & Brown, 2020).

4.3.5 Potential impact overview

Table 16 provides an overview of potential impacts of airspace and ATM-related improvements discussed in this section. With the exception of the non-European ATM efficiency improvement and part of the CO_2 emissions reduction delivered by improved NAT-efficiency and the introduction of wake energy retrieval, all improvements concern EU+ airspace.

Table 16: Potential CO_2 emissions reductions to be delivered by airspace and ATM-related improvements per flight

Measure	Potential CO_2 emissions reduction	Starting year	Delivered by	Remarks
Single European Sky / SESAR – intra-EU+	5.1%	2020	2035	
Single European Sky / SESAR – extra-EU+	1.5%	2020	2035	Intercontinental departures only
Single European Sky / SESAR – further CO_2 emissions reduction potential	2%	2025	2040	
Non-European ATM efficiency improvement	2.1%	2020	2040	Intercontinental departures only
Improved North-Atlantic flight-efficiency	2.9% × 0.45 = 1.3%	2020	2027	Flights from Europe to North-America
Wake energy retrieval	3%	2025	2032	Flights from Europe to North-America
		2030	2040	Other flights, up to 50% combined

4.4 Ground operations at airports

This section considers ground operations. As indicated in Section 1.4, the present study is limited to emissions from aircraft operations, here further limited to emissions while parked at the gate or stand, and associated to movement between the gate and runway. As such, this section does not consider emissions generated by for example ground support equipment (GSE). Also, emission reductions following from (improved) information sharing and collaborative decision making, as considered within the SESAR programme, are assumed to be included in the potential improvement numbers listed in Section 4.2.4. For the present section, this leaves two main items of interest: reduced emission taxi and reduced APU usage. These are treated in Sections 4.4.1 and 4.4.2, respectively. Section 4.4.3 provides an overview of potential impacts.

It is relevant to note that besides reducing CO_2 emissions, the measures listed in this section often also reduce noise and other emissions and thereby contribute to improving local air quality. Furthermore, following ACI EUROPE's commitment for net zero carbon emissions by 2050 (ACI Europe, 2019) and an accelerated clean energy transition in the European Union, it is assumed that by 2050 at the latest, ground-based energy supplies at airports that are used to replace aircraft-based power generation are completely renewable.

4.4.1 Reducing taxi emissions

At the start and end of every flight mission, the aircraft needs to move from the apron to the runway and vice versa. In case the aircraft does so using its own power, this is called taxiing. In case another vehicle is used, this is called towing. For departing flights, taxiing or towing is generally preceded by push-back using a push-back truck. Even though the amount of fuel burnt during the transport between apron and runway is limited compared to the fuel burnt during flight, there are various ways in which this consumption can be further reduced[92].

An option available and regularly applied today is reduced engine taxi, in which one or more of the aircrafts' engines are shut down during taxiing. Various analyses have shown this can reduce taxi fuel consumption by 20 to 40% for arriving and 20 to 45% for departing flights (AviationPros, 2011; Koudis, Hu, Majumdar, Ochieng, & Stettler, 2018; Fleuti & Maraini, 2017; Ithnan, Selderbeek, Beelaerts van Blokland, & Lodewijks, 2013; Deonandan & Balakrishnan, 2010). Figures for departing flights are slightly higher, for instance because of longer taxi-out times (due to aircraft sequencing, possible de-icing, etc.) and the higher aircraft weight at that time, and below 50% due to engine warm-up requirements for the non-operational engine(s)[93]. Combining these numbers, an improvement potential of 30% is estimated for each arriving and 35% for each departing aircraft that moves from all-engine taxi to reduced engine taxi.

Opportunities to further reduce emissions during taxiing are electric taxi and operational towing – the latter using a tow tractor powered by fossil fuels, bio-fuels or electricity. As industry development of solutions integrating an electric motor in the aircraft gear were recently abandoned (Dubois, 2019), the remainder of the text is focussed on operational towing[94], for which certified systems currently only exist for use on some single aisle aircraft. In this procedure, the aircraft engines can remain switched off during the majority of ground operations. The emission savings depend on the energy used by the tow tractor, noting it has to return to the apron (or runway) after towing the aircraft. For various alternatives powered by bio-fuels, estimates range from 25% to 75% compared to aircraft taxiing with all engines running (Deonandan & Balakrishnan, 2010; Ithnan, Selderbeek, Beelaerts van Blokland, & Lodewijks, 2013). If an electric tow truck is used, potential savings increase to 85% of taxi emissions (Srivastava, 2018; EEA, EASA & EUROCONTROL, 2019). Taking into account that aircraft power would have to be sourced from the APU if the engines are not running, the effective savings are assumed to be 75%. Other potential benefits of autonomous tow vehicles or systems include reduced noise (if electric) and other gaseous emissions.

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[92] In order to avoid double counting of potential emissions reduction with SES(AR), discussed in Section 4.3.1, benefits to be delivered through e.g. (support systems for) surface movement planning, System-Wide Information Management (SWIM), etc.

[93] Deonandan and Balakrishhnan (2010) estimated warm-up time to be between 2 and 5 minutes. Hemmerdinger (2016) notes an industry standard of "less than 1" minute.

[94] Nevertheless, e-taxi solutions might receive renewed interest (Airbus, 2013). Savings potential is estimated to be similar, although the aircraft weight increase due to the e-taxi system is a key challenge to overcome.

There is little public information about the amount of fuel that is used during taxiing operations compared to the total amount of fuel consumed during a flight. Lacking a more recent reference that takes a broader perspective than one airport, airline or aircraft type, generic estimates are sourced from a standard work on aircraft design. This states that after having taxied to the runway, a departing aircraft has lost 1% of the weight it had as it begun the taxi phase due to burning fuel (Roskam, 1985). Upon arrival, the weight decrease is approximately 0.5% for landing, taxi and shutdown[95]. Assuming some 35% of the starting weight of long-haul aircraft is fuel, a 1% weight decrease corresponds to 3.5% of fuel consumed during taxi-out. For taxi-in, 0.5% of the weight of the aircraft and passengers can be translated to approximately 1% of the original fuel weight[96]. Adding these together results in 4.5%. However, fuel consumption has reduced since the aforementioned source was published. Using the 1968 to 2014 compounded annual rate of fuel burn reduction of 1.3% per year (Kharina & Rutherford, 2015), the 4.5% is decreased to 3%. For single aisle aircraft, generally used on short haul routes, more information is available. Lawson (2016) approximates that 6% of fuel is burnt on the ground. With 1% for ground APU usage (based on Department for Transport (2017)), this leaves 5% for taxi fuel, which is consistent with assumptions by Schäfer, Evans, Reynolds & Dray (2015) and results by Turgut et al. (2014) and Fleuti & Maraini (2017).

From 2020 up to 2025, the adoption of reduced engine taxi is here assumed to increase from a currently estimated 40 to 80%, yielding a reduction in mission-level fuel consumption of 0.2 to 0.4% for arriving and departing short haul flights and 0.1 to 0.3% for arriving and departing long haul flights[97]. A 80% limit is set to take into account operational circumstances where reduced engine taxi might not be safe, for instance due to increased single-engine jet blast. The split between short haul and long haul aircraft is set at 3500 kilometres. From 2025 up to 2035 commercial application of electric taxi or electrified operational towing solutions is anticipated. Compared to reduced engine taxi, this has the potential of delivering an additional benefit of 0.8% to 1.2% for short haul and 0.3% to 0.9% for long haul flights[98]. Due to the scope of the present study, benefits for arriving aircraft are only taken into account for intra-EU+ flights. As operational towing also relieves the aircraft of the need to carry taxi fuel, an additional weight saving of 175 to 600 kilogrammes is estimated[99] – to be translated into an additional fuel saving using a cost of weight factor of 3.5% per flight hour (the same as used in Section 4.2.2). This only considers taxi-in fuel, as taxi-out fuel is not carried along over the flight.

In addition to the aforementioned changes to the energy source used for transporting the aircraft between apron and runway and vice versa, it is relevant to qualitatively address the influence of airport design as well. Small distances between the runway and terminal of course reduce taxi emissions, but there are other less straightforward measures that can have a positive effect. Examples include high-speed runway exits and associated high-speed taxiway turns, multiple taxiway-runway connections allowing for intersection take-offs and taxiways that allow aircraft to taxi around active runways, preventing them from waiting and idling (Fala, Uday, Le, & Marais, 2014). Although improvement potential is likely to exist, a lack of quantitative input data makes that these measures are not included in the model.

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[95] As most almost all of the fuel will be burnt during the flight, the weight upon arrival is notably lower than on departure – even more so for long-range aircraft.

[96] (1 – 0.35) / 0.35 × 0.5% = 1.85 × 0.5% ≈ 1%

[97] Taxi fuel savings of 30% to 35% × 3% to 5% of total emissions × (80 – 40)% application.

[98] In case all engines are used, taxi accounts for 3 to 5% of total fuel burn. If reduced engine taxi is used – yielding 30 to 35% reductions – in 80% of cases, taxi emissions reduce to 2.6% (taxi-in) and 1.8% (taxi-out) for short haul flights and 0.6% (taxi-in) and 2% (taxi-out) for long haul flights. This assumes a 40:60 split over taxi-in and -out for short haul flights and a 2:7 split for long haul flights, following footnote 96. Electric operational towing reduces taxi emissions to 2% for short haul flights and 1.2% for long haul flights in total. (In that case, mission fuel consumption of short haul flights would be reduced by 3 ppt, largely consistent with performance estimates of (recently shelved) e-taxi solutions incorporating electric nose gears (Airbus, 2013; Air Transport Action Group, 2015; Dubois, 2019).) The remaining difference hence becomes 0.8 to 1.2 ppt for arriving and departing short haul flights and 0.3 to 0.9 ppt for arriving and departing long haul flights.

[99] For long haul aircraft, it was found using Roskam (1985) that the fuel required for taxi-out is approximately 3.5% of the total fuel weight. For taxi-in, this was estimated to be 1% - or 2/9th of the total fuel used for taxiing. Applying the fuel burn improvement since the publication of Roskam lowers the taxi fuel amount to 3%, without changing the ratio. As such, it is estimated that 2/9 × 3% = 0.667% of the fuel weight for long haul aircraft is consumed using taxi-in. Assuming 35% of the take-off weight of such an aircraft is fuel, the taxi-in fuel weight is 0.667% × 35% = 0.233% of the take-off weight. Given a typical long haul take off weight of 250 tonnes, this translates into 582.5 kilogrammes. For short haul aircraft, the taxi fuel was found to be 5% of total fuel. Applying the same ratio to split this number between taxi-out and taxi-in and assuming fuel weight now only makes up 20% of the take-off weight, 5% × 2/9 × 20% = 0.222% of the take-off weight is estimated to be taxi-in fuel. Given a typical short haul take off weight of 80 tonnes, this translates into 177.6 kilogrammes.

4.4.2 Reduced APU usage

According to the UK Department for Transport (2017, p. 109), 1% of the emissions of a flight is associated with the use of the auxiliary power unit (APU), which is used to power on-board systems. Feeding aircraft with electrical ground-power from a fixed (FEGP) or mobile source (e-GPU) and/or using fixed or mobile pre-conditioned air (PCA) enables a reduction in APU usage. Based on data from Heathrow, Zurich and Barcelona El Prat airports, a fuel saving potential of 0.4% per flight is assumed (ATAG, 2015). Given the fact that various airports already apply these practices, this number is reduced to 0.3% to be realised between 2020 and 2025. A fairly long implementation period is anticipated as the full emission reduction potential can only be realised when renewable energy is used. In newer aircraft, this reduction might also be realised by fuel-cell powered APUs, discussed in Section 3.3.1.

4.4.3 Potential impact overview

Table 17 provides an overview of potential impacts of the ground-related operational improvements at airports discussed in this section. 'SH' indicates short haul flights (below 3500 kilometres); LH indicates long haul flights (3500 kilometres and up). Weight savings listed in the column 'potential CO_2 emissions reduction', for example as a result of lighter cabin equipment or reduced fuel load, are translated into fuel savings on a flight-by-flight basis using a cost-of-weight computation (further explained in Section 4.2.2, specifically footnote 60 on page 56).

Table 17: Potential CO_2 emissions reduction to be delivered by ground-related operational improvements at airports per flight

<table>
<tr><th>Measure</th><th>Potential CO₂ emissions reduction</th><th>Starting year</th><th>Delivered by</th><th>Remarks</th></tr>
<tr><td>Reduced engine taxi – SH</td><td>0.2%</td><td>2020</td><td>2025</td><td rowspan="2">Intra-EU+ arrivals only</td></tr>
<tr><td>Reduced engine taxi – LH</td><td>0.1%</td><td>2020</td><td>2025</td></tr>
<tr><td>Reduced engine taxi – SH</td><td>0.4%</td><td>2020</td><td>2025</td><td rowspan="2">Departures only</td></tr>
<tr><td>Reduced engine taxi – LH</td><td>0.3%</td><td>2020</td><td>2025</td></tr>
<tr><td>Electric taxi / operational towing – SH</td><td>0.8%</td><td>2025</td><td>2035</td><td rowspan="2">Intra-EU+ arrivals only</td></tr>
<tr><td>Electric taxi / operational towing – LH</td><td>0.3%</td><td>2025</td><td>2035</td></tr>
<tr><td>Electric taxi / operational towing – SH</td><td>1.2% + 175 kg weight reduction</td><td>2025</td><td>2035</td><td rowspan="2">Departures only, weight saving modelled using 3.5% cost of weight per block hour</td></tr>
<tr><td>Electric taxi / operational towing – LH</td><td>0.9% + 600 kg weight reduction</td><td>2025</td><td>2035</td></tr>
<tr><td>Reduced APU usage</td><td>0.3%</td><td>2020</td><td>2025</td><td></td></tr>
</table>

4.5 Drivers and barriers

The previous section already showed and discussed the substantial amount of complexities associated with ATM and aircraft operations. The current section specifically discusses drivers and barriers – elements inspiring or speeding up fuel burn improvement and aspects hindering or slowing the realisation of potential emissions savings.

4.5.1 Drivers

Besides the all-encompassing and ever-increasing political, governmental and societal push towards reducing CO_2 emissions, various specific developments and trends drive the implementation of the ATM and operational measures described in this chapter. It is stressed that these developments are *drivers*: they directly or indirectly contribute to a particular effect, but need not necessarily be the most effective agents for change.

As holds for the other chapters, this section describes what the authors of this report have determined to be the most important drivers, rather than presenting an exhaustive listing. Nevertheless, especially given the attention this chapter pays to emissions around airports, it is acknowledged that CO_2 reductions often yield benefits in terms of improved air quality and reduced noise emissions in the landing and take-off (LTO) cycle. Similarly, measures designed to reduce these environmental impacts can result in reductions in CO_2. On the other hand, there are also situations where trade-offs are necessary.

Current and short-term: reducing cost, automation and improving CNS accuracy and performance
Already at present, reducing fuel consumption and CO_2 emissions is often in line with reducing direct operating cost. This provides airline business with a clear economic incentive to reduce their environmental impact. In case the share of fuel(-related) costs in the total direct operating cost increases, this driver is strengthened. This might for instance be the result of an increase in oil price, or a reduction in ATM charges or crew cost.

As relevant for the aviation sector as for many other sectors, increasing computational power, (big) data availability and artificial intelligence (AI) present opportunities in airspace and flight modelling, simulation, prediction and optimisation. This is relevant for almost all aspects treated in this chapter. Examples include improving weather predictions, taking more parameters into account in flight (re-)planning efforts, predicting future aircraft trajectories and associated separation distances, and improving revenue management systems to realise higher load factors. Further towards 2050, these developments are crucial in further ATM automation.

Related to the previous item, increasing accuracy and performance of communication, navigation and surveillance (CNS) equipment, such as ADS-B and ground- or space-based augmentation systems, enable more precise positioning and navigation. This is absolutely necessary for effective wake energy retrieval (discussed in Section 4.3.4), but also enables reduced separation minima. This in turn might increase available airspace capacity, such that more aircraft can achieve their optimum flight path and profile in both a horizontal and vertical dimension. For such potential benefits to be captured in a safe manner, a much higher predictability of traffic mentioned in the previous paragraph is one of the many requirements that must be met.

Medium and long-term: accommodation of other airspace users, further automation and personnel changes
Although their environmental impact is not considered in this report, the introduction of drones and urban air mobility systems undoubtably presents challenges to the current ATM system and drives ATM innovation. Closely coupled to AI and increased automation, techniques initially developed to file and check flight plans of automated flight systems (which lack a pilot to communicate through) might someday be applied to larger commercial aircraft as well. Combined with improved flight planning software and flight management systems, this could enable real-time changes to flight trajectories in order to make use of favourable weather conditions.

An additional driver for automation is formed by (anticipated) changes in personnel duties. Air traffic control officers are likely to shift towards a more supervisory position and single pilot cockpits are foreseen in the next decades. Possible personnel shortages can further strengthen this driver. In the shorter term, increased automation can be used to support air traffic control officers in their duties and improve their efficiency.

4.5.2 Barriers

In addition to the drivers identified in Section 4.5.1, numerous developments or industry characteristics make it more difficult to realise the improvements laid out in this chapter. An overall barrier, also applicable to other pillars considered in this report, is formed by the substantial (financial) risks associated with most – if not all – potential improvements that are outlined.

Further discussing barriers, it is relevant to re-emphasize the complexity identified at the beginning of this chapter. Although in all cases encapsulated in a regulatory environment, airlines can fairly independently carry out some weight reductions (e.g. reducing supplies), whereas OEMs need to be involved in cases that might influence the functioning of the aircraft. Similarly, reducing CO_2 emissions en-route requires a joint effort by airlines as well as ANSPs – who also have to take into account other (possibly military) airspace users. Last, ground handlers influence efforts towards reducing APU and taxi emissions.

Interdependencies and lack of alignment

This complexity is not a barrier per se, although it generally requires a lot of discussion and negotiation to actually enable change. Different actors have different interests and ANSPs and airport operators face dilemmas in trading off between reductions in noise and reductions in emissions. Airports are scored based on departure punctuality – even though making sure one flight departs on time might require an incoming aircraft to deviate from its optimised descent profile[100]. Airlines have to balance environmental efforts to maintaining competitive cost levels. And at a regulatory and political level, national interests and lack of political willingness are often cited as barriers to progress in the realisation of the Single European Sky that (as seen in Section 4.3.1) can substantially contribute to lowering CO_2 emissions. In general, different priorities and the requirement to balance the numerous interdependent factors (e.g. CO_2 emissions, noise and local air quality, as well as non-environmental aspects) hamper progress towards lowering the environmental impact of aircraft operations.

Traffic growth and fragmentation

In addition to the aforementioned shortage of and focus on specific and clearly-defined common goals (by both industry as well as governmental or regulatory organisations), some more specific barriers can be mentioned. A primary challenge is ensuring a sustainable COVID-recovery, followed by accommodating the post-COVID long-term traffic growth that is anticipated – also in this report. As indicated in Section 4.3.1, a number of organisations and individual industry experts are worried that the improvement potential in ATM is reduced by an increasing number of flights[101]. A lack of standardised ways of exchanging data between parties (ANSPs amongst each other, but also with other parties) and limited interoperability make for a fragmented ATM system, hindering faster and more universal implementation of new procedures. Besides, some actors have for instance cited a lack of competition amongst ANSPs as hurdle towards innovation. Notwithstanding the fact that other mechanisms – such as customer satisfaction and feedback, the ANSP Performance and Charging Scheme and changing legislation – are (put) in place to stimulate innovation, it is true that competition can act as a catalyst for change.

New entrants

Despite its listing as a driver, the increasing variety (and number) of airspace users comes with disadvantages as well. Rather than being able to design the airspace system for only commercial aircraft of a certain weight class, other types of vehicles – with different operational limitations – have to be integrated into the system. This might result in a situation where compromises have to be made. Another barrier closely related to a driver is that the aviation sector

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[100] ACI EUROPE has embraced the shift towards arrival management and punctuality, even though station management of airlines is not seldomly assessed on departure punctuality.

[101] As a concrete example: if safety concerns require the current separation standards, and traffic between A and B in a particular period of time is increased, some of that additional traffic might have to take a detour through less congested parts of airspace – even though this increases fuel burn and CO_2 emissions.

for a variety of reasons is not the easiest to new entrants – although entrepreneurial spirits might exactly be the ones best suited for introducing step-change innovations, for example in terms of artificial intelligence.

Regulation, certification and authorisation

Last, it is noted that time- and cost-intensive regulation, certification and authorisation processes are a barrier to realising change rapidly. The international context, and the need for rules and regulations to be consistent around large parts of the globe, makes this a difficult problem to solve. Industry experts spoken to in the context of this study further indicated that constraints on personnel availability for non-operational tasks sometimes make it more difficult to achieve progress quickly.

4.6 Policies and actions

Having identified a substantial list of potential improvements with respect to ATM and aircraft operations in the previous sections, it is stressed again that these will not realise themselves on their own. Policies and actions from governments as well as industry are necessary to realise the full potential and impact of the solutions discussed. They are often directly related to the drivers and barriers discussed in Section 4.5.

Given the fact that many of the possible improvements can be implemented in the short- to medium-term, decisive and quick actions are necessary. This holds as much for the development and implementation of policies as for efforts to be taken by sector parties.

The remainder of this section treats policies (Section 4.6.1) and actions (Section 4.6.2) in greater detail. Although overlap does exist, policies are mostly related to government or regulatory bodies, whereas actions are largely aimed at the aviation industry.

4.6.1 Policies

The present section provides an overview of policies that are deemed necessary to unlock the potential improvements in ATM and aircraft operations discussed in this chapter. These are derived from literature as well as expert input gathered in the development of Destination 2050.

More specifically, many of the policy recommendations on European ATM stem from or are inspired by fairly recent and still highly relevant reports on the possible future of the SES (ECA, 2017; Wise Persons Group on the Future of the Single European Sky, 2019; SESAR JU, 2019a; ICB, 2019). Given the sheer size and impact of this program, the majority of the present section is dedicated to SES. In reference to the aforementioned studies, it is stressed that whereas these take a broader look at realising the full set of anticipated benefits of the SES (including safety, capacity and cost-efficiency), the present report is limited to potential improvements reducing the environmental impact of aviation.

Irrespective of the exact policy measure, it is stressed in general that long-term, consistent and widely applicable policies are key. This is essential to reducing uncertainty and risk to manageable levels, allowing businesses to plan, invest and prepare for change.

Single European Sky: towards a network-centric and digital ATM system, with regulation and R&D to match

The most important task to realise the environmental improvement potential associated with SES is to replace the rather fragmented system of today with a coherent, network-centric and collaborative ATM system. Defragmentation, enhanced collaboration and a mindset-shift focused on balancing local interests with network interests, should deliver the results that European citizens have been waiting for far too long[102], rather than prioritise the requirements or preferences of any individual ANSP or airspace user. Indeed, as outlined in the communication on the Green Deal, "work on adopting the Commission's proposal on a truly Single European Sky will need to restart, as this will help achieve significant reductions in aviation emissions" (EC, 2019i, p. 10). At the most strategic level, this first requires agreement upon and complete commitment, also by the Member States as shareholders in their ANSPs and by air traffic controllers as the crucial operators, to these shared specific, measurable, achievable, realistic and time-bound objectives[103]. Second, it requires the realisation of concrete milestones – starting now. The following paragraphs outline a number of these, which together help cut CO_2 emissions across European airspace. Even though the present section primarily addresses governmental or regulatory bodies, the required involvement and participation of industry partners is stressed: results cannot be achieved without a joint effort.

Consistent with observations in the aforementioned reports, the conclusion that the FABs as originally intended are not likely to deliver their anticipated benefits is reaffirmed. Therefore, other ways to achieve those same benefits have to be – and are – found[104]. Ever-increasing computational power and networking opportunities were previously listed as important drivers. They enable real-time collaboration, data sharing and virtualisation – moving towards a situation in which airspace boundaries and national sovereignty considerations can be respected, but no longer negatively impact ATM environmental performance (and by extension: Europe's climate neutrality ambitions) as they presently do. This increases possibilities for solutions such as cross border arrival management (XMAN), which reduces the need for aircraft to be placed in holding patterns prior to landing. As a complete and real-time flow of information between stakeholders (ANSPs and airspace users, possibly others) is essential, standardisation of data formats and protocols is required[105]. Relevant stakeholders should be consulted in the development of such standards, in order to guarantee a future-proof foundation. Newly-created ATM Data Service Providers[106] might play a role in supporting a data exchange infrastructure or in effectively collecting and re-distributing relevant information. The development and distribution of consistent near-term traffic flow predictions, made possible by processing all relevant data, is a closely related task. All of this could eventually bring us to a collaboratively operated ATM based on shared goals – including goals with respect to environmental performance and sustainability.

Although efforts to realise this collaborative, cooperatively operated network should start sooner rather than later, it is noted that such changes will take years to fully materialise. In the shorter term, a stronger coordinating role for the Network Manager[107] (as proposed in SES II+ regulation) can be a first step towards a more network-centric view of European ATM. Proposals for airspace re-configuration and redesign of airspace sectors[108] or the creation of a seamless European upper airspace system[109] are also noted as tangible opportunities. Especially the latter measure further advances the ideas of Free Route Airspace and (Advanced) Flexible Use of Airspace. Reducing the differences between unit rates, for example through the introduction of a common upper airspace route charge[110], might (wilfully or not) disincentivise airline operators from using possibly more fuel consuming routes, although possible negative

[102] Following recommendation 2 by the European Court of Auditors (2017), recommendation 2 from the Airspace Architecture Study (SESAR JU, 2019a) and recommendations 1 to 3 by the Wise Persons Group on the Future of the Single European Sky (2019).
[103] Following recommendation 1 by the European Court of Auditors (2017) and paragraph 77 of its report.
[104] Following recommendation 2 by the European Court of Auditors (2017) and recommendation 2 from the Airspace Architecture Study (SESAR JU, 2019a).
[105] Following recommendation 3 by the Wise Persons Group on the Future of the Single European Sky (2019).
[106] Following recommendation 2 from the Airspace Architecture Study (SESAR JU, 2019a) and recommendation 4 by the Wise Persons Group on the Future of the Single European Sky (2019).
[107] Following recommendation 1 by the Wise Persons Group on the Future of the Single European Sky (2019).
[108] Following recommendation 1 from the Airspace Architecture Study (SESAR JU, 2019a).
[109] Following recommendation 9 by the Wise Persons Group on the Future of the Single European Sky (2019).
[110] Following recommendation 9 by the Wise Persons Group on the Future of the Single European Sky (2019), and also discussed in the SES2+ Staff Working Document (EC, 2020a).

consequences should not be overlooked. Financial or other incentives might additionally be used to stimulate more environmentally-friendly flight paths or equipage[111].

In order to guarantee the implementation and application of (technical developments driving) the aforementioned measures, regulatory frameworks should be aligned. Among other things, this means that key performance indicators in the SES Performance and Charging Scheme should be (re-)designed – with input from industry – in such a way that adequate accountability is guaranteed[112]. An updated environmental KPI, for instance, might consist of one part targeted at ANSP performance and one part targeted at airspace user performance. In case in-flight rerouting enables a reduction of flight distance even below the SCR[113], the efforts by both ANSPs and operators should be acknowledged – for example as 'bonus' that can be used to compensate for lower performance elsewhere in the system. In order to take into account that the shortest route might not be most fuel-optimal[114], it should be investigated whether it is possible to objectively determine the most fuel-optimal route and use that distance (or fuel burn metric) – rather than the shortest distance (or fuel burn metric) – in aforementioned environmental KPIs. Such KPIs should take the interdependencies between different (environmental or other) performance areas into account, possibly by defining a particular altitude below which noise is prioritised, and above which CO_2 emissions are focussed on (Ministry of Infrastructure and Water Management, 2020b, pp. 78-79). Reiterating that the Performance and Charging Scheme aims to mitigate negative effects of the monopolistic status of numerous ANSPs, liberalisation might be actively stimulated (e.g. in data and tower service provision) and should in any case not be hampered[115].

In assigning accountability and ownership, the SESAR Joint Undertaking should be held more strictly accountable to the delivery of SESAR Solutions[116] – with the NM or ANSPs subsequently assessed or (financially) stimulated based on the time between delivery and implementation in the operational environment[117]. Such stimuli should strike a balance between rewarding first-movers and preventing unsynchronised deployment, for those cases where synchronisation is required to deliver benefits. National Supervisory Authorities (NSAs) should be able to independently and effectively supervise the ANSPs in their Member State[118]. Given sometimes different local or national priorities, for example in the trade-off between emissions and noise nuisance, it is proposed to investigate how these interdependencies can be accurately reflected in performance targets or requirements. Using separate KPIs for en-route and TMA performance might be one of the available options – although this would contradict efforts increasing harmonisation.

In further support of technology and procedure research and development, the public R&D funding scheme should be reviewed. Whereas current EU ATM R&D efforts are limited in time to 2024, a structure (SESAR JU or other) should be created to address the longer-term R&D effort[119]. This should be fully aligned with the relevant timelines and specifically promote realising innovations that significantly reduce the environmental impact of aviation and thereby improve the situation for the European public at large[120]. Work has already started in this area, in the form of the proposed SESAR 3 Joint Undertaking, clearly focused towards making a contribution to the CO_2 emissions reductions modelled in this study. This will not only strengthen ATM research and innovation capacity in the EU, but explicitly aims "to develop and accelerate the market uptake of innovative solutions to establish the Single European Sky airspace as the most efficient and environmentally friendly sky to fly in the world" (SESAR 3 JU, 2020). In order not to

[111] Following recommendation 5 by the Wise Persons Group on the Future of the Single European Sky (2019), as well as EC (2020a)
[112] Following recommendation 6 by the European Court of Auditors (2017).
[113] A possibility clearly observed in EUROCONTROL (2019b).
[114] Or climate optimal, as for example researched in the Horizon 2020 ClimOP-project (cf. https://cordis.europa.eu/project/id/875503).
[115] Following recommendations 4 and 10 by the Wise Persons Group on the Future of the Single European Sky (2019).
[116] Following recommendation 8 by the European Court of Auditors (2017).
[117] Although formulated more broadly in this report, this policy recommendation aligns well with recommendation 5 by the Wise Persons Group on the Future of the Single European Sky (2019).
[118] Following recommendation 3 by the European Court of Auditors (2017), and also discussed in the SES2+ Staff Working Document (EC, 2020a).
[119] Following recommendation 7 by the European Court of Auditors (2017).
[120] Following recommendations 5 and 7 by the European Court of Auditors (2017).

endanger deployment of currently developed SESAR solutions – bringing proven sustainability and environmental benefits – by the impacts of the COVID-19 pandemic, full public funding for that deployment might be considered.

Last, policies should be put in place to ensure steady progress on delivering the benefits of SES. Although some progress has been made in the previous 15 years and some of the complications during that time have provided relevant insights that support the present recommendations put forward in this section, a repetition of steps would be highly unfortunate. In case new insights in three, five or ten years' time indicate the pathway outlined in this report is not the best way forward, swift action should be taken to adapt plans and meet the agreed-upon goals. Further delays in delivering the potential improvements of a more network-oriented and digitalised ATM system to the European public cannot be afforded.

Quantifying – but most importantly: realising – the further CO_2 emissions reduction potential that might be captured by fuel and CO_2 optimised trajectories and resolving possible persistent inefficiencies should receive notable policy attention. As noted in Section 4.3.1, detailed system-level assessments on the potential impact of optimising for CO_2 emissions seem to be lacking – but as EUROCONTROL (2020a) suggests, might indicate very worthwhile improvement potential. Following such assessments, current regulations or stimuli focused on reducing distance flown might show to be an impediment to achieving more fuel optimal routes, and should be altered.

Speeding up communication, navigation and surveillance innovation

Although relevant to the context of the Single European Sky, but certainly not limited to it, financial or other incentives should be considered as a means to increase technology uptake at the side of airspace users. Examples might be a 'most capable, best served' scheme, or using a framework rewarding early movers, for instance through financial incentives or a modulated route charge[121]. In any case, procedures should reflect modern technology and realise the improvements contained within rather than maintaining 'backwards compatibility' for a small number of airspace users. Policy measures contributing to the operational use of technology that is currently available can provide quick wins and should be implemented as soon as possible. This also means that – although instantaneous implementation cannot be expected or required from operators – implementation and transition periods should be kept relatively short.

Even beyond readily available technology, improved CNS accuracy and performance – and regulatory changes capitalising on these technology improvements – are essential to delivering some of the other benefits noted in this chapter, and to do so in a safe manner. Wake energy retrieval most certainly is one of those concepts for which regulatory changes with respect to separation minima will be necessary. Given the ambitious timelines proposed in the present study, it should be investigated sooner rather than later how safe implementation can be guaranteed. The knowledge and evidence-base gained this way might – in a longer term – contribute to more widespread application of reduced separation minima. Although such measures have not been considered in detail in this report, it is noted that this can be one way to resolve the current and future capacity shortages – leading to substantial amounts of additional CO_2 emissions.

Beyond the Single European Sky

Although European policymakers have no direct influence on airspace design and ATM elsewhere around the world, they should do their utmost to stimulate regions and States around the world to improve ATM efficiency. This can, for example, be done through international structures as ICAO, international cooperation with other important ATM operators and perhaps also through provisions included in bi- or multilateral air service agreements.

[121] Following recommendation 3 from the Airspace Architecture Study (SESAR JU, 2019a) and recommendation 5 by the Wise Persons Group on the Future of the Single European Sky (2019).

Guaranteeing environmentally friendly ground operations

Focusing on improvements to airport operation beyond those addressed in the SESAR-programme, incentives or regulations should be put in place to guarantee environmentally friendly ground operations. This should consider incentives (e.g. allowing accelerated depreciation) for replacing fossil-fuel based ground support equipment by bio-fuel or electrically powered alternatives. Similarly, options to require newly constructed or renovated gates or remote stands to be equipped with electrical ground power (FEGP or using an e-GPU) and/or pre-conditioned air can contribute to making sure infrastructure constraints do not limit a reduction in APU usage. Rather than only applying such requirements to new developments, another option would be to set minimum equipment levels airport-wide. If such measures are contemplated, technical enablers, including sufficient renewable electrical capacity, should be made available. Furthermore, the recovery of associated costs by airport operators has to be taken into account. In case of replacement of current infrastructure, the aforementioned idea of accelerated depreciation might be used. In addition to having these more sustainable installations in place, their use has to be guaranteed – through either cost-stimuli or enforceable mandates.

Enabling electrification and other alternative energy sources

With numerous potential improvements relying on a substantial supply of renewable electricity (e.g. electrical ground power, electrical operational towing; possibly extended by electric aircraft in the longer term), policies to further drive and accelerate the clean energy transition are required. This also holds for possible infrastructural changes related to other sustainable energy sources, most notably hydrogen (further discussed in Section 3.3 and Chapter 5).

4.6.2 Actions

Whereas Section 4.6.1 was mostly aimed toward governments and regulatory bodies, the current section describes what actions from the aviation industry are necessary to unlock the potential in reducing CO_2 emissions in the ways described in this chapter. Given the fact that many different actors might be involved in realising a particular improvement the actions are listed per (group of) improvement measure following the structure of this chapter rather than per actor. The section ends with a number of overall actions that apply to the industry as a whole.

Aircraft operations: improving flight planning, reducing weight and optimizing aircraft condition

Although it might not come easy, the necessary industry actions to realise the improvement potential listed in Section 4.2 are relatively straightforward. Aircraft operators should further increase their efforts towards:

- improving flight planning, using the latest available software solutions;
- reducing weight, by starting up or continuing weight reduction programmes, and by reducing or altogether putting an end to tankering operations; and
- improving aircraft surface and engine condition.

The potential improvements described in Section 4.2, widely available best practices and knowledge exchange between different aircraft operators can help identify the most suitable and cost-effective measures to realise aforementioned benefits (ATAG, 2015; ICAO, 2014b; Becken & Pant, 2020). Especially for SMEs developing solutions to enable such benefits might benefit from in-kind support and/or direct financial investment from established parties.

In case new flight management systems are introduced into the market, aircraft operators should be quick to upgrade their fleets. Although this will require a not insignificant investment, savings associated with fuel cost (as well as cost for carbon offsetting, carbon capture and/or emissions allowances) will allow operators to recuperate that investment in a reduction of operating cost. OEMs, equipment manufacturers and MRO providers should fully support and actively promote retrofitting aircraft in service.

Air traffic management: putting the latest technology in operation

Requiring cooperation with OEMs, equipment suppliers and MRO providers, airlines should make sure their aircraft are equipped with state-of-the-art communication, navigation and surveillance equipment. Following the supportive policies proposed in Section 4.6.1, the systemwide ATM-benefits unlocked by this new technology will be translated into benefits for the operator. Furthermore, savings in fuel(-related) cost are anticipated to offset one-time expenditures. Additionally, policies rewarding first movers (as proposed in Section 4.6.1) can be used to make such investments even more worthwhile.

The above action holds true for ANSPs as well. The system-wide data and information sharing, discussed at length in Section 4.6.1, should be supported throughout Europe. As indicated there, data exchange formats and protocols should be standardised, but ANSPs might also opt to replace their bespoke systems by commercial-off-the-shelf applications, or commission the development of a shared system for use throughout Europe. Stimulated by regulations or incentives, ANSPs should implement delivered SESAR innovations in a consistent and rapid manner – such that the environmental benefits they allow can be enjoyed without delay.

Specifically for wake energy retrieval, a concept of operations (CONOPS) should be developed by industry and regulators collaboratively. This must first of all concern safety aspects, which are of paramount importance. In addition, airlines should work out how costs and benefits are to be distributed between the two aircraft in a pair. This is easier to implement when both aircraft are operated by the same airline and can be considered part of a (transatlantic) joint venture in case two airlines have such a partnership, but is expected to require more thought in case airlines are unrelated – or might even directly compete with each other on a particular route. Although the competitive airline environment is respected and valued, it should not stand in the way of achieving reductions in aircraft emissions. Given its role in clearing inter-airline debt as well as its international standing, IATA might play a role in this.

Ground operations: reducing emissions from aircraft taxi and APU usage

In the quest of reducing ground emissions from aircraft, numerous actions are to be taken. First of all, the various stakeholders involved in taxi operations should work to further adopt and standardise reduced engine taxi procedures. Special attention should go out to applying this widely for departing flights, as these show the largest potential, yet face particular specific challenges. In addition to developing procedures to do so safely and efficiently, airlines should make sure to stimulate or instruct their cockpit crews to indeed apply these measures. In a slightly longer term, a joint and industry-wide effort should be made to enable electric taxi or (electric) operational towing. Specifically, this includes the following tasks:

- For OEMs to aid (or directly collaborate with) tractor manufacturers in their development of the necessary equipment, for example by assisting with testing and certification, and – if necessary – developing upgrades to the nose landing gear in order to support this new load case. In any case, OEMs should make sure their (future) products are fully compatible with operational towing. Furthermore, appreciating the larger (absolute) impact of electrical operational towing on long-haul aircraft, systems suitable for widebody aircraft should be developed.
- For airports and tractor manufacturers, with input from ANSPs and airlines, to determine the best way of implementing operational towing, balancing e.g. environmental sustainability, reliability and cost-effectiveness. Such considerations might drive the tractor design (speed, power, energy capacity), as well as infrastructure requirements (charging stations, possible additional airside service roads for tractor movement).
- For ANSPs to work together with airports, tractor manufacturers and airlines to develop a concept of operations for autonomous towing, as well as the supporting infrastructure, on-board hardware and software to support such a concept.

Given the complex, highly regulated and capital-intensive nature of the industry (as outlined in Sections 1.1 and 4.5.2) in-kind or capital investment by established organisations in new entrants developing such solutions might be considered to speed up innovation – and thereby speed up delivery of the associated benefits.

Fitting with electric taxi and electrical operational towing, but not strictly limited to it, airport operators should future-proof their electricity systems. In the medium term, that entails ensuring support for charging electrically powered equipment (ranging from ground support equipment to complete hybrid- or battery-electric aircraft). Starting now, this includes making sure to offer airlines electrical ground power at both gates as well as remote stands (through FEGP or e-GPU-systems) and pre-conditioned air, the latter somewhat dependent on the local climate observed at the airport. This holds for the construction of new aircraft stands, but should also be taken up in the modernisation efforts of existing infrastructure. Policies that incentivise the acquisition of environmentally friendly equipment (as proposed in Section 4.6.1) ease the capital expenditure burden on airports and/or handling agents. Besides such stimuli, parties should also appreciate – and take into account in their business plans – the generally lower operating and maintenance cost associated to electrical rather than fossil-fuel powered equipment. Of course, (further) efforts to lower and ultimately eliminate the carbon content of electricity used should be pursued. This can take the form of equipping terminal buildings with solar panels, for example, but also to exclusively procure renewable electricity from power suppliers.

In addition to aforementioned efforts, airports should uphold best practices when it comes to runway and taxiway design – including, for instance, high-speed runway exits and preventing aircraft from having to (wait in order to) cross other active runways. As for aforementioned infrastructure investment, these considerations should be taken into account in new developments, but might also be applied in an effort to improve existing infrastructure. When combined with larger maintenance works, the impact on the operation can be limited as much as possible. Similarly, but with a reduced need for infrastructure adjustments, improvements can be realised by implementing SESAR-solutions focused on ground operations.

Last, airlines and airports should include sustainability requirements in tenders for handling services and ground service equipment. This way, other companies in the value chain are stimulated to take their responsibility when it comes to reducing CO_2 emissions. For existing contracts, handling agents should be promoted to work sustainably. Even though emissions savings associated to limiting unnecessary use of ground service equipment is considered outside the scope of the present project, stimulating sustainable behaviour now can contribute to a changed mindset urgently required in the years to come.

Overall: a truly collaborative effort in decarbonisation

Highlighted previously in Section 4.5.2 and exemplified in numerous actions earlier in this section, it is stressed here once again that a collaborative industry effort is urgently required to effectively address the decarbonisation challenge facing commercial aviation. Respecting of course the responsibilities and authority of various stakeholders over different parts of the operational process, actors should not limit their sustainability efforts to the elements they directly control. A renewed balance between local and network-level optima should be strived for by all relevant actors. Replacing a profit-first mindset (having cost-efficiency as a boundary condition, and optimising for sustainability) by a sustainability-first attitude (the other way around) might be a stimulating fresh perspective.

This joint approach – of which the recent Aviation Round Table Report as well as the joint commissioning of this study might be seen as major examples – gives rise to a number of more concrete actions. Aligning goals is one; further sharing knowledge and best practices is another. Data sharing and tackling operational inefficiencies from multiple perspectives at once would be a next. Airlines which share fuel consumption data with ANSPs, for example, might help quantify further CO_2 emissions reduction potential or assist air traffic control officers in helping to drive down the environmental impact of flights by providing them with more information on the consequences of their instructions in terms of fuel consumption and CO_2 emissions[122].

Finally, increasing sustainability efforts on a corporate or industry-wide level also requires increasing awareness of the importance of sustainability and fuel efficiency with operational employees: pilots, ATCOs, handling agents, maintenance personnel and airport employees. It also means that organisations should provide adequate time and resources for their staff to work on sustainability initiatives – rather than asking them to do it ‘on the side’.

[122] If one of two aircraft has to be rerouted, for instance, such data could be used to determine the most environmentally friendly detour – also taking into account possible additional fuel burn required to make up time during the rerouting.

5 Sustainable aviation fuels

Eight pathways have been ASTM approved as alternative drop-in fuels to make aviation more sustainable. Towards 2050 additional pathways are expected to get certified including extending the blending limit to 100%. The sustainability of the fuel is considered in terms of life-cycle emission reductions including the effect of land use change and socio-economic impacts. The sustainability criteria in the EU are defined by the RED II framework mainly based on life-cycle emission reductions and caps on high ILUC-risk feedstocks. The analysis therefore considers 'advanced feedstocks' made from non-food crops, residues and renewable electricity. Production of these fuels mainly takes place in the EU based on regional supply chains. For e-fuels also the import of hydrogen is considered from regions outside the EU such as North Africa and Middle East.

Based on the announced production facilities, announced or implemented national blending obligations and EU hydrogen production and imports, the SAF potential in 2030 is estimated at 3.2 Mt (equivalent to 6% of total fuel consumption). SAF contribution in 2030 may be increased if a strong political support is given to SAF development. The life-cycle CO_2 savings are estimated according to the RED II GHG savings thresholds. The SAF potential in 2050 is based on the comparison with other roadmaps taking into account multiple sectors of the economy. In 2050 the SAF amount is estimated at 32 Mt, equivalent to 83% of total kerosene consumption. The value is based on scenarios and verified against feedstock availability predictions. In 2050 CO_2 savings over the life-cycle are estimated at 95% for biofuels and 100% for power to liquid fuels. Scenarios for the deployment of SAF are closely connected and influenced by assumptions on the policy framework, as such this analysis presents a possible pathway for the uptake of SAF in 2030 and 2050.

The policies and actions towards 2030 define the basis for a coherent long term policy framework which enables upscaling of production. This includes diversifying the mix of feedstocks and production processes, and setting up a monitoring and accounting framework. To create a stable market different types of incentives are considered to bridge the price gap with fossil fuels such as carbon pricing. Towards 2050 the policies focus on the division of sustainable feedstocks between different sectors, taking into account that aviation will continue to rely on liquid fuels. To ensure a minimum uptake of sustainable fuels an EU wide blending obligation is considered.

5.1 Introduction

In the last 15 years the aviation industry has focused on developing alternative "drop-in" fuels to reduce the environmental impact of aviation. Drop-in fuels can be blended with conventional kerosene (up to a certain percentage) and are certified for use in the existing fleet and therefore require no changes to the aircraft, engine or infrastructure. The boundaries of the current certification blending limits may be extended in the future, requiring changes to either the current engines and fuel systems or the chemical composition of the fuel, to reach larger shares of sustainable aviation fuels. More recently, research has also focused on the use of power to liquid fuels.

Sustainable aviation fuels (SAFs) have a major potential in reducing the climate impact of the aviation industry as the net CO_2 emissions over the life-cycle can currently be reduced up to 80% and in the future up to 100%. Especially in the short term using sustainable drop-in fuels presents a major opportunity to achieve in-sector emission reductions while using the existing fleet. Development of the SAF market can lead to regional business opportunities, job creation and might position the European Union as a frontrunner in this upcoming industry.

Despite the many benefits, major challenges remain for a successful deployment of SAF. Stringent sustainability criteria should form the basis of the policy framework and the industry actions. The development and the application of these criteria are essential for airlines, fuel producers, states and international organisations like ICAO. These criteria aim to achieve carbon reductions combined with positive socio-economic impact while avoiding competition with food and feed supply and negative ecological impacts such as deforestation. The main economic barriers are related to the higher cost compared to fossil kerosene and the investment risks associated with a new market. Development and deployment of SAF is also influenced by political decisions such as the recently announced European Green Deal. Europe's energy transition towards full decarbonisation affects the availability of renewable energy for all sectors of the economy including aviation.

This chapter gives an overview of ASTM certified fuels and other potentially interesting fuels, the available feedstocks and the related production processes, and finally the potential deployment of SAF in 2030 and 2050. The analysis includes the main drivers and barriers that influence the future deployment of SAF and that define the level of uncertainty. The successful deployment of SAF is directly connected to a long term policy framework in combination with industry ambitions and political focus. The chapter therefore ends with an overview of industry and government actions.

5.2 Sustainability

The definition of sustainability in the context of SAF is defined by ATAG as "something that can be continually and repeatedly resourced in a manner consistent with economic, social and environmental aims, specifically something that conserves an ecological balance by avoiding depletion of natural resources and does not contribute to climate change" (ATAG, 2017). Sustainability is therefore not limited to GHG reductions but also takes into account land use change (LUC) and socio-economic impacts. Some feedstocks for the production of biofuels are typically grown on cropland which can also be used for the production of food or feed. It is important to ensure that the production does not compete with these primary resources. LUC takes place when biofuels cause modifications in the use of the land (e.g. from forest to crop) either in the same cropland the biofuel is grown (Direct LUC) or elsewhere (Indirect LUC) due to, for example, supply and demand constraints. This may cause eventually indirect emissions due to the loss of CO_2 capture by photosynthesis by former trees or due to the release of CO_2 stored in trees or soils resulting from the clearance of high carbon stock land like forests for the production of biofuel crops. One major way to mitigate the risk of land use change is to use residues, waste materials and by-products for the production of sustainable fuels (Sustainable Aviation, 2020b).

Sustainability criteria

These criteria should evaluate the sustainability of the fuel over the entire life-cycle, from feedstock production and conversion to fuel production and distribution including usage on-board of the aircraft, while taking into account the geographical location and thereby the local social economic context. Stringent sustainability criteria are the most important aspect when considering the deployment of SAF as they directly determine to which extent the alternative fuels are truly sustainable. They are an essential element in the policy framework aiming to guarantee true sustainability. It is therefore important to work towards a worldwide robust set of sustainability criteria that applies to all policies and regulations worldwide. A number of standards have been developed that include social, economic and environmental sustainability criteria. Several of these standards for identifying criteria for sustainability assessment are described more in detail in the following paragraph.

Sustainability standards

The Roundtable on Sustainable Biomaterials (RSB) Standard is seen as a strong and trusted sustainability standard according to World Wildlife Fund (WWF), International Union for Conservation of Nature (IUCN), and Natural Resources Defence Council (NRDC) (ICAO, 2019 Environmental Report, 2019a). It is based on 12 principles that ensure lasting solutions without creating social and environmental challenges: legality; planning, monitoring and continuous improvement; greenhouse gas emissions; human and labour rights; rural and social development; local food security; conservation; soil; water; air quality; use of technology, inputs, and management of waste; and land rights (ICAO, 2019 Environmental Report, 2019a). Other internationally recognized standards have also been developed such as the International Sustainability and Carbon Certification (ISCC). This scheme certifies biomass over the entire supply chain from origin to the final market. The scheme is based on six principles: protection of biodiverse and carbon rich areas; good agricultural practice; safe working conditions; compliance with human, labour and land rights; compliance with laws and international treaties; and good management practices and continuous improvement.

Renewable Energy Directive

In Europe, the Renewable Energy Directive (RED) and its recast towards 2030 (called RED II) specify the sustainability criteria for the fuel and the feedstocks to be eligible under the scheme (EC, 2019b; EC, Renewable Energy – Recast to 2030 (RED II), 2020g). Further details on European policy are given in Section 5.3. Key elements of the RED II include:

- Minimum level of GHG emission saving;
- Areas of high carbon stock (wetland, forest and peat land) should not be used for fuel production;
- Land with high biodiversity should not be used for biofuels production.

The minimum level of GHG savings for the fuels to be eligible under the framework is shown in Table 18.

Table 18: GHG savings thresholds according to RED II framework

Plant operation start date	Transport biofuels	Transport renewable fuels of non-biological origin	Electricity, heating and cooling
Before October 2015	50%	-	-
After October 2015	60%	-	-
After January 2021	65%	70%	70%
After January 2026	65%	70%	80%

One major concern is that the EU policy framework still partially allows feed and food crops for the production of fuels. In the recast towards 2030 (RED II) the framework sets limits on high ILUC-risk biofuels which will gradually decrease to zero by 2030. These limits consist of a freeze at 2019 levels for the period 2021-2023, gradually decreasing from the end of 2023 to zero by 2030 (EC, 2019c). Member states are not able to count the volumes covered by these limits towards their renewable energy target.

Voluntary standards approved in the EU

For biofuels the EU has approved a list of voluntary sustainability standards (including RSB and ISCC) that meet the EU sustainability criteria (EC, 2020k). By selecting a voluntary scheme, the aviation sector can apply more stringent criteria then the existing Renewable Energy Directive. Leading airlines have indicated that they prefer to use strong and trusted sustainability standards that aim for the highest sustainability levels.

Life-cycle GHG emissions - analysis and methodology

The life-cycle GHG reductions that can be obtained with SAF compared to fossil fuels mostly vary between 25-95%. Life–cycle emissions refer to the emissions produced during feedstock production and transport, conversion to fuel, fuel transport and distribution, including the final use in the aircraft engine. By adding up all the emissions of the individual steps the total GHG emissions of the fuel are obtained. This approach is called a life-cycle assessment (LCA).

The assessment of the life-cycle emissions is most accurate when individual regional supply chains are analysed. Nevertheless, reference values for different conversion processes and feedstocks give a good indication of the difference between pathways and geographical locations. As an example this report shows the default values and the methodology used by ICAO for CORSIA eligible fuels.

In June 2019, ICAO published the analysis and methodology to calculate the life-cycle GHG emissions for CORSIA eligible fuels including the effect of indirect land use change (ICAO, CORSIA Eligible Fuels, 2019). The life-cycle assessment methodology calculates the carbon dioxide equivalent (CO_2e) emissions of CO_2, CH_4 and N_2O from well-to-pump activities (WTP) and CO_2 emissions from well-to-wake (WTWa) fuel combustion. The default core life-cycle values (without taking into account land use change) are given in Table 19.

Table 19: Default core LCA values for CORSIA eligible fuels without taking into account ILUC effects (ICAO, 2019). The values are compared with a fossil baseline to show the reduction percentage.

Conversion process	Feedstock	LCA gCO_2e/MJ	% emissions savings compared to fossil-kerosene baseline of 89 g CO_2eq/MJ
Fischer-Tropsch (FT)	Agricultural residues	7.7	91%
	Forestry residues	8.3	91%
	Municipal Solid Waste (MSW), 0% NBC	5.2	94%
	MSW, NBC as % of total C	NBC × 170.5 + 5.2	
	Short-rotation woody crops	12.2	86%
	Herbaceous energy crops	10.4	88%
Hydro-processed esters and fatty acids (HEFA)	Tallow	22.5	75%
	Used cooking oil	13.9	84%
	Palm fatty acid distillate	20.7	77%
	Corn oil	17.2	81%
	Soybean oil	40.4	55%
	Rapeseed oil	47.4	47%
	Camelina	42	53%
	Palm oil - closed pond	37.4	58%
	Palm oil - open pond	60	33%
	Brassica carinata	34.4	61%
Synthesized IsoParaffins (SIP)	Sugarcane	32.8	63%
	Sugarbeet	32.4	64%
Iso-butanol Alcohol-to-jet (ATJ)	Sugarcane	24	73%
	Agricultural residues	29.3	67%
	Forestry residues	23.8	73%
	Corn grain	55.8	37%
	Herbaceous energy crops	43.4	51%
	Molasses	27	70%

Conversion process	Feedstock	LCA gCO_2e/MJ	% emissions savings compared to fossil-kerosene baseline of 89 g CO_2eq/MJ
Ethanol Alcohol-to-jet (ATJ)	Sugarcane	24.1	73%
	Corn grain	65.7	26%

The ILUC analysis, performed by ICAO for CORSIA eligible fuels, uses two different economic equilibrium models and then compares the results. The models take into account emissions due to changes in vegetative living biomass carbon stock, emissions due to changes in soil carbon stock, and emissions debt equivalent to forgone carbon sequestration (ICAO, CORSIA Eligible Fuels, 2019). This analysis can serve as a reference to compare and understand the environmental impact of different fuels. The default ILUC emissions under CORSIA are shown in Table 20. Negative modelling values suggest that high soil carbon sequestration and biomass carbon from producing cellulosic crops will be larger overall than associated emissions from land use change.

Table 20: Default ILUC emission values for SAF pathways, in g CO_2e/MJ (2019)

Region	Feedstock	Conversion process	Default ILUC value
USA	Corn	Alcohol (isobutanol) to jet (ATJ)	22.1
USA	Corn	Alcohol (ethanol) to jet (ATJ)	25.1
Brazil	Sugarcane	Alcohol (isobutanol) to jet (ATJ)	7.3
Brazil	Sugarcane	Alcohol (ethanol) to jet (ATJ)	8.7
Brazil	Sugarcane	Synthesized iso-paraffins (SIP)	11.3
EU	Sugar beet	Synthesized iso-paraffins (SIP)	20.2
USA	Soy oil	Hydroprocessed esters and fatty acids (HEFA)	24.5
Brazil	Soy oil	Hydroprocessed esters and fatty acids (HEFA)	27
EU	Rapeseed oil	Hydroprocessed esters and fatty acids (HEFA)	24.1
Malaysia & Indonesia	Palm oil (open/close pond)	Hydroprocessed esters and fatty acids (HEFA)	39.1
USA	Miscanthus	Fischer-Tropsch (FT)	-32.9
USA	Miscanthus	Miscanthus Alcohol (isobutanol) to jet (ATJ)	-54.1
USA	Switchgrass	Fischer-Tropsch (FT)	- 3.8
USA	Switchgrass	Alcohol (isobutanol) to jet (ATJ)	-14.5
USA	Poplar	Fischer-Tropsch (FT)	- 5.2
EU	Miscanthus	Fischer-Tropsch (FT)	-22
EU	Miscanthus	Alcohol (isobutanol) to jet (ATJ)	-31

Additional benefits of SAF

The use of sustainable aviation fuels has a positive effect on other GHG emissions and air quality emissions which are out of the scope of this work. Current drop-in SAFs (that are blended with conventional kerosene) significantly reduce SO_x and PM emissions; furthermore, these SAFs generally also reduce CO and UHC emissions, whereas a minimal reduction to no effect is found for NO_X emissions (Booz Allen Hamilton, 2018). A reduction in these emissions contributes to improving the air quality around airports.

A lower aromatic and sulphur content also lead to differences in contrail and cirrus formation. Contrails form as the water vapour emitted by the engine at high altitudes condenses into droplets or ice crystals. Particles, such as soot and sulphur, influence the formation of contrails (Lee, et al., 2010). A lot of research is currently performed to assess the overall climate impact of various types of SAF blends including 100% synthetic fuels. According to the recently published study on hydrogen powered aviation, using a 100% synthetic fuel may reduce the overall climate impact by 30% to 60%, assuming a fully carbon neutral production process (McKinsey & Company, 2020). This is mainly due to reduced formation of contrail and cirrus clouds. These non-CO_2-effects are, as mentioned in the introduction, outside the scope of this roadmap.

5.3 Current EU policy framework

The overall policy framework in the EU for the production and promotion of energy from renewable sources is the Renewable Energy Directive (RED) 2009/28/EC. The European Commission states that this directive is "aimed at keeping the EU a global leader in renewables and, more broadly, helping the EU to meet its emissions reduction commitments under the Paris Agreement" (EC, 2019b).

Under the recast to 2030 (called RED II) the EU established renewable energy targets and translated these targets in a climate and energy framework. In 2030 a binding target of 32% of renewable energy has been set with a possible revision by 2023 (EC, 2019b). Under this general target, a specific target for road and rail transport fuels has been set at 14% renewable energy by 2030 (EC, 2019d).

Within this policy framework, sustainable aviation fuels can opt in to contribute to the 14% transport target but are not subject to an obligation (EC, 2019d). This means that when sustainable aviation fuels are deployed in a Member State, that Member State is allowed to count these fuels towards its national renewable energy target. For aviation fuels the system includes a multiplier of 1.2. This multiplier allows fuel suppliers to count the contribution of non-food renewable fuels 1.2 times their energy content towards the targets. For comparison, multipliers have also been applied to renewable electricity production for use by electric road or train transport with a factor of 4 and 1.5, respectively. Inclusion of these options in national regulations depends on political decisions in the transposition processes.

As mentioned previously, the RED and RED II define the sustainability criteria for the fuels. This includes minimum GHG reductions and incorporates a cap on high ILUC-risk feedstocks. The RED II framework is based on a list of feedstocks. It should be noted, however, that the list is not exhaustive; some feedstocks may therefore not be included in the list. In Annex IX the feedstocks are divided into advanced feedstocks in Part A and capped feedstocks in Part B. The RED II poses a cap on feedstocks in Part B as these feedstocks have a high ILUC-risk. To promote innovation the obligation includes a specific sub-quota for advanced biofuels coming from feedstocks listed in Annex IX, Part A, increasing from 0.5% in 2021 to at least 3.6% in 2030 (ICCT, The European Commission's renewable energy proposal for 2030, 2017).

Under the EU Emissions Trading System (EU-ETS) airlines can purchase SAF instead of purchasing ETS allowances. If the fuel complies with the sustainability criteria defined in the RED, it is attributed zero emissions under the scheme (EEA, EASA & EUROCONTROL, 2019). If the price of EU-ETS allowances is higher than the cost of SAF, this may form a direct incentive for airlines to purchase SAF.

5.4 Feedstocks and production processes

The aviation industry will move towards a variety of renewable biomass feedstocks and renewable electricity sources. These feedstocks include used cooking oil, agricultural residues, forestry residues, municipal solid waste, some types of energy crops[123] (crops whose primary target is the production of end-use energy carriers). For each feedstock different conversion processes can be used to reach a fuel that meets current jet fuel specifications. Most of these pathways are currently under development, with only Hydro-processed Esters and Fatty Acid (HEFA) currently commercially available – although in very limited amounts.

An overview of the feedstocks and production processes is given in this section. In terms of biofuels, this report focuses on so called 'advanced biofuels', namely biofuels produced from non-food crops or residues and biofuels produced with advanced processes from non-food feedstocks.

5.4.1 Feedstocks

Feedstocks are often categorized into biomass feedstocks and renewable electricity. Biomass feedstocks can be divided into forest biomass, agricultural residues, energy crops and already processed biomass. Biomass can be converted to liquid biofuels. Renewable electricity can be produced by a variety of renewable sources such as wind, solar and hydro. Renewable electricity can be used directly to power hybrid/electric aircraft or it can be converted to sustainable liquid fuels such as hydrogen and synthetic kerosene. For the production of synthetic fuels renewable electricity can be used to capture carbon from the air thereby creating a fuel based solely on renewable electricity input (and water for the production of hydrogen).

Forestry biomass is currently an important source of renewable energy accounting for around half of the EU's total renewable energy consumption (Khawaja & Janssen, 2014). Until now it has mainly been used to support material demand, but the demand for energy purposes is expected to take over in the future (Bentsen & Felby, 2012).

Agricultural residues are often categorized in primary and secondary agricultural residues. Both types can be used for energy production. Primary residues are the result of primary agricultural operations (such as straw from grass species), whereas secondary agricultural residues are produced during the processing of crops into food or other products (Khawaja & Janssen, 2014). Europe has a large cereal production; therefore these residues originate mainly from wheat, maize, barley and rye production (Bentsen & Felby, 2012).

Already processed biomass includes for example sewage sludge, municipal solid waste and manure. These types of biomass have different properties and are collected in many different ways.

Energy crops are often categorized in two types: perennial herbaceous crops (such as miscanthus and switchgrass) and woody crops known as short rotation coppice (SRC) (such as willow and poplar). The s2biom project defines these non-food lignocellulosic crops as "crops that are unsuitable for human or animal food consumption and are grown exclusively or primarily for the purpose of producing biomass for energy and/or material purposes in an agricultural rather than a forestry context" (Khawaja & Janssen, 2014). The project also identifies that these crops can be converted to energy following two pathways: the production of biofuels or the production of heat and power; noting that the latter option is more common at the moment.

[123] Only energy crops which do not compete with food and feed are considered for this roadmap.

5.4.2 Production processes

This section gives a short overview of the types of production processes with their technology readiness level in combination with selected feedstocks. Only a number of these production processes have been certified for the use in aviation as further detailed in the next section 5.5.

Hydro-processed Esters and Fatty Acids (HEFA)
HEFA is the most mature SAF pathway currently commercially available with technology readiness level 8-9 (de Jong, et al., 2017). It is very similar to the Hydrotreated Vegetable Oil (HVO) process for making road transport fuels with the addition of further hydrocracking. The main feedstocks are waste and vegetable oils. For the future other feedstocks like oil-bearing algae are being investigated. These feedstocks undergo a deoxygenation reaction followed by the addition of hydrogen in order to break down the compounds into hydrocarbons (Pavlenko, Searle, & Christensen, 2019). Further refining steps are used to obtain a mix of fuels including kerosene.

Synthesis gas Fischer-Tropsch (FT)
This process mainly uses lignocellulosic biomass of municipal solid waste to produce a mix of road and aviation fuels. Conversion to fuel is achieved through gasification of feedstocks into synthesis gas (a mix of carbon monoxide and hydrogen) (Pavlenko, Searle, & Christensen, 2019). Using biomass the technology readiness level is approaching TRL 7-8 (E4tech (UK) Ltd & studio Gear Up, 2019).

Power to liquid (PtL) Fischer-Tropsch
This process creates synthesis gas by using hydrogen and CO_2 either from industrial facilities or captured from the air. In a largely decarbonized system the CO_2 source will eventually come from Direct Air Capture (DAC) technology. DAC technology is currently estimated at TRL 6 (Schmidt & Weindorf, 2016).

Direct Sugars to Hydrocarbons (DSHC)
This pathways uses genetically modified microorganisms (like yeasts or bacteria) to convert sugar into hydrocarbons or lipids (E4tech (UK) Ltd & studio Gear Up, 2019). One specific example is Synthesized Isoparaffins (SIP). This route converts sugary feedstocks (currently sugar cane) through fermentation and upgrading into farnesane. Depending on the feedstock DSHC has TRL 7-8 for sugar feedstocks and TRL 5 for cellulosic feedstocks (E4tech (UK) Ltd & studio Gear Up, 2019).

Alcohol-to-jet (AtJ)
As the name also mentions, this process turns alcohol into jet fuel. Through fermentation sugars, starches, or hydrolysed cellulose are converted into alcohol (isobutanol or ethanol), then processed and upgraded into fuels (Pavlenko, Searle, & Christensen, 2019). AtJ pathway is currently at TRL 6-7 (E4tech (UK) Ltd & studio Gear Up, 2019).

Hydrotreated Depolymerized Cellulosic Jet (HDCJ)
This pathway includes liquefaction technologies like pyrolysis and Hydrothermal Liquefaction (HTL). Pyrolysis transforms lignocellulosic biomass or solid waste into bio-crude oil which can be upgraded to jet fuel (E4tech (UK) Ltd & studio Gear Up, 2019). The production of jet fuel through pyrolysis is at maximum TRL 6 (E4tech (UK) Ltd & studio Gear Up, 2019). This process is undergoing certification for qualification as jet fuel. HTL uses water and biomass at high temperatures and pressures to produce bio-crude which can be upgraded to jet fuel (E4tech (UK) Ltd & studio Gear Up, 2019). HTL is being demonstrated at small scale, its TRL is estimated at 5-6 (E4tech (UK) Ltd & studio Gear Up, 2019). This process may in the future undergo certification for use in aviation.

Aqueous Phase Reforming (APR)
This process converts biomass-derived oxygenated compounds with a catalyst into a mix of hydrocarbons (E4tech (UK) Ltd & studio Gear Up, 2019). Using conventional sugar feedstocks the process has TRL 5-6, with lignocellulosic

feedstocks it is still at lab scale with TRL 3-4 (E4tech (UK) Ltd & studio Gear Up, 2019). This process is undergoing certification for the qualification as jet fuel.

Product slate

The production processes presented in the previous sector can produce many fuel types including kerosene and diesel. Therefore production facilities can choose to optimize the process for different outputs. If the jet fuel output is maximized the amount of kerosene produced will become much larger than the diesel percentage. An overview of the percentage of jet fuel as a percentage of total fuel output from the plant is given in Table 21. The table presents two scenario's in which jet output is maximized and in which other fuels output is maximised.

Table 21: Product slate depending on process optimization as percentage of jet fuel compared to total fuel output (Sustainable Aviation, 2020b)

Pathway	Jet % when optimized for other fuels output	Jet % when optimized for jet output
HEFA	14%	70%
FT (gasification & power to liquid)	20%	50%
Aerobic fermentation	0%	100%
AtJ catalysis	25%	90%
Pyrolysis (with catalytic upgrading)	20%	60%
HTL (with catalytic upgrading)	20%	60%
APR (with catalytic upgrading)	20%	60%

5.5 ASTM certification

Each combination of feedstock and production process needs to be certified by the ASTM, the American Society for Testing and Materials, to ensure the safe operation of flights with current aircraft and engine technologies. The fuel should meet the ASTM specifications in order to qualify for use in the existing fleet. Currently, eight conversion processes have been certified for use in commercial aviation. Currently all fuels approved under ASTM D7566 have been certified to a maximum blending limit ranging between 10% to 50%, with most fuels meeting the 50% limit. Furthermore, co-processing of renewable feedstocks with crude oil-derived middle distillates in petroleum refineries has been added to Annex A1 of ASTM D1655. An overview of currently certified pathways and pathways under approval by ASTM is given in Table 22.

Table 22: Approved pathways and pathways under approval under ASTM (CAAFI, 2020)

ASTM Certification status	Pathway	Feedstocks	Blending limit by volume
Approved under ASTM D7566	Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Biomass such as municipal solid waste (MSW), agricultural and forest wastes, and wood and energy crops.	50%
Approved under ASTM D7566	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	Plant and animal fats, oils and greases (FOGs)	50%
Approved under ASTM D7566	Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	Sugars	10%
Approved under ASTM D7566	Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)	Biomass such as MSW, agricultural and forest wastes, and wood and energy crops.	50%

ASTM Certification status	Pathway	Feedstocks	Blending limit by volume
Approved under ASTM D7566	Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Starches, sugars, cellulosic biomass	50%
Approved under Annex A1 of ASTM D1655	Co-processing of renewable feedstocks with crude oil-derived middle distillates in petroleum refineries.	Renewable lipids (plant and animal fats)	5%
Approved under ASTM D7566	Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK)	Bio-derived hydrocarbons(tri-terpenes produced by the Botryococcus braunii species of algae), fatty acid esters, and free fatty acids	10%
Approved under ASTM D7566	Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)	Fatty acids and fatty acid esters, or more generally various lipids that come from plant and animal fats, oils and greases (FOGs)	50%
Phase 2 Testing	Hydro-deoxygenation Synthetic Kerosene (HDO-SK)	Sugars and cellulosics	To be determined
Phase 2 Testing	Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)	Sugars and cellulosics	To be determined
Phase 1 OEM Review	High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK)	Renewable plant and animal fats, oils and greases	To be determined
Phase 1 Research Report	Integrated Hydropyrolysis and Hydroconversion (IH2)	Multiple	To be determined
Phase 1 Testing	Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	Sugars and lignocellulosics	To be determined

Aircraft and engine manufacturers are currently investigating the effect of increasing the blending limit to 100% for some pathways. The main difference in fuel composition is the amount of sulphur and aromatics contained in the fuel and the viscosity of the fuel. Safety needs to be ensured over the entire lifetime of the engine, the fuel system and the airframe. The amount of aromatic compounds has an effect on the volume and mass of sealings immersed in the fuel (Zschocke, Scheuermann, & Ortner, 2012). This could be solved by using a different type of sealings or by adding additives to the fuel to meet certain chemical specifications.

Industry experts do not expect major hurdles in increasing the blending limits for their newest engines to operate on fully synthetic fuel, but this has yet to be demonstrated. Industry experts highlight that it may also have positive effects on engine maintenance over the life-time, but no references can be given yet as this is currently being investigated.

5.6 Production cost

This section shows that even the cheapest technologies, like HEFA, are still more expensive than the fossil jet fuel. Policy support options to deploy these sustainable fuels on the market are discussed in section 5.10. The costs for SAF are estimated by IATA between two and seven times the cost of fossil kerosene (IATA, IATA Sustainable Aviation Fuel Roadmap, 2015). ICCT estimates the cost between two to eight times the cost of fossil kerosene (Pavlenko, Searle, &

Christensen, 2019). The cost is influenced by many factors such as equipment and installation costs and feedstock costs. The costs mentioned in this section are referenced from literature. These costs refer to the minimum viable selling price which may differ from the final sales price that fuel suppliers ask on the market. To select the most promising fuels, CO_2 emission reductions over the life-cycle in combination with the minimum selling price should be considered. This analysis can be performed by calculating the CO_2 abatement costs.

HEFA

The best understood production process is HEFA. This is the only process commercially available today. The costs of this route can therefore be estimated with the most certainty. The minimum viable price is estimated in the EU between 1.9 to 2.8 times the costs of fossil jet fuel (given a Jet-A1 price of € 0.39 per litre) as shown in Table 23. These costs are primarily dependent on the feedstock costs (such as used cooking oil), which are not expected to go down due to increased competition with other sectors (Pavlenko, Searle, & Christensen, 2019). The price of HEFA based jet fuel is therefore not expected to decrease over time.

Table 23: Overview of minimum viable price estimates for HEFA in the EU per litre and per tonne, with the density of kerosene equal to 0.8 kg/l.

Pathways	Feedstocks	€/litre	€/tonne	Compared with fossil at 0.39 €/litre[124]	Source
HEFA	Soy oil, palm oil, Palm fatty acid distillate and used cooking oil	0.88-1.09	1100-1363	2.3-2.8	Pavlenko, Searle & Christensen (2019)
HEFA	Used cooking oil	0.76-0.84	950-1015	1.9-2.2	EASA, EEA & EUROCONTROL (2019)
HEFA	Used cooking oil	± 1	± 1,300	2.6	de Jong et al. (2017)

By putting a price on carbon, the fuel price no longer only depends on its quantity, but also on the CO_2 reductions compared to fossil jet fuel. It is therefore important to take the CO_2 reductions into account when comparing the cost of fossil jet fuel with sustainable fuels. For illustrative purposes, the CO_2 abatement costs are given in Table 24 depending on carbon savings between 60% and 100% with respect to Jet-A1. The minimum selling price for HEFA (1176 €/tonne) is estimated at 2.4 times the reference Jet-A1 price in 2018 (490 €/tonne).

Table 24: HEFA CO_2 abatement costs depending on GHG reduction levels assuming a HEFA price of 1176 €/tonne compared to 2018 jet fuel prices.

Assumed life-cycle CO_2 reductions	Illustrative CO_2 abatement cost (€/tonne)[125]
60%	362
75%	289
100%	217

Other pathways

In general, costs are expected to decrease with technological improvement, learning and the effects of economies of scale. The costs for first-of-a-kind facilities are expected to be higher than subsequent production facilities.

For new pathways the costs are often estimated using models because data from commercial operations is not available. These models use chemical and efficiency data of existing pilot facilities to estimate operational and capital costs for larger facilities. Especially the equipment and installation costs are often difficult to predict; capital costs are the most uncertain for processes at an early stage of development (Pavlenko, Searle, & Christensen, 2019).

[124] Jet-A1 price in 2018

[125] Calculated as (SAF price – Jet A1 price) / (CO2 saving × Jet A1 emission factor). Jet A1 emission factor = 3.16.

Cost estimates for bio-based fuels in the EU have been analysed by De Jong et al. The minimum selling prices for lignocellulosic feedstock are shown in Table 25. These costs already take into account technological learning. For first-of-a-kind facilities the costs are expected to be higher. For pioneering plants the cost can increase by 40% to 80%. If solely the price is considered without taking into account the life-cycle GHG reductions, the most promising routes according to this analysis are HTL and Pyrolysis followed by FT and AtJ. The costs for these pathways range between 2.7 and 7.1 times the price of fossil jet fuel. DHSC is the most expensive pathway with costs around 9.4 to 12.7 times the price of fossil jet fuel.

Table 25: Overview of minimum viable price estimates of SAF pathways in the EU according to de Jong et al. based on 2000 t dry biomass input per day (de Jong, et al., 2017). Prices for forestry residues and wheat straw assumed to be 190 and 730 €/tonne dry matter respectively.

Pathway	Feedstocks	€/tonne	€/litre[126]	Compared with fossil at 0.39 €/litre[127]
Fischer-Tropsch	Forestry residues	1670	1.34	3.4
Fischer-Tropsch	Wheat straw	2445	1.96	5.0
Hydrothermal Liquefaction	Forestry residues	930	0.74	1.9
Hydrothermal Liquefaction	Wheat straw	1300	1.04	2.7
Pyrolysis	Forestry residues	1335	1.07	2.7
Pyrolysis	Wheat straw	1780	1.42	3.7
Alcohol-to-Jet	Forestry residues	2300	1.84	4.7
Alcohol-to-Jet	Wheat straw	3445	2.76	7.1
DSHC	Forestry residues	4595	3.68	9.4
DSHC	Wheat straw	6185	4.95	12.7

ICCT analysed the costs of various production pathways in the EU including the CO_2-equivalent abatement costs. These costs are shown in Table 26. After HEFA, the lowest CO_2-equivalent abatement costs are calculated for the FT pathways (between € 400 – € 800 per tonne) and AtJ pathway depending on the type of feedstock used (€ 800 per tonne in the least expensive case). The assumed GHG reductions are different per pathway and feedstock type.

Table 26: Overview of minimum viable price estimates of SAF pathways in the EU according to ICCT including cost of carbon abatement (Pavlenko, Searle, & Christensen, 2019). Density of kerosene assumed equal to 0.8 kg/l.

Pathway	Feedstocks	€/tonne	€/litre	Compared with fossil at 0.39 €/litre[127]	CO_2e abatement cost[128] €/tonne
FT gasification	MSW	1675-2338	1.34-1.87	3.4-4.8	± 400-500
AtJ	Corn, sugarcane, agricultural residues and energy crops	2000-3125	1.60-2.50	4.1-6.4	± 800-4500
SIP	Sugar cane molasses	5000	4.00	10.3	± 2500
FT power to liquid	Renewable electricity and CO_2 point sources	3125	2.50	6.4	± 800

The main characteristics of the costs shown in Table 26 are (Pavlenko, Searle, & Christensen, 2019):

- **FT-gasification**: very low feedstock costs; capital costs account for 80% of cost on per litre basis; second cheapest pathway after HEFA; GHG savings of around 85%.
- **AtJ**: costs largely depend of the type of feedstocks used; using corn and sugarcane results in lower prices than using agricultural residues or energy crops; GHG savings vary per feedstock type ranging from 10% to 80%.

[126] Density of kerosene assumed equal to 0.8 kg/l
[127] Jet-A1 price in 2018
[128] The carbon abatement costs are calculated as the difference between the levelized costs and a fossil jet fuel price of €0.39 per litre and dividing by the carbon reductions for a litre of fuel. Carbon reductions are based on CO_2 equivalent emissions (gCO2e/MJ). Numbers have been estimated based on Figure 6 page 15.

- **SIP**: high feedstock costs combined with low efficiency lead to high costs compared to other pathways; costs are very dependent on the capital expenditure; GHG savings of around 50%.
- **Power to liquid**: costs are mainly influenced by the price of electricity; GHG savings of around 85%.

Power to liquid

The development of power to liquid fuels is expected to grow on the long term. On overview of the minimum selling prices in the EU is given in Table 27. DAC technology increases the cost compared to using CO_2 from existing industrial applications due to the lower technological maturity level and the lower efficiency of the process. Technological maturity and efficiency are expected to improve with large scale deployment. Overall price estimates for power to liquid fuels range from 2.3 to 6.4 times the price of fossil jet fuel. Assumptions on renewable electricity prices have a major impact on the predicted costs. The renewable electricity should come for additional installations specifically built to supply fuel factories.

For illustrative purposes, the CO_2 abatement costs for the minimum selling price estimates given in Table 27 can be calculated assuming carbon savings of 85% and a jet fuel price of € 0.39 per litre. The abatement costs would range between approximately € 245 and € 980 per tonne.

Table 27: Minimum viable prices for power to liquid jet fuel in the EU according to different sources. Density of kerosene assumed equal to 0.8 kg/l.

Pathway	Feedstocks	€/litre	€/tonne	Compared with fossil at 0.39 €/litre[129]	Source
PtL FT	Renewable electricity and DAC	1.3	1675	3.4	German Environment Agency (2016)
PtL FT	Renewable electricity and CO_2 point sources	0.9	1144	2.3	German Environment Agency (2016)
PtL FT	Renewable electricity and CO_2 point sources	2.5	3125	6.4	Pavlenko, Searle & Christensen (2019)
PtL FT (2030)	Renewable electricity and DAC	1.9	2338	4.8	McKinsey & Company (2020)
PtL FT (2050)	Renewable electricity and DAC	1.2	1530	3.1	McKinsey & Company (2020)

For 2050 two additional sources have been found which estimate the minimum selling prices outside the EU. The McKinsey report estimates prices based on imports from Middle East whereas the IEA report estimates a global average price. These values are given in Table 28.

Table 28: Minimum viable prices for power to liquid jet fuel specifically for 2050. McKinsey estimated is based on imports from and IEA is a global average. Density of kerosene assumed equal to 0.8 kg/l.

Year	Feedstocks	€/litre	€/tonne	Compared with fossil at 0.39 €/litre[129]	Source
2050	Import from Middle East - Renewable electricity and DAC	0.8	935	1.9	McKinsey & Company (2020)
2050	Global average - Renewable electricity and DAC	1.3	1658	3.4	International Energy Agency (2020)

[129] Jet-A1 price in 2018

5.7 Supply potential in 2030

ICAO collected data during the 2019 ICAO Stocktaking Seminar which show that worldwide production capacity of SAF was 0.005 Mt[130] per year between 2016 and 2018. This is far less than 1% of total jet fuel demand in that period. Nevertheless, it is a major step towards commercialization and growth in this sector (ICAO, 2019 Environmental Report, 2019a).

Until now the most significant volumes were produced by the World Energy Paramount facility in California, USA using the HEFA technology. In recent years the market has expanded and multiple companies worldwide have announced plans for the production of SAF: SkyNRG, Fulcrum, LanzaTech, Neste, Velocys, UPM, Red Rock (ICAO, 2019 Environmental Report, 2019a). The increasing level of focus and upfront commitment of different stakeholders in the supply chain shows that this sector can continue to grow in the future.

Since 2009, SAF volumes were regularly supplied at six airports worldwide (ICAO, 2019 Environmental Report, 2019a). In Europe, SAF is commingled in the fuel system at a regular basis at Oslo Airport and Stockholm Arlanda airport. Most of this SAF is coming from the World Energy facility in California and being transported to Europe. The following paragraph analyses the future SAF uptake and production of SAF in the EU.

Availability of biomass in the EU

Total fuel consumption from flights departing Europe in 2030 is estimated around 67 Mt. Assuming a biomass to fuel efficiency factor of 55%, this would require 120 Mt (4.8 EJ[131]) of biomass feedstocks. For the year 2030 the EU project S2Biom conducted in 2014 estimated a biomass potential between 10.9 and 22.7 EJ (Khawaja & Janssen, 2014). Within the same range the study “Scenarios and Preconditions for Renewable Jet Fuel Deployment towards 2030” utilises a potential supply of 11.2 EJ per year in 2030 (de Jong, et al., 2017). It is important to note that multiple sectors of the economy rely on this biomass to transition to renewable energy sources. It is likely that only a portion of the potential supply will be delivered to the transport sector of which a portion will be used for aviation. De Jong et al. estimate that the projected demand from electricity production, heat and road transport remains below the supply reaching a level of 60% in 2030, which would be equal to 6.7 EJ (de Jong, et al., 2017)[132]. The remaining feedstocks (4.5 EJ) could potentially be used for other sectors such as aviation. However, not all feedstocks are equally suitable for the production of fuels and some require more processing steps than others. Waste oils, for example, can be easily transformed into fuels for transport and are allowed to count twice towards the renewable energy target of EU Member States (de Jong, et al., 2017). This combination causes an increase in demand and an increase in competition for these feedstocks between sectors.

Cellulosic wastes and residues collected in the EU are another example of a promising feedstock with limited supply. The study Wasted found that if all this material were converted to biofuels it would lead to 36.7 Mtoe per year for all transport modes (Harrison, et al., 2014). In 2014, when the study was conducted, this was equivalent to 12% of road fuel consumption in the EU. In 2030 the study estimated this amount could supply 16% of road fuel demand. This shows that the supply of these feedstocks is limited and that competition with road transport will potentially increase in the 2030 timeframe.

Import of biomass

Import of biomass from outside the EU will remain very limited as shown in two recent studies. According to the EC communication “In-depth analysis in support of the COM (2018) 773”, 10 Mtoe of biomass imports are expected in

[130] 6.45 million litres = 0.00516 Mt
[131] Conversion factor = 0.04 EJ/Mt
[132] The study “Scenarios and Preconditions for Renewable Jet Fuel Deployment towards 2030” does not take into account the target for advanced biofuels under the RED II, which may lead to a higher utilisation of waste and lignocellulosic feedstocks.

2030 and 2050 (EC, 2018c). When looking more specifically at advanced biomass the PwC study "Sustainable and optimal use of biomass for energy in the EU beyond 2020 (BioSustain)", estimates these will remain as low as 1-2 Mtoe per year. Of this biomass, not all will be suitable for producing biofuels and more specifically biokerosene. Furthermore, only a portion will be used for aviation. As they represent such a small portion of total biomass availability in the EU, imports of biomass are not further considered for this roadmap.

Announced SAF production in the EU

Accompanying the political and social focus many companies have announced plans for opening production facilities in the EU. The following plans have been publicly announced:

- SkyNRG has recently announced the opening of the first dedicated production facility for SAF in the EU based on the HEFA technology. The DSL-01 plant will be operational starting in 2022 and produce 100,000 metric tonnes of SAF in 2030 (ICAO, 2019 Environmental Report, 2019a).
- Neste has announced they can produce up to 100,000 tonnes per year of sustainable jet fuel (worldwide). It is looking for further expansion of their existing facilities in the Netherlands and Finland.
- Altalto Immingham Limited, a collaboration between Velocys, British Airways and Shell, plans to open a commercial waste to fuel plant in the UK. The plant is expected to be operational starting in 2024.
- Total La Mède in France converted a former oil refinery to a biorefinery with a maximum capacity of 500,000 tonnes of fuel (for both road transport and aviation).
- As part of a broad project consortium, the renewable energy company Ørsted and Copenhagen Airport aim to develop a hydrogen and sustainable transport fuel facility. The project has the potential to displace 5% of fossil fuels at Copenhagen Airport by 2027 and 30% by 2030.
- Pilot facilities have also been announced:
    - Quantafuel facility in eastern Norway based on forestry residue feedstocks supported by the Norwegian airport operator Avinor;
    - Rotterdam The Hague Airport synthetic fuel facility with green hydrogen and direct air capture;
    - Heide refinery announced future production of synthetic kerosene through the use of surplus wind energy generated locally which will be purchased by Lufthansa. Hamburg Airport is also involved in the collaboration.

Some existing facilities in the EU which currently produce biodiesel for road transport could also be used for the production of jet fuel as the product slate can be adjusted. Facilities that produce biodiesel based on HEFA or FT technology can be tuned to produce larger portions of kerosene, making kerosene their primary product instead of a co-product. The product slate of HEFA plants can be tilted up to 70% jet fuel production as shown in Table 21.

Goals and blending obligations in the EU

Many EU countries are developing or considering their own regulations for the mandatory blending of SAF as shown in Table 29. These countries thereby take a leading role in the deployment of SAF while international agreements are being discussed. The ambitions of the industry and the ongoing discussions at EU Member State level will be used to estimate the amount of SAF in 2030 in combination with the announced production facilities.

Table 29: Overview of industry goals, government ambitions, regulations and ongoing discussions for a blending obligation

Country	Blending level[133]	Type of target	Status	Source
Norway	0.5% in 2020	Mandate	Implemented	Norwegian Government (2019)
Sweden	1% in 2021 5% in 2025 30% in 2030	Mandate	Ongoing discussion	Greenair Communications (2019)

[133] These percentages most likely refer to fuel volume, but this has not always been specified by the sources found.

Country	Blending level[133]	Type of target	Status	Source
Germany (Aireg)	10% in 2025	Aspirational industry goal	-	IATA (2015)
Netherlands	starting 2023	Mandate	Ongoing discussion	Ministry of Infrastructure and Water Management (2020a)
	14% in 2030	Aspirational goal	-	Royal Schiphol Group et al. (2018)
France	1% in 2022	Mandate	Ongoing discussion	Squadrin & Schmit (2020)
	2% in 2025	Aspirational goal	-	Greenair Communications (2020)
	5% in 2030			
	50% in 2050			
Spain	2% in 2025	Mandate	Ongoing discussion	Martinez (2018)
Finland	30% in 2030	Mandate	Ongoing discussion	Biofuel International (2019)
UK	32% in 2050	Aspirational goal		Sustainable Aviation (2020b)

SAF supply

The total SAF supply is estimated at 3.2 Mt in 2030, approximately equal to 6% of European aviation fuel consumption in 2030. This estimate falls within the range of the recently published report "Joint Policy Proposal to Accelerate the Deployment of Sustainable Aviation Fuels in Europe" which estimates European-based SAF production between 1.5 and 7 Mt per year by 2030 (World Economic Forum, 2020). SAF contribution in 2030 may be increased if a strong political support is given to SAF development. From a global perspective Europe would realise a frontrunner position. The ICAO Environmental report 2019 estimates global SAF production may reach up to 6.5 Mt (8 billion litres) per year in 2032. This would imply that Europe would account for 50% of global SAF production.

Model assumptions biofuel

Based on announced production facilities in the EU in combination with announced or considered national blending obligations and industry goals, the amount of biofuels produced for aviation is estimated at 2 Mt in 2030. It is assumed that the SAF is produced in the EU with mainly regional supply chains. The estimated SAF supply of 2 Mt requires roughly 1% of the available biomass in the EU in 2030 assuming a total potential of 11.2 EJ and conversion efficiency of 55%.

Industry goals and national mandates set before 2030 will likely be met with HEFA technology and HEFA compatible feedstocks unless specified otherwise. Building new facilities and scaling up production requires several years. It is therefore likely that most production facilities in 2030 will be based on the commercially available HEFA technology.

E4Tech estimates that the global mix of production pathways in 2030 will consist for 60 to 70% HEFA in a road and aviation optimized scenario respectively (E4tech (UK) Ltd & studio Gear Up, 2019). An even higher percentage is estimated by de Jong et al., predicting a share of 90% HEFA technologies in 2030 based on a gradual SAF integration scenario (de Jong, et al., 2017). This study stresses that a sub-target for lignocellulosic biofuels could increase the share of other pathways and feedstocks up to 50% within the 2030 timeframe.

De Jong et al. identify a risk for a lock in effect on the long term if the focus remains on the HEFA pathway. Advanced pathways, such as Fischer-Tropsch, Alcohol-to-Jet and Pyrolysis, diversify the mix of feedstocks leading to higher supply potential and larger GHG reductions. Advanced fuels would fail to develop if the short term efforts are focused on the more cost effective HEFA technology (de Jong, et al., 2017).

To increase the available biomass potential and to avoid competing with other sectors, multiple studies recommend diversifying the mix of feedstocks and to focus on advanced feedstocks that remain largely unexploited, such as agricultural and forestry residues and non-food lignocellulosic crops (de Jong, et al., 2017; Searle, Pavlenko, Kharina, & Giuntoli, 2019).

Hydrogen

As hydrogen aircraft are only foreseen to enter the fleet from 2035 onwards (as shown in section 3.3.3.1), by 2030 hydrogen available to the aviation sector will be used either in the production process for biofuels or renewable fuels of non-biological origin (such as power to liquid kerosene). The amount of hydrogen available for aviation was calculated in chapter equal to 0.65 Mt in 2030.

Based on announced production facilities, it was assumed that 2 Mt of SAF are produced, of which 70% based on the HEFA technology and the remaining based on advanced biofuel production pathways. The HEFA pathway requires approximately 4% of hydrogen by mass of feedstock (Karatzos, McMillan, & Saddler, 2014). Other production processes with lignocellulosic feedstocks require more hydrogen, and are therefore estimated at 10% by mass of feedstock. The hydrogen required for the production of HEFA would therefore be equal to 0.1 Mt and the amount required for other production processes with bio-feedstocks also 0.1 Mt. In total 0.2 Mt of hydrogen will be used to supply the announced production facilities. This leaves approximately 0.4 Mt of hydrogen which can be used for the production of power to liquid fuels for aviation, for example by using the Fischer-Tropsch process.

From a mass balance perspective, 0.4 Mt of hydrogen will lead to 1.2 Mt of PtL-kerosene via Fischer-Tropsch (Shell, 2018). It should be noted that when converting hydrogen to synthetic fuel, 15% to 30% of additional energy will be required either to capture CO2 from point sources or to capture CO2 from the air, and to synthesize hydrocarbon fuels (McKinsey & Company, 2020; International Energy Agency, 2020).

The minimum life-cycle GHG savings threshold for power to liquid fuels is 70% to fall under the RED II requirements. This report considers only renewable hydrogen as feedstock. To large extent it is also assumed that renewable electricity will be used, therefore the average GHG savings are increased to 85% over the life-cycle.

Model assumptions

The SAF uptake in 2030 is modelled based on three parameters: pathway type, CO_2 savings and cost. An overview of model assumptions is given in Table 30:

- HEFA is assumed to make up 44% of the SAF mix. The total HEFA production in the EU is estimated at 1.4 Mt in 2030. The minimum selling price for HEFA in the EU is estimated at € 1170 per tonne (2.4 times the price of Jet-A1 in 2018).
- Other biofuel pathways are estimated to make up 19% of the SAF mix. The production costs for the most promising pathways are estimated by various sources to be on average € 2765 per tonne (4 times the price of Jet-A1 in 2018) as many first-of-a-kind facilities need to be built. These costs are assumed 40% higher than average due to the use of pioneering plants which require technological learning and upscaling.
- Power to liquid fuels are estimated to make up 37% of the SAF mix. The levelized costs are assumed to be on average 4 times the price of Jet-A1 in 2018 as many first-of-a-kind facilities need to be built. These costs are assumed 40% higher than average due to the use of pioneering plants which require technological learning and upscaling.
- The price of fossil kerosene is expected to increase to € 600 per tonne in 2030 excluding carbon pricing.
- The life-cycle CO_2 savings for biofuels (including the effects of land use change) are estimated based on the RED II GHG savings threshold. This leads to CO_2 abatement costs around € 280 per tonne for HEFA, € 1050 per tonne for the other bio-based pathways.
- The life-cycle savings of 85% are assumed for power to liquid fuels based on renewable hydrogen as a feedstock. This leads to CO_2 abatement costs around € 860 per tonne.

Table 30: Overview of SAF model assumptions for 2030. Total SAF supply is estimated at 3.2 Mt, equal to 6% of European aviation fuel consumption in 2030.

Pathway and feedstocks	SAF amount	Percentage of SAF fuel mix	Life-cycle CO_2 saving	Minimum selling price (€/tonne)	CO_2 abatement costs (€/tonne)[134]
HEFA pathways with various waste and residue feedstocks	1.4 Mt	44%	65%	1170	280
Advanced feedstocks combined with FT, ATJ, SIP	0.6 Mt	19%	65%	2765	1050
Power to Liquid FT	1.2 Mt	37%	85%	2900	860
Total / average	3.2 Mt	100%	72%	2274	640

5.8 Supply potential in 2050

For 2050 the estimate of the SAF amount has an even higher degree of uncertainty than for 2030. The main factors that influence this uncertainty are:

- economic capacity of the fuel industry to invest in new production facilities;
- ambition of the industry;
- political focus;
- regulatory support;
- energy transition pathways for other sectors; and
- (Europe's) decarbonisation strategy.

The analysis for the SAF amount is 2050 is based on a comparison between different scenarios from various publications. The SAF amount presented in these publications is used to give an ambitious, but at the same time realistic, target for the SAF amount taking into account feedstock availability, costs and industry ramp-up within the context of a European energy transition.

5.8.1 Feedstock availability

In recent years more research has been conducted on the feasibility of a 100% renewable energy system worldwide. Most publications have found this is technically feasible and economically viable with a sector-coupled integrated system (Hansen, Breyer, & Lund, 2019). Despite being potentially unlimited, global energy transition pathways developed by IRENA, IPCC, Shell and Teske estimate a share of renewable energy between 43-93% in 2050 to limit global temperature rise to well below two degrees (IRENA, 2019). This sections looks more specifically at the biomass and renewable electricity availability in the EU in the 2050 timeframe.

Biomass

For all sectors of the economy the worldwide biomass potential is estimated by various energy transition scenarios between 67-160 EJ. The EU biomass potential has been analysed in different studies. A Joint Research Centre report

[134] Calculated as (SAF price – jet fuel price in 2030) / (CO_2 saving × Jet A1 emission factor). Jet A1 emission factor = 3.16. Jet fuel price in 2030 = 600 €/tonne.

from 2015 estimates the potential between 8-21 EJ in 2050. A recent study by CE Delft estimates the potential in 2050 between 17-31 EJ per year (Leguijt, et al., 2020). The main sources of biomass analysed in the studies are forest biomass, agricultural residues, energy crops and already processed biomass such as sewage sludge, municipal solid waste and manure. Results presented by different studies vary substantially whether the theoretical, technical, economic or sustainable potential are considered. This is clearly illustrated in the paper by Bentsen and Felby from 2012 that estimates the biomass potential between 8-75 EJ per year in 2050 (Bentsen & Felby, 2012). By comparing all kinds of studies with variations in sustainability constraints and geographic scope (only EU27 or including Balkan and former Soviet states) the potential range and uncertainty become very large.

In general, most studies agree on the lower end of the range which is estimated around 8 EJ per year. The median value according to Bentsen and Felby of 24 EJ per year is consistent with the average value identified by the recent CE Delft study. The value of 24 EJ lies just above the maximum identified by the JRC study.

The main growth potential is identified for energy crops, whereas residues from agriculture and forestry are not expected to increase significantly (Bentsen & Felby, 2012). Growth potential for energy crops however also has the largest uncertainty. The main growth potential is found for non-food lignocellulosic energy crops whereas traditional food crops (such as rape seed, sugar or starch crops) are not expected to increase by much. The sustainability of lignocellulosic bioenergy crops depends on the type of land they are grown on. Displacing high-carbon stock lands such as forests has a negative environmental and climate impact, whereas using low-carbon stock land such as abandoned agricultural land can support biodiversity and has little or no carbon debt (ICCT, Sustainability challenges of lignocellulosic bioenergy crops, 2018).

The available biomass can supply multiple sectors of the economy including heat, power, plastics, road, maritime and aviation. It is difficult to predict how the biomass will be divided among sectors. This depends on multiple factors such as the feasibility to switch to other forms of renewable energy such as solar and wind. Road transport could, for example, shift to full electrification in the 2050 timeframe.

Renewable electricity

According the European Commission’s strategy “A Clean Planet for all” 80% of the electricity mix will come from renewable sources (including nuclear) in 2050. The share of electricity in final energy demand in Europe is expected to rise from approximately 23% in 2017 to 53% in 2050 (EC, 2018b; EEA, 2020).

A study commissioned by the European Parliament found that it will be cost-efficient to decarbonize the energy system by converting surplus renewable electricity to fuel (van Nuffel, Gorenstein Dedecca, Smit, & Rademarkers, 2018). In a decarbonized energy system hydrogen and e-fuels act as a sink for electricity surpluses preventing wasting harvested energy that is not used directly. This improves the flexibility of the network, making it possible to cope with fluctuations in demand.

Despite aviation representing a limited portion of the total EU energy consumption, it remains difficult to predict how the renewable electricity supply will be divided between different sectors of the economy and how fast it can be scaled-up to meet demand.

SAF scenarios

Various reports have been compared to analyse the level of uncertainty associated with the expected amount of SAF in 2050, an overview is given in Table 31. The most important distinction needs to be made between reports that take 100% SAF as a starting point (top-down analyses) compared to reports that estimate the amount of SAF that follows from a sector-wide energy transition in combination with economic feasibility and a policy framework (bottom-up analyses). It is important to realise that the overall fuel consumption depends on assumptions on fuel efficiency improvements and the demand for air travel. For a given SAF amount, lower overall fuel consumption leads to a higher SAF percentage in 2050.

Table 31: Overview of reports that estimate SAF uptake in 2050

Scope	Report	Total fuel consumption	SAF percentage	SAF amount	Remarks
Worldwide	Energy Transitions Commission (2019), Mission possible	600 Mt (26 EJ)	100%	600 Mt	Total fuel consumption based on ICAO estimates
	Searle et al. (2019), ICCT – Long term aviation fuel decarbonisation	654 Mt[135]	21%[136]	139 Mt	Literature results given in barrels of oil equivalent[137]
EU	Uslu (2017), TNO – Market Analysis	55 Mt	57% (1.5TECH)	31 Mt	Literature results given in Mtoe[138]
		48 Mt	55% (1.5LIFE)	26 Mt	
	De Jong et al. (2017), Renewable jet fuel in the European Union	112 Mt	36% (Delayed action)	40 Mt	
		110 Mt	77% (Full adoption)	85 Mt	
	Baker et al. (2017), Ecorys – Potential for Advanced Biofuels in Europe	56 Mt	44% (Medium)	25 Mt	Literature results given in Mtoe[138]
			52% (High)	29 Mt	
UK	Sustainable Aviation (2020b), UK sustainable fuels roadmap	14 Mt	32%	4.5 Mt	

Global scenarios

The worldwide scenarios show a very high level of uncertainty, mainly depending on the division of sustainable feedstocks between different sectors of the economy. Increasing SAF production is considered viable only if sufficient sustainable feedstocks (biomass and renewable electricity) are available from a sector-wide perspective.

ICCT expects heat, power, plastics and road vehicles to use 83% of the available biomass with 9% being delivered to the aviation sector (Searle, Pavlenko, Kharina, & Giuntoli, 2019). Specifically in Europe the study identifies a strong use of biomass in the power sector. Increasing the percentage used by transportation would require a major shift of the European power sector to solar and wind.

The Mission Possible report estimates 45 EJ of biomass input would be required to meet the entire energy demand from aviation in 2050, leading to 45-60% of (worldwide) available biomass going to the aviation sector (Energy Transitions Commission, 2019).

Even if it would be technically possible to allocate large amounts of sustainable feedstocks to the aviation industry as opposed to other current users, the fuel industry has to be able to ramp-up production significantly faster than historic ramp-up of ethanol and biodiesel for road transport. ICAO estimates it would require approximately 170 new large bio-refineries to be built every year from 2020 to 2050 to achieve complete replacement of fossil kerosene with SAF (ICAO, 2019 Environmental Report, 2019a).

Furthermore, 100% SAF may not be the most cost-effective solution in a global framework for carbon pricing and emissions reduction. As shown in the next chapter on economic measures, carbon abatement costs for SAF will remain more expensive than achieving emission reductions in other sectors worldwide. Within Europe, however, EU-

[135] Estimate based on figure 1 in ICCT publication: total jet fuel demand in 2050 13 million barrels oil equivalent per day.
[136] Estimate based on figure 1 in ICCT publication.
[137] Value in Mt is calculated based on the following conversion factors: 1 tonne of Jet A1 = 44,196 MJ and 1 million barrels of oil equivalent = 0.00611932395 EJ.
[138] Value in Mt is calculated based on the following conversion factor: 1 Mt of Jet A1 = 1.0556 Mtoe.

ETS prices are expected to increase to similar levels as the carbon abatement costs for SAF (further explained in section 6.4), creating a direct incentive to increase the SAF uptake.

European scenarios

All EU scenarios presented in Table 31 predict a lower SAF uptake compared to total fuel consumption. These scenarios have different assumptions in terms of fuel consumption, ambition level and type of sustainable fuels used.

The 1.5TECH and 1.5LIFE scenarios analysed by TNO cover all sectors of the economy and aim to reach net zero GHG emissions by 2050 and thus pursuing efforts to limit global temperature increase to 1.5°C. The 1.5TECH scenario is more driven by technology whereas the 1.5LIFE scenario is more driven by business and consumption patterns. The 1.5LIFE and 1.5TECH scenarios indicate that the supply to the aviation sector will not cover the entire fuel consumption in 2050 being limited to around 55-57% SAF, equivalent to 26-31 Mt. The 1.5LIFE and 1.5TECH scenarios estimate that e-fuels could provide 10% and 34% (respectively) of aviation's energy demand in 2050 while direct use of renewable electricity is estimated to remain low (1%); biofuel consumption is expected to remain the major source of sustainable fuels accounting for 23% to 45% of the mix (Uslu, 2017).

The Ecorys report considers the uptake of advanced biofuels which is estimated around 25-29 Mt (Baker, et al., 2017). With advanced biofuels the study refers to biofuels produced from lignocellulosic feedstocks (such as agricultural and forestry residues), non-food crops (such as grasses, miscanthus and algae), or industrial waste and residue streams. The feedstocks considered are selected based on having low CO2 emissions and reaching zero or low ILUC impact. The overall biofuel uptake lies close to the overall SAF uptake estimated by the 1.5LIFE and 1.5TECH scenarios. Both reports also have consistent estimates for the overall fuel consumption around 50-55 Mt.

The scenarios presented by De Jong et al. assume higher overall fuel consumption around 110 Mt and higher SAF amounts. The 'delayed action' scenario predicts 40 Mt of SAF, equivalent to 36% of total fuel consumption. The 'full adoption' scenario predicts up to 85 Mt, equivalent to 77%. In this context 'full adoption' refers to SAF being used to cover the emission gap up to the industry goal of -50% net emissions in 2050 compared to 2005 emission levels. This publication highlights that the 'full adoption' scenario requires an extremely high rate of feedstock and capacity deployment. In particular a high deployment of lignocellulosic biofuel production capacity which increases from nearly zero to 26 Mt per year over the course of 15 years (de Jong, et al., 2017).

5.8.2 SAF supply

For this roadmap 32 Mt of sustainable aviation fuels is assumed in 2050, equivalent to 83% of total kerosene consumption. This amount is based on the 1.5TECH scenarios presented in Table 31 in combination with the European hydrogen strategy and predicted hydrogen demand for the production of power to liquid fuels.

European SAF production is seen as an integral part of Europe's energy transition towards full decarbonisation and energy independence, therefore the majority of the production capacity is assumed to be built in Europe based on locally resourced feedstocks. Production capacity will vary per region. Regional supply chains are envisioned to achieve the highest level of sustainability.

Biofuels for aviation

The 1.5TECH scenario is the closest to the analysis performed in this roadmap, in terms of ambition level (net zero emissions by 2050), technology focus and overall fuel consumption. Furthermore, the 1.5TECH scenario considers a mix of biofuels and e-fuels which is also consistent with the scope of this roadmap. This scenario estimates that the amount of biofuels for aviation will be 13 Mt in 2050.

The required feedstock input would be equivalent to 24 Mt assuming a conversion factor of 55%. These 24 Mt of biomass feedstock would be approximately equal to an energy content of roughly 1 EJ (by taking a conversion factor of 0.04 EJ/Mt). A conservative analysis can be done by taking the lower-end value of biomass availability, equivalent to an energy content of 8 EJ per year in 2050, to identify the percentage of these feedstocks required for aviation. This would require 12% of biomass availability in the EU. Taking a more optimistic value for the total biomass availability of 24 EJ, the percentage required by aviation to power the fleet on biofuels would be 4%. The share of biomass attributed to aviation is therefore considered both realistic and feasible in a sector wide context. Therefore it is considered technically feasible to produce aviation biofuels based on European resources only.

It is envisioned that production pathways such as FT, AtJ and DSHC will be further developed for the conversion of advanced feedstocks. The mix of pathways and feedstock is difficult to predict for the 2050 timeframe. The CO_2 life-cycle savings are expected to increase to 95% as advanced feedstocks are increasingly being used and the entire supply chain for sustainable fuels is further optimized in line with the circular economy strategy of the EU.

Power to liquid fuels

In chapter 3.3.3.2 the amount of hydrogen available for the aviation sector was estimated at 12.3 Mt. Given the introduction of hydrogen aircraft in 2035, by 2050 a large portion of the single aisle fleet within Europe will use liquid hydrogen to directly power the aircraft. Based on the energy efficiency of these aircraft as defined in the technology chapter, the amount of hydrogen consumed by these aircraft is estimated at 3.7 Mt in 2050. Any additional hydrogen will be used as feedstock to produce power to liquid fuels and for the production process of biofuels[139]. This leaves 8.6 Mt of hydrogen for the production of power to liquid fuels and as feedstock in the production processes of biofuels.

Biofuel production processes are estimated to require approximately 7% of hydrogen by mass of feedstock. The hydrogen required for the production of biofuels (13 Mt) would therefore be equal to 1.8 Mt. This leaves around 6.8 Mt of hydrogen which can be used for the production of power to liquid fuels for aviation, for example by using the Fischer-Tropsch process. From a mass balance perspective, 6.8 Mt of hydrogen will lead to 19 Mt of PtL-kerosene via FT (Shell, 2018). The 19 Mt estimate is used as model assumption for the amount of power to liquid fuels in 2050. This estimate also lies close to the 1.5TECH scenario which considers the amount of e-fuels to be 18 Mt in 2050 (Uslu, 2017).

Model assumptions

In 2050 the fuel mix will consist of 13 Mt of biofuels, 19 Mt of synthetic fuels, in total equal to 32 Mt of sustainable fuels. An overview of model assumptions is given in Table 32.

The most promising bio-based routes in terms of cost in combination with CO_2 emission reductions were found to be HEFA, FT, AtJ and pyrolysis. The minimum selling prices for these pathways were presented in section 5.6 for a variety of different feedstocks. These prices vary depending of the type of production process, the type of feedstocks, the demand for these feedstocks and the improvement in process efficiency and technological learning. The average minimum selling price of all these combinations (production process + feedstock) is estimated at approximately €1790 per tonne in 2050. Assuming life-cycle reductions of 95% the CO_2 abatement costs are estimated at €366 per tonne.

[139] Additional energy is required to go from gas to liquid hydrogen. This additional energy should also be generated using sustainable sources. This amount of energy is not calculated in the report.

The minimum selling prices for power to liquid fuels have been estimated for EU production based on the average values presented in Table 27 and for imports based on the average values presented in Table 28. Assuming 15% will be imported from outside the EU, the average price is estimated at €1557 per tonne. For the production of power to liquid fuels, the CO_2 life-cycle savings are expected to increase to 100%. This results in CO2 abatement costs of €274 per tonne.

Table 32: Overview of model assumptions for 2050

Fuel type	Amount	Percentage of fuel mix	Average minimum selling price (€/tonne)	Average life-cycle CO_2 reductions	Average CO_2 abatement costs (€/tonne)[140]
Biofuel	13 Mt	34%	1790	95%	366
Power to liquid	19 Mt	49%	1557	100%	274
Fossil	6 Mt	17%	690	n/a	n/a
Total kerosene	**38 Mt**	**100%**	-	-	-
Total SAF	**32 Mt**	**83%**	-	-	-

Division between intra-EEA and extra-EEA

For 2050, the Roadmap foresees that the CO_2 abatement costs of SAFs become equivalent to the compliance costs of EU-ETS and significantly higher than the compliance costs of global carbon credits at €160 per tCO_2 (for price developments see Section 6.4). Hence, it is likely that airlines will purchase SAFs on flights with the highest costs for alternative CO_2 abatement: intra-EEA flights. Therefore, the SAF uptake on intra-EEA flights is assumed 100%. Any remaining SAF is used on extra-EEA flights. In 2050, this implies a SAF uptake of 78% on extra-EEA flights.

Increased blending level

An advantage of drop-in SAF is the use of existing aircraft engines and existing fuel supply infrastructure at airports. However, from a technical perspective the certification barrier of 50% (for most pathways) needs to be overcome to reach a 83% overall SAF uptake. Safety of the engine and the aircraft need to be guaranteed and therefore sound testing will be required. Increasing the blending range up to 100% to include fuels with lower aromatic content is deemed technically feasible within the 2050 timeframe. This may however create additional costs for retrofitting aircraft which are not taken into account in the modelling.

Accounting system (book & claim system)

To achieve the lowest cost and highest efficiency an accounting framework similar to the framework for renewable electricity might be needed: airlines should be able to purchase SAF attributes (similar to Guarantees of Origin for renewable electricity) and only airlines that have purchased such SAF attributes can claim the associated emission reductions. These attributes should be issued for uplifted SAF, but any airline, regardless of whether it effectively tanks SAF or not, should be able to buy them. SAF production facilities may not be distributed evenly in Europe. Some areas will have more feedstocks than others. To increase the use of regional supply chains, the production facilities are likely to be built close to these regions. The SAF could then be distributed to the nearest airports, as long as this does not require changes to the existing fuel supply infrastructure. The airport infrastructure will supply a given amount of SAF through its fuel system, but only airlines that actually purchase the SAF attributes will be able to account for it in the booking system. Airlines should be given the possibility to then decide on which flights to actually account for the SAF. This prevents airlines from carrying extra fuel on-board if SAF is not available at a certain airport. Airlines that aim for higher CO_2 emission reductions will decide to buy a larger amount of SAF and distribute the SAF in the most economic efficient way across the fleet. If the price of EU-ETS allowances remains higher than CORSIA offsets, it is likely that airlines will decide to use the SAF on intra-European flights first, the remaining being taken into account on international flights.

[140] Calculated as (SAF price – jet fuel price in 2030) / (CO_2 saving × Jet A1 emission factor). Jet A1 emission factor = 3.16. Jet fuel price in 2050 = 690 €/tonne.

5.9 Drivers and barriers

The previous section showed and discussed the elements that influence the deployment of sustainable aviation fuels. This section shows the main drivers and barriers that can speed up or slow down the deployment of SAF.

5.9.1 Drivers

The main driver for the use of SAF is its potential to decrease CO_2 emissions within the aviation sector. It is therefore a short to long term solution that can decarbonize all types of flights including long range flights. It is an energy alternative that can also be used on the short term as many types of fuels have already been approved for the current fleet and infrastructure. Drop-in fuels lead to direct benefits that are not limited by the time it takes for a new technology to slowly propagate through an aviation fleet. On the long term additional non drop-in fuels such as hydrogen are expected to be certified for the use on-board aircraft.

Technological alternatives in other sectors, like electric cars, are already available today and can be scaled up to fully electrify the fleet. Speeding up the introduction of alternative technologies in other sectors will enable biomass feedstocks to be used in sectors that are more difficult to electrify, such as aviation. Aviation can therefore be considered a priority sector for the use of advanced biomass feedstocks. Furthermore, aviation can benefit from the upscaling of renewable electricity production for other sectors, as it will lower the costs for the production of hydrogen and power to liquid fuels.

The SAF market is expected to develop and grow offering many business and job opportunities in Europe. The economic viability of SAF is expected to increase with higher carbon prices through EU ETS (see section 6.3), in combination with complementary incentives (see section 5.10) that reduce the project risk and the minimum selling price. As multiple sectors of the economy decarbonize, carbon allowances outside the sector are expected to become increasingly rare and therefore more costly, making SAF a more viable investment. Furthermore, the price of SAF is expected to decrease due to technological learning and upscaling of production. For the EU this new SAF market can contribute to increasing its energy independence if locally resourced feedstocks and regional supply chains are established.

The environmental benefits of SAF are not limited to GHG reductions but also contribute to better air quality around airports due to lower sulphur and fine particle emissions. Potential health benefits due to lower emissions vary depending on the fuel type and blending level. Less fine particle emissions also lead to lower contrail formation which decreases the overall climate impact. Furthermore, a lower level of aromatic compounds in the fuels may lead to less maintenance on engines and therefore lower maintenance costs.

5.9.2 Barriers

The overarching barriers that have been discussed extensively in this study are:

- sustainability;
- availability; and
- price.

These overarching barriers result from a series of more complex and detailed elements which largely relate to the immature stage of the SAF market. Barriers can be divided into technological, socio-economic and policy barriers.

Technical barriers

New feedstocks and production processes need to be developed to increase the feedstock base. These technologies currently have low TRL levels that need testing in pilot facilities before upscaling of production can take place. For biofuels this includes technologies such as alcohol to jet and pyrolysis. In particular for hydrogen electrolyser technology needs to be further developed and for power to liquid fuels the efficiency of direct air capture technology needs to improve.

Biomass is a limited resource in the EU. Particular types of biomass, such as used cooking oil, are easily converted in liquid fuels for transport. For these types of biomass, competition with the road sector is expected to increase on the short term. New types of biomass feedstocks, such as non-food lignocellulosic crops and algae, need to be investigated for the production of aviation fuels. These ‘advanced feedstocks’ need to be assessed in terms of environmental and socio-economic impact to reach higher sustainability levels.

Renewable electricity production needs to be scaled-up in the EU. At the moment it is only a small part of the EU electricity mix whereas the demand is expected to increase drastically towards 2050. This includes setting up the required infrastructure and logistics. Additional renewable electricity installations are required for the production of hydrogen and power to liquid fuels.

Engines and aircraft need to be tested, and if needed adapted, to assure the blending limit can be increased to 100%. By increasing the blending limit, specific chemical properties of the fuel may change, such as a lower sulphur and aromatic content. This process requires testing to ensure safety of the airframe and engine over the entire life-time of the aircraft.

Research is required on the additional climate and health benefits of synthetic fuels and hydrogen. This includes the effect of lower fine particle emissions in the formation of contrails and lower NO_X emissions due to lower engine combustion temperatures.

Economic barriers

A price gap exists between SAF and fossil kerosene. This price premium directly affects airline competitiveness and revenues due to an increase in operational costs. Furthermore investors are faced with a multitude of issues that contribute to a higher investment risk: lack of a long term policy framework; high upfront capital investments; uncertain costs due to low technological maturity and future price developments. The production costs of SAF are expected to decrease with technological learning and upscaling of production. Current market-based measures such as EU-ETS and CORSIA are not sufficient to provide a direct incentive for SAF. The price of carbon within these frameworks needs to increase to make SAF cost competitive. The affordability of SAF can be improved by using a multitude of incentives, for example funding mechanisms in combination with an EU wide blending mandate. The incentives should cause as little market distortions as possible, avoid carbon leakage and avoid additional cost increase due to lack of market competition.

For new pathways additional investments are needed to get fuels through the certification process compared to road transport fuels. The qualification process requires time as technical specifications need to be checked. Furthermore, a stable market for road transport biofuels already exists including blending mandates. Tilting the product slate to produce more jet fuel often increases costs for producers making it less attractive compared to the production of biodiesel.

Policy barriers

Investments in production facilities and projects in the energy sector often have a lifetime of 15 to 20 years. A policy framework with a similar timeframe provides investors with more certainty thereby lowering the project risk. A long term vision towards 2050 helps to direct investments into renewable energy projects such as the production of sustainable liquid fuels. The current RED II framework has a limited timeframe until 2030. A proper long term EU framework with clear, transparent and robust sustainability criteria and a challenging, but realistic ambition would make it possible to deliver impact without level playing field distortions.

With the current framework a price gap exists between fossil kerosene and sustainable aviation fuels. To reduce the price gap and create a stable market various types of incentives should be considered in the policy framework: ranging from strengthening the current EU-ETS framework for carbon pricing to introducing additional incentives such as funding mechanisms and blending mandates. These policy measures thereby support the development of new production processes and advanced feedstocks. Additional elements of the policy framework are discussed more in detail in Section 5.10.1.

5.10 Policies and actions

Having identified a substantial emission reduction potential from the use of sustainable aviation fuels, it is stressed again that these will not realise themselves without supporting measures. Policies and actions from both governments (including international organisations such as ICAO) as well as the aviation sector are necessary to realise the full potential and impact of the solutions discussed.

Although overlap does exist, policies are mostly related to government or regulatory, whereas actions are largely aimed at the aviation industry.

5.10.1 Policies

To increase the supply and demand for SAF a long term policy framework at EU level will be essential to reduce aviation’s carbon footprint. Based on the barriers and enablers identified in the previous section elements of the policy framework are specified.

This section starts with the overarching elements of the policy framework including an overview of possible incentives. Then it specifies which form the basis for specific elements which are relevant in the 2030 and 2050 timeframe.

Policy framework

This section includes policy recommendations for the development of a European policy framework for SAF in collaboration with governments. The high-level objectives include:

- Establish a long term policy framework (>15 years);
- Include stringent sustainability criteria in policy framework;
- Ensure a uniform and coherent framework for level-playing field at EU level and regional level;
- Coordinate and promote action at European level;
- Enable and increase the deployment of SAF in the EU;
- Include incentives based on EU financial funding mechanisms to reduce the price difference with fossil fuels;
- Create a European platform gathering all the actors in the value chain as a way to foster route to ambition.

To reach these objectives elements of the policy framework have been further elaborated for 2030 and 2050 in the next sections.

Incentives

To increase the SAF uptake, different mechanisms can be considered to reach cost parity. The preferred type of incentive depends on the goal of the policy framework. Besides carbon pricing, governments can use multiple funding mechanisms to lower the price gap and/or reduce the project risk for investors. These include input or output subsidies, capital grants, auctioning mechanisms and contracts for difference. The EU has multiple options for providing funding by using new or existing financial instruments. Depending of the technology readiness level, the availability of feedstocks, the required capital investment and the project lifetime the most appropriate funding mechanism can be selected. At the moment not enough literature is available to specify exactly which type of funding mechanism is preferred in which context. Additional research should be done on this subject as soon as possible. This has also been highlighted in the recent inception impact assessment within the EU project ReFuelEU Aviation.

The following type of incentives can be used:

- **Carbon pricing**: directly incentivizes the best performing fuels proportionally to the life-cycle carbon reductions (including ILUC effects).
- **Blending obligation (mandate):** impose a minimum share of SAF over a certain time period to be supplied to airlines or used by airlines. The blending obligation may include sub-quotas or additional specifications, such as the minimum level of CO_2 reductions compared to fossil jet fuel. This reduces the investment risk.
- **Voluntary offtake agreements**: the buyer commits to buying a certain amount of the product for a certain price over specified time. This reduces the project risk.
- **Funding mechanism**: the EU can channel funds through EU financial instruments or regulations (e.g., EU emissions trading scheme, EU-ETS Innovation Fund). Member States could also fund SAF projects taking into account restrictions from State aid rules. Financial instruments may for example be:
    - **Capital grant**: the producer receives a subsidy for the construction of the facility. This is often used for first-of-a-kind large demonstration facilities.
    - **Input subsidy**: this is seen as a reduction in feedstock costs.
    - **Output subsidy**: the producer receives a subsidy per quantity of production. This reduces the minimum selling price.
    - **Loan guarantee**: loans used to run/build the facility will be paid back. This mainly decreases the project risk, reduces cost of capital and attracts other funding. Usually loan guarantees are provided by States.
    - **Contract for difference:** implementing a guaranteed price floor by means of a reverse auction. If the fuel drops below the price floor, the government will pay the difference to the value of the price floor for the duration of the contract (Searle, Pavlenko, Kharina, & Giuntoli, 2019). This decreases the project risk.
- **Central auctioning mechanism**: SAF producers would be invited by a central auctioning authority to bid at the lowest price to supply a certain volume of SAF to the aviation market over a certain period (EC, ReFuelEU Aviation - Inception impact assessment, 2020f).

Incentives for SAF may influence the cost of fuels for other sectors like road transport and the other way round. Two studies are presented here with two different points of view. ICCT highlights that it would be more cost effective to support advanced fuels for the road sector in the near-term (Searle, Pavlenko, Kharina, & Giuntoli, 2019). Tilting the product slate to jet fuel is costly for some technologies; therefore, producing larger volumes of road fuels during technological development would decrease the cost. The study suggests incentivising the entire product slate regardless of end-use sector. Jet fuel would initially be a co-product of the process, but it would increase in volume as the road sector electrifies. The Energy Transitions Commission suggests using both or either a “green fuel” mandate specifically for aviation preferably at global level starting with regional level and carbon pricing. It highlights that incentives to replace fossil kerosene are a priority and should be taken despite the higher cost of sustainable aviation fuels (Energy Transitions Commission, 2019).

Policy strategy towards 2030

Given that currently very limited SAF production takes place, the policy framework should focus on increasing the SAF production capacity in Europe based on feedstocks sourced primarily in the EU. This can be achieved by strengthening the existing policy framework and setting the basis for a future long-term policy framework.

In the coming years, the policy framework should consider a combination of the following elements:

1. Diversify the mix of pathways and increase the feedstock pool given the limited availability of sustainable feedstocks:
    a. Perform R&D on new feedstocks and new production processes;
    b. Set-up pilot plants and first-of a kind facilities.
    c. Incentivize new technologies to prevent a lock-in effect on commercially available technologies:
        i. Define specific (complementary) support for R&D;
        ii. Define specific (complementary) support for pilot plants and first-of-a-kind facilities;
        iii. Define specific (complementary) support for new production pathways.
2. Scale-up commercially available technologies to increase the total EU SAF production and create a mature market:
    a. Incentivize pathways proportionally to the CO2 emission reductions over the life-cycle (including ILUC effects) to reduce the price gap with fossil fuels
    b. Strengthen the RED II policy framework
        i. Enable EU production and regional supply chains
        ii. Revise the multiplier for aviation
        iii. Strengthen the sustainability requirements
    c. Strengthen the EU-ETS carbon pricing system
3. Introduce an EU blending mandate based on careful analysis of timing and conditions
4. Set-up a monitoring scheme for the use of SAF and share knowledge between stakeholders
5. Set-up an accounting framework for the use of SAF

1. Increasing the feedstock pool and developing new technologies

Given the limited availability of sustainable feedstocks (both biomass and renewable electricity) in the EU the policy framework should focus on diversifying the mix of feedstocks to increase the feedstock base. This can be achieved by investing in research and development of new feedstocks and new production processes. The most promising technologies can be further investigated in terms of pilot plants followed by first-of-a kind facilities. Supporting new pathways increases technological learning and increases the process efficiency which lowers the production costs of future facilities. Defining specific incentives for new pathways therefore enables scale-up of production in the long term. These incentives should take into account that new pathways are often capital intensive and therefore require large upfront investments. This can be done, for example, by offering capital grants for first-of-a kind facilities. Capital grants decrease the project risk by offering investors a predefined amount of money. This grant is therefore not dependent on the duration of the policy framework and not dependent on the lifetime of the production facility. Incentives per litre of SAF are often met by using the cheapest pathways which are already commercially available, unless additional eligibility criteria are specified (for example subtargets for specific SAF types or GHG reduction thresholds). If commercially available fuels use the bulk of the subsidies, it creates a lock-in effect on these commercially available fuels instead of increasing the mix of SAF types.

2. Scale-up of commercially available fuels

The policy framework should also aim to increase the total SAF production by using already commercially available technologies such as HEFA. This can be done by further improving the existing RED framework and EU-ETS.

The RED (and RED II) framework should increase the focus on life-cycle GHG reductions instead of limiting the fuel selection to a list of feedstocks. A life-cycle analysis of the fuels could be performed in a similar way to the analysis done for ICAO CORSIA eligible fuels including core GHG emissions and ILUC impact. Furthermore, the RED II does not guarantee that production takes place in the EU. The system could be improved to incentivize regional supply chains that aim to achieve the highest possible life-cycle reductions by limiting transport and distribution of feedstocks. Furthermore, a revision of the current 1.2 multiplier for aviation could enable higher production levels. Revising the multiplier should however not divert renewable energy supply from other users but enable the overall renewable energy production in the EU to increase.

The most effective way to directly incentivize the best performing SAFs is carbon pricing. This measure and its related policy actions are described in the section on economic measures. On the short term, the carbon price within EU-ETS and CORSIA is expected to be much lower than the carbon abatement costs for SAF. Carbon pricing within EU-ETS is expected to increase as a result of the declining emission cap. In the 2030 timeframe however the EU-ETS price is not expected to cover the price gap. Therefore, additional forms of incentives are needed complementary to carbon pricing. Complementary incentives can focus on reducing the project risk, reducing the minimum selling price or both as explained in Section 5.10.1. Currently not enough information is available to select the exact combination of incentives. Many elements influence the type of incentives needed such as project lifetime, capital investment, regional socio-economic conditions and technological maturity. Additional research should be done to define the most effective type of incentives on top of carbon pricing mechanisms. These incentives should be coordinated at EU level by using an EU financial funding mechanism.

3. EU blending obligation

To increase the SAF uptake a policy option would be to introduce an EU wide blending obligation. A variety of policy options should be taken into account when designing the mandate. The ReFuelEU Aviation initiative is currently analysing the conditions needed for the implementation of a mandate such as sustainability criteria, timing and amount. In general, the following principles can be used as requirements for the design of the mandate:

- Ensure stringent sustainability criteria are met;
- Stimulate the most cost efficient technologies;
- Cause as little market distortions as possible;
- Avoid carbon leakage;
- Avoid additional cost increase due to lack of market competition.

The advantage of using a mandate is that the EU has more certainty that a minimum level of SAF is supplied to aviation. Furthermore, it directly influences CO_2 emissions from flights departing or within the EU. The risk of introducing a mandate while the market is not mature is the lack of competition between producers leading to an unnecessary increase in SAF prices. If a mandate is introduced in a very short timeframe and without strict sustainability criteria, it will likely be met by lower sustainability fuels as these are cheaper and more easily available. It is therefore recommended to announce the introduction of a mandate at least a couple of years in advance such that investments can be made and production of highly sustainable pathways can be scaled-up in time. The mandate for aviation should contribute to increasing the overall renewable energy use and production in the EU (without diverting existing resources from other users). Therefore, an increasing mandate for aviation fuels can be accompanied by a decreasing mandate for the road sector as the amount of electric cars increases and the road sector moves away from liquid fuels.

An EU wide mandate increases the level playing field. In general, most parties believe a mandate at EU level is preferable over a variety of national mandates to avoid level playing field distortions. Many EU countries are already considering of have already implemented a blending obligation. Norway has introduced a blending obligation on the supplier of 0.5% with advanced feedstocks starting in 2020. Furthermore, the Netherlands has announced a blending obligation starting in 2023 if no European agreement is reached beforehand. The following countries are also in the process of introducing a mandate: France, Spain, Sweden and Finland. These proactive actions taken by countries may distort the level playing field, therefore coordination at EU level is preferred.

4. Facilitation and monitoring

Exchanging knowledge between stakeholders along the entire value chain can facilitate the uptake of SAF. Aviation stakeholders (such as manufacturers, airlines and airports) can exchange information with fuel producers and government representatives to identify common goals and to discuss barriers and enablers to increase SAF uptake. For example, to speed-up the introduction of new pathways, technological support can be provided to producers along the certification process. Another topic may focus on sharing best practices between airlines to increase the efficiency of setting-up offtake agreements (taking into account the boundaries of competition law). Furthermore, the SAF uptake has to be monitored to understand if the established policy mechanisms have the desired effect and whether these mechanisms need to be adjusted.

5. Accounting framework

An accounting framework similar to the framework for renewable electricity should be developed in the EU. The framework should take into account that SAF production may not be distributed evenly across Europe. Production facilities are likely to be built close to the available sustainable feedstock sources. Fuel supply to airports will then need to be organised in the most cost-effective manner, using existing infrastructure. This should also reduce the life-cycle GHG emissions of the fuel as transport and distribution are minimized. The accounting framework should give airlines the possibility to claim the use of SAF in the most economically efficient way across the fleet, regardless of where SAF has been physically uplifted. For example, airlines may decide to redistribute the SAF claims to intra-European flights if the price of EU-ETS allowances remains higher than CORSIA carbon credits. This prevents airlines from carrying extra fuel on-board if SAF is not available at a certain airport.

Policy strategy towards 2050

Long term policy framework should:

1. Increase renewable energy production in the EU for all sectors and focus on energy efficiency improvements in all sectors;
2. Allocate sustainable feedstocks between sectors based on technological alternatives to fossil fuels:
    - Ensure that a minimum amount of sustainable feedstocks (biomass and renewable electricity) is available to the aviation sector by taking into account that aviation strongly relies on liquid fuels;
    - Ensure that technological developments in other sectors benefit from new technologies developed for aviation and the other way round;
    - Speed-up the introduction of alternative technologies in sectors that have these alternatives (such as electric cars, electric ground vehicles and electric aircraft for short ranges).
3. Increase sustainability of the fuels from an environmental and socio-economic perspective:
    - Increase life-cycle CO_2 savings including the impact of land use change;
    - Ensure sustainability criteria are constantly assessed.
4. Ensure a minimum amount of SAF is used on all flights:
    - Introduce a more stringent EU mandate.
5. Incentivise all pathways proportionally to the CO_2 reductions over the life-cycle:
    - Strengthen EU-ETS framework to make SAF price competitive on the long term.

6. Incentivise the use of SAF on international flights that are covered by worldwide offsetting programs:
    - Strengthen CORSIA framework to make SAF price competitive on the long term.

On the long term the main question to be answered by the policy framework is the division of sustainable feedstock between various sectors of the economy. Current studies predict that EU renewable energy production will not be able to meet the entire demand in the 2050 timeframe, but that it can be scaled-up eventually to meet demand from all sectors. It is therefore of upmost importance to focus on energy efficiency improvements in all sectors.

Aviation will remain dependent on liquid fuels even in the long term. Full electrification of aviation using batteries is deemed technologically feasible only for short range flights. Furthermore, from 2035 onwards, hydrogen is expected to be used on intra-European flights up to 2000 km (per Section 3.3.3). Nevertheless, it is important to allocate feedstocks to aviation for the production of power to liquid fuels and biofuels. For sectors that have technological alternatives like the road sector, the policy framework should help to speed-up the introduction of these new technologies. That also holds for aviation market segments in which alternative energy sources can play a notable role.

Sustainability criteria for the fuels should form the basis of the policy framework. These criteria should therefore be constantly assessed and whenever necessary improved. This includes both environmental and socio-economic assessments. The framework should aim to increase the GHG reductions over time by using advanced feedstocks and by creating regional supply chains. Technologies that are potentially carbon free such as the production of hydrogen and power-to-liquid fuels with direct air capture are therefore promising technologies on the long term.

Towards 2050 this report estimates that carbon pricing under EU-ETS will be more expensive than using sustainable aviation fuels. This will create a direct incentive for airlines to purchase SAF instead of fossil kerosene on intra-EU flights. For international aviation however, carbon abatement costs for SAF are expected to be 2 times higher than the carbon costs under CORSIA. SAF produced in Europe would thereby not be able to compete with the price of global carbon credits. For international aviation complementary policy measures will be needed to ensure a minimum SAF uptake is reached on international flights departing Europe. This can be achieved by using a blending obligation in combination with complementary incentives to make SAF more affordable. The mandate is expected to increase gradually by taking into account total fuel demand and efficiency improvements. The mandate should stimulate the use of carbon reduction technologies in a cost-effective way and ensure stringent sustainability criteria are met, while avoiding carbon leakage and distortion of competition. The gradually increasing mandate for aviation should also take into account the technological development of other sectors. As the road sector is expected to gradually electrify and move away from liquid fuels, these sustainable liquid fuels can be used in aviation.

5.10.2 Actions

The policies described in the previous section are accompanied by actions. Given a common goal, the actions will focus on the elements the stakeholders can directly influence.

Aircraft manufacturers

For manufacturers the actions focus on designing and testing equipment to increase the blending level of SAF up to 100% and to get new pathways certified in ASTM. Manufactures design and test the aircraft, the engine and the individual components to be compatible with current fuel specifications and future energy sources. For synthetic fuels the equipment needs to be certified for fuels with lower aromatic content up to no aromatic content. For hydrogen the engine and aircraft require substantial design changes which need certification and testing. For new pathways manufacturers provide technological support throughout the certification process. The required design changes will depend on the chemical composition of the fuel. Communication and information sharing will improve efficiency and collaboration with other stakeholders. In particular, manufacturers can support policy makers and standard making bodies.

To increase the SAF uptake manufactures can play a role by setting up offtake agreements for engine testing, flight testing and deliveries. Furthermore, they can invest in new production processes and feedstocks to increase technological learning and to increase the overall uptake.

Airports

The actions for airports focus on providing the relevant infrastructure. Infrastructure for SAF can vary depending on the geographical location of the airport. In some cases, fuel suppliers might set up production facilities directly on-site or SAF produced elsewhere can be transported by trucks or pipelines to the airport. It is critical that airports receive already blended SAF, which can be treated as Jet-A1, without any adjustments in the existing infrastructure. On-site blending would require separate infrastructure, in particular for recertification to Jet-A1. This would not be a cost-effective option. In some cases, dedicated storage facilities might be set up for biofuels and synthetic fuels and liquefaction facilities are needed for the storage of liquid hydrogen. They can be located either on- or off-site the airport; the most cost-effective option will depend on local circumstances. For hydrogen in particular, new distribution networks will be required, as contrary to drop-in SAF, it will not be possible to use the same pipelines as those supplying fossil kerosene.

To increase the SAF uptake airports can contribute by supporting and facilitating purchase agreements between stakeholders in the value chain. Furthermore, they can invest in new production processes and feedstocks to increase technological learning and to increase the overall uptake. Related initiatives are being implemented by Royal Schiphol Group in collaboration with KLM and other companies, aiming to establish a production plant for SAF based on waste such as used cooking oil, and Copenhagen Airport, which recently partnered with SAS and several other Danish companies to set-up a production facility for power-to-liquid fuels.

To promote the use of SAF, if deemed desirable at the local level, airports can investigate modulating airport charges based on the amount/percentage of SAF used by airlines or based on their CO2 emissions. Modulating airport charges based on SAF would strengthen the environmental component of the charges as it addresses both climate related emissions and air quality improvements. Some airports are also using other types of financial incentives to support the deployment of SAF. For instance, through its Sustainable Aviation Fuel Programme, Swedavia offers to cover up to 50% of the SAF cost premium to airlines uplifting SAF at one of its airports.

Airlines

Airlines have a major role to play in the deployment of SAF. The commitment of an airline to purchase a certain amount of SAF over a defined time period from a supplier has a valuable role in project risk mitigation and improves the chances of financing the production facility. These off-take agreements are often negotiated before the production facility is constructed. Airlines are very sensitive to fuel price variations and therefore off-take agreements usually include a form of risk pricing, such as a price floor and a price ceiling (IATA, IATA Sustainable Aviation Fuel Roadmap, 2015). The risk mitigation may be done together with intermediaries such as large investment banks. Purchase agreements allowed the first European projects to be financed. For example, KLM has committed to an off-take of 75,000 tonnes per year which has enabled the first dedicated European SAF plant to be constructed in The Netherlands. To increase the feedstock base and develop new technologies, airlines can also contribute to investments in new feedstocks and new production processes. For example, Transavia invested into a pilot facility for the production of power to liquid kerosene at Rotterdam airport.

Airlines also have a major role to play towards customers. Airlines can offer special programs to costumers to purchase SAF, thereby inviting customers to play an active role in the transition towards sustainable fuels in aviation. For example, Lufthansa offers passengers a personal book-and-claim system called Compensaid (Compensaid, 2020). SAS offers customers the option to purchase 20 minutes of flight time powered by biofuel (Kaminski-Morrow, 2019). This biofuel will be used to replace fossil jet fuel within SAS’s operations (not necessarily on that specific flight). KLM offers corporate customers the opportunity to be a part of the KLM Corporate Biofuel Program. The investments are then used to bridge the price gap between fossil fuel and SAF. Furthermore, the airline can actively communicate about the projects and activities in which it is currently investing. This includes the airlines ambition and current involvement in financing SAF production facilities.

To increase SAF uptake airlines can support and collaborate with policy and standard making bodies. For example, by sharing information to define the most suitable incentives to bridge the price gap with fossil fuels making SAF more affordable, or by defining the type of accounting and monitoring framework in the EU.

6 Economic measures

Economic measures assign a price to greenhouse gas emissions, ensuring that producers take the climate costs of their emissions explicitly into account in their business decisions. This internalisation of climate costs is increasingly recognised as a key mechanism to reduce emissions. Emissions can be priced through levies as well as emission trading and offsetting schemes. Emission trading and offsetting schemes reduce emissions in a more cost-effective way than levies and ensure that a specific emission target is reached (provided that quality criteria are met).

This study therefore focuses on trading and offsetting schemes. Since 2012, EU ETS covers emissions from intra-EEA flights. CORSIA has a global reach and shall be introduced in 2021 for international flights. The schemes differ in approach, geographical coverage, applicability and ambition level. It is yet unclear how both measures will develop and co-exist in the future. One global measure is preferred to prevent market distortion and carbon leakage. However we consider it likely that multiple schemes remain in place.

The prices of allowances and carbon credits shall increase over time, as the most cost-effective measures are taken first. This will eventually lead to a price whereby carbon removal projects become economically attractive to investors. Any remaining emissions in 2050 can therefore be compensated by allowances and carbon credits stemming from carbon removal projects. This allows the aviation industry to reach net zero CO_2 emissions by 2050.

6.1 Introduction

For a long time, greenhouse gas emissions (GHGs) have remained unpriced. This allowed companies to emit GHGs at no cost. As a result products were priced below the social optimum, which led to levels of supply and demand above the social optimum. Economic measures assign a monetary value to emissions. This internalisation of emission costs ensures that producers explicitly take these costs into account in their business decisions. It incentivises producers to reduce their emissions.

The pricing of greenhouse gas emissions (GHG) is increasingly recognised as a key mechanism to reach the Paris climate goals (CDP, 2017; World Bank Group, 2019; IMF, 2019a). In 2019, 57 carbon pricing initiatives were implemented or in preparation[141]. More initiatives are expected as countries seek cost-effective ways to reach their climate goals. Out of the 185 Parties that submitted their Nationally Determined Contributions (NDCs) to the Paris Agreement, 96 Parties (representing 55 percent of global GHG emissions) have stated that they are planning or considering carbon pricing as a tool to meet their commitments (World Bank Group, 2019).

Although carbon pricing is seen as a key component to decarbonise, literature indicates that it needs to be complemented with a mix of other policies to drive the required changes in a 1.5° C scenario (IPCC, 2018a). The large scale transformation of sectors also requires policies that for instance support research and development. Such

[141] Prices differ significantly between jurisdictions. Most are still too low to incentivise investments at the scale needed to reach the Paris climate goals (OECD, 2018a; UNEP, 2018; World Bank Group, 2019). The IPCC, International Monetary Fund (IMF) and the OECD all pushed for strengthening and accelerating carbon pricing.

complementary policies mean that the reduction goals can be achieved with a lower carbon price (CDP, 2017). This study suggest a combination of measures and policies.

This chapter focuses on economic measures. Section 6.2 introduces various types of pricing mechanisms and discusses their effectiveness. Section 6.3 describes the measures in more detail and indicates how these measures and carbon prices may develop until 2050. The relevant drivers and barriers are discussed in Section 6.5. Required policies and actions are presented in Section 6.6.

6.2 Types of pricing mechanisms

Carbon emissions can be priced through levies (taxes and government charges), emission trading and offsetting schemes (ICAO, 2015).[142] Each can be used to internalise the cost of emissions, leading to more socially optimal levels of supply and demand and incentivising producers to reduce their emissions. However, there are important differences in terms of administrative costs, efficiency, risk of market distortion and assurance that a specific emission target is being met:

- **Administrative costs:** The administrative costs of levies might be lower than those of emission trading and offsetting. Taxes and government charges are levied on passengers and/or flights (CE Delft & SEO Amsterdam Economics, 2019). This leads to limited administrative costs to airlines. Emissions trading and offsetting require airlines to respectively obtain emission allowances and carbon credits to cover their emissions. Airlines therefore need to estimate their future emissions, report their actual emissions, determine an optimal strategy to gather the required allowances or carbon credits and finally to obtain them in the market. This is a more complicated process which leads to higher administrative costs. However it should be noted that part of these costs are made regardless by airlines for instance to determine optimal fleet renewal pathways and fuel hedging strategies and to inform investors on their sustainability efforts;
- **Efficiency:** Emissions trading and offsetting are more effective in reducing emissions than levies for a number of reasons. First, the former incentivise airlines to reduce their emissions as the number of allowances or carbon credits needed is directly related to their emissions. Levies on passengers or flights which show no relationship to emissions do not stimulate airlines to reduce their emissions. Levies can however be designed in a way that they do incentivise airlines to reduce their emissions. Secondly, the trading of allowances and carbon credits between sectors and states ensures that emissions are reduced where this can be achieved at the lowest cost. Put differently: each invested euro leads to the largest emission reduction. Levies only allow for in-sector reductions, whereas out-of-sector reductions might be much more cost-effective. Thirdly, the revenues of auctioned emission allowances are (partly) invested in reducing carbon emissions. Globally, an estimated 70 percent of ETS revenues is used for environmental spending. For carbon taxes this is only 15 percent (IMF, 2019a);
- **Risk of market distortion / carbon leakage:** The cost-effectiveness of emission trading and offsetting schemes increases with the size of the market for allowances or carbon credits. The larger the market in terms of sectoral and geographical coverage, the broader the scope for emission reduction projects. This ensures that investments flow to the most cost-effective emission reduction projects, increasing the effectiveness of the market-based measure. Taxes and government charges are levied on a national or airport level which may lead to market distortions, negatively affecting the competitive position of based airlines. The Irish, German and Dutch ticket taxes have shown that airlines reduce capacity and/or cancel planned expansions after the introduction of these taxes (KiM, 2011). Moving capacity to other airports is however only possible for airlines that operate from multiple bases. Airlines operating from one base, do not have any outside options. To avoid the tax, passengers

[142] The focus of this chapter is on measures that price carbon emissions. Measures that increase the cost of emissions in an indirect way, for instance by abolishing fuel subsidies and excise duty exemptions are left out of the analysis. Such measures may however be implemented when additional emissions reductions are necessary.

might divert to more distant airports. Studies on the Dutch ticket tax have shown this effect (SEO Amsterdam Economics, 2009; SEO Amsterdam Economics, 2019). Diverting to more distant departure airports leads to an increase in emissions of surface transport. This means that national taxes are ineffective in reducing carbon emissions and may reduce national welfare (CPB & PBL, 2016). The same holds true, albeit to a lesser extent for multilateral levies or emission trading and offsetting schemes. Global economic measures are therefore preferred over local measures;
- **Certainty on reaching emission target:** well-designed emission trading and offsetting schemes allow governments to cap future net emissions at a level which corresponds to an emission target. This ensures that the emissions target is being met. A levy does not cap emissions and it remains unsure to what extent emissions will eventually be reduced. When the levy is set at a level that is too low, the emissions target will not be met. Consequently, this may mean that the levy needs to be adjusted. In case the levy is too high, it may depress demand and emissions to levels that are socially not optimal. Emissions targets are therefore met with more certainty by emission trading and offsetting schemes than with levies (IMF, 2019a).

6.3 Smart economic measures

Emission trading and offsetting reduce carbon emissions most efficiently and at the same time ensure that emission targets or climate goals are being met. Such measures are therefore referred to as ‘smart’ economic measures and are to be preferred over levies. In this study we therefore assume that carbon emissions from flights departing from European airports are priced through a smart economic measure. The next section describes emission trading and offsetting schemes in more detail.

- **Emission trading:** Emission trading schemes or cap-and-trade schemes require producers to cover their emissions through emission allowances. Allowances are certificates that allow the holder to emit one unit of a particular pollutant, such as a tonne of CO_2. The number of available allowances is capped at a level which corresponds to the emissions target. This ensures that the target will be met. Producers can either reduce their emissions or buy allowances on the market (trade). Governments can either sell allowances or give them away for free. Allowances sold at auctions generate revenues for the government that can be used to support innovations or reduce existing taxes. In 2019, 20 emission trading systems were in force spanning 27 jurisdictions and covering around 8 percent of global GHG emissions (ERCST, et al., 2019). The systems in the EU and South Korea are the only ones that include the aviation sector (World Bank Group, 2019). Over the next five years six more jurisdictions are putting in place emission trading systems, including China and Mexico. The Chinese system initially only covers the power sector; later it shall be expanded to other sectors including aviation. Another 12 jurisdictions are considering a system as part of their climate policy (ERCST, et al., 2019);
- **Offsetting:** Offsetting schemes require producers to offset emissions that exceed a certain threshold through carbon credits. A carbon credit represents the certification that a tonne of CO_2 has been reduced or avoided compared to a scenario without the offsetting scheme. The overall threshold is translated in thresholds for individual producers. When producers want to increase their output, they shall either have to reduce their emissions to the threshold level and/or buy credits on the market to offset any emissions over and above the threshold.

In both systems producers shall reduce their emissions when the cost of doing so is lower than the cost of acquiring allowances or carbon credits on the market. When emission targets become more ambitious, the price of allowances and carbon credits increase. Consequently, more emission reduction projects become economically viable. Smart economic measures therefore ensure that the most cost-effective measures are taken first[143].

The effectiveness of smart economic measures depends on their design. First, compliance should be high to ensure that the majority of emissions is covered and producers cannot evade the system and undermine its working. Second, when an airline buys an allowance or carbon credit, this should respectively reduce the right to emit of its seller or represent actual emission reductions realised by a project which would not have taken place without the scheme. Third, the market for allowances or carbon should be sufficiently large. The market is broadened when more sectors and countries take part in the measure.

6.3.1 EU Emissions Trading Scheme (ETS)

ETS is the cornerstone of EU's policy to combat climate change and its key tool to reduce GHG emissions in a cost-effective way. At present it is the world largest carbon market.

Initially the ETS only covered the power industry and heavy industry. Since 2012, aviation also falls under the EU-ETS and is still the only transport mode included in the scheme[144]. Originally it was designed to cover the emissions of all flights from, to and within the EEA[145] (full scope). In 2013, the scope was reduced to intra-EEA flights through the 'stop-the-clock' decision after strong opposition from various countries outside the EU.[146] With the 'stop-the-clock' decision the EU also allowed the International Civil Aviation Organization (ICAO) to develop a global measure (CORSIA, see below). Airlines active in the European Economic Area (EEA) need to monitor, report and verify their emissions and surrender allowances for those emissions. The reduced scope shall remain in place until the end of 2023, after which it reverts to its full scope unless there will be a revision in light of CORSIA.

Figure 11: Illustration of cap-and-trade scheme

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[143] In a well-functioning system, prices tends towards the marginal abatement cost of carbon (Synapse Energy, 2016).
[144] EU-ETS covers CO2-emissions from the power and heavy industry as well as aviation. In addition it covers N2O-emissions from the production of various acids and glyoxal and perfluorocarbons (PFCs) from aluminium production. For aviation EU-ETS only covers CO2-emissions.
[145] The EEA includes the EU Member States plus Iceland, Liechtenstein and Norway.
[146] The United States for instance adopted the 'EU ETS Prohibition Act' which would allow its authorities to forbid airlines based in the United States to comply with the system.

Two types of emission allowances exist within the EU-ETS system. General allowances (EUAs) and aviation allowances (EUAAs). Fixed installations (power and heavy industries) need to cover their emissions through general allowances. Airlines can use both the general and aviation allowances for compliance. In the next trading period (2021-2030) fixed installations are also allowed to use aviation allowances.

In the current trading period (2013-2020) operators are also allowed to use international offset credits from the Clean Development Mechanism (CDM).[147] According to the provisions in the revised EU ETS Directive, international credits can no longer be used for compliance in the next trading period (2021-2030) as the EU has a domestic emissions reduction target (UNFCCC, 2017; Carbon Tracker, 2018; EC, 2018a).

Cap

The number of available allowances is capped and is reduced each year to ensure that the climate targets of the EU will be met. Over the current trading period (2013-2020) the number of general allowances issued is reduced by a linear reduction factor of 1.74 percent per year (of the average quantity of allowances over the 2008-2012 period). This should result in an emission reduction of 5 percent by the end of the trading period, compared to the average emissions in the 2004-2006 period. The number of aviation allowances is not reduced over the current trading period.

The number of allowances put into circulation decreased by 37 million or 1.8 percent per year on average since 2013 (see Figure 12). Although CO2-emissions from aviation increased, total CO_2-emissions of all sectors included in the EU ETS declined by 43 Mt CO_{2e} over the same period (2.3 percent per year on average see Table 34). This shows that the EU-ETS brings about real emission reductions, first in those sectors where abatement costs are lowest.

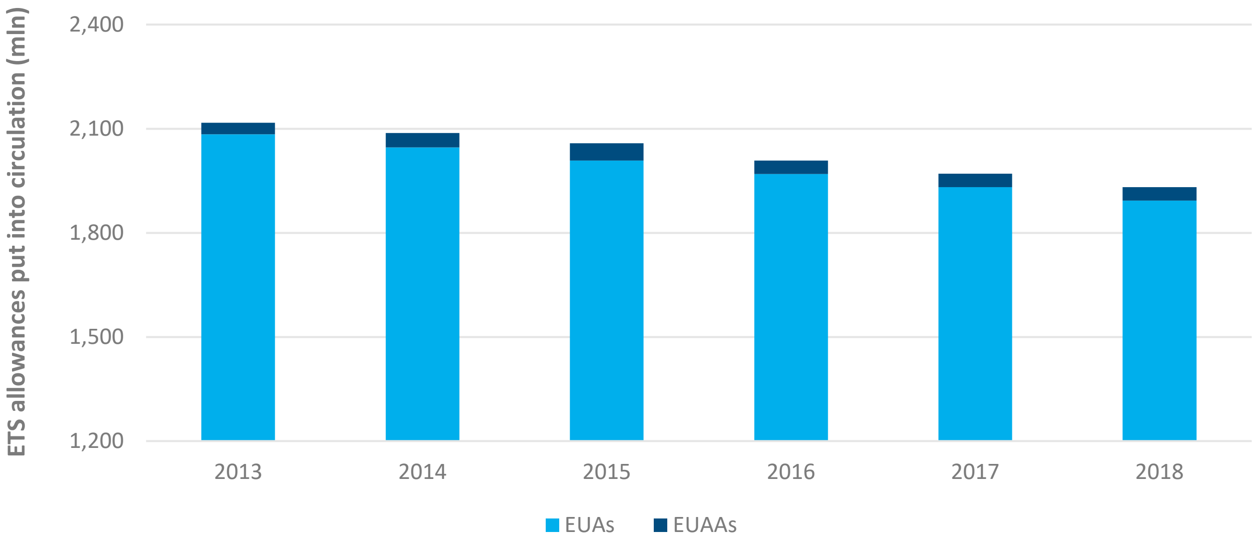

Figure 12: Number of allowances put into circulation (source: European Commission (2018a), analysis by authors)

As mentioned above a cap-and-trade system only works when compliance is high. In the EU ETS system 99 percent of emissions are covered by allowances. For the aviation sector the compliance rate was 98 percent. In the past various airlines have paid fines of over € 1 million each for non-compliance with the EU-ETS. These airlines later complied with the system (EC, 2018a; EC, 2017).

[147] The credits are no longer surrendered directly, but may be exchanged for allowances at any time during the calendar year.

Over the next trading period (2021-2030) both the general cap and the aviation cap are reduced by 2.2 percent per year to reach ETS specific reduction target of 43 percent (compared to 2005 levels) by 2030[148]. The European Green Deal contains more ambitious goals, and recently, the European Commission clarified these with a proposed target of reducing emissions by 55 percent by 2030, compared to 1990 levels. This may lead to a stronger reduction target for the sectors covered by the EU-ETS and thus a larger linear reduction factor. For 2050 the Green Deal aims for net zero GHG emissions.

Carbon removal

In order to limit the temperature rise to 1.5C by the end of the century, CO_2-emissions should be reduced by 45 percent in 2030 (compared to 2010 levels) and reach net zero in 2050. According to the IPCC (2018b) these targets can only be met by deep emission reductions in all sectors in combination with Carbon Dioxide Removal (CDR) from the atmosphere. CDR is needed to compensate for any residual emissions that cannot be mitigated by 2050.

Modelling assessments by the European Commission have also shown that technological innovations and the use of alternative fuels are not sufficient to reduce emissions to zero. The EC framework to achieve climate-neutrality recognised the need for greenhouse gas removals to compensate for any remaining emissions from sectors that cannot be fully decarbonised (EC, 2020d). The European Green Deal contains a 90 percent reduction target for the transport sector, indicating that the transport sector is seen as one of the sectors in which emissions cannot be completely reduced to zero in 2050.

It is therefore likely that carbon removal projects lead to the issuance of ETS allowances and/or dedicated carbon credits which can be used by the aviation sector to compensate for a part of its emissions that cannot be mitigated by 2050. This means that even under a net zero target, there may still be allowances and carbon credits made available through carbon removal projects in the EU. The price of the allowances and/or carbon credits equals the cost of removing carbon emissions from the atmosphere. This means that the price of allowances and carbon credits cannot exceed the cost of carbon removal.

There are various ways to remove CO_2 from the atmosphere, such as afforestation and reforestation (planting trees), Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS). Afforestation and reforestation rely on purpose-grown tree to removes CO_2 from the air as part of the photosynthesis process. BECCS relies on purpose-grown biomass (plants and tree) to capture CO_2. The biomass is subsequently harvested and combusted to produce power. The CO_2 that is released during the combustion process is captured and stored. DACCS removes CO_2 directly from ambient air by placing large volumes of air in contact with chemicals known as sorbents.

The various options differ widely in terms of maturity, potential, costs and risks (IPCC, 2018b). According to a recent study by the IEA (2020) afforestation/reforestation and BECCS are the most cost-effective options, with cost estimates ranging between $5 and $85 per tCO_2 removed. However, their main disadvantage is that they require vast amounts of land and water which limits their potential.

DACCS is more expensive mainly due to the low concentration of CO_2 in ambient air[149]. Compared to afforestation/reforestation and BECCS it does not require much land and water and therefore has the potential to remove large amounts of CO_2 from the atmosphere.[150] However, the separation process requires significant amounts of (renewable) energy and heat (Gambhir, 2019; Realmonte, 2019). Cost estimations range between € 30 (Breyer, 2019) and $ 1,000 (House, 2011) per tCO_2 removed, with most estimations lying in the € 100 to € 500 range.[151] The UK Committee on Climate Change (2019) assumed a price of 300 pounds per tCO_2 for DACCS in 2050.

For carbon removal within Europe we base our price estimation on the cost of Direct Air Capture as afforestation /reforestation and BECCS require vast amounts of land which might not be available. Based on the literature we therefore assume a value of € 315 tCO2 for carbon removals within Europe. For carbon removal projects outside Europe we expect the average costs of carbon removal to be lower. First, because of the larger potential for afforestation /reforestation and BECCS projects due to greater land availability. Second, because DACCS might be less costly in regions with a large supply of (renewable) energy and heat. For carbon removal projects outside Europe we therefore assume the middle value as published by the IEA (around $175 or € 160 per tCO_2 removed). This is in line with the estimated cost of carbon credits in 2050 (see below), indicating that carbon removal projects over time become cost-effective alternatives to carbon avoidance projects. It is therefore fair to assume that in 2050 carbon credits may be issued from carbon removal projects for € 160 per tCO_2.

[148] For the sectors not covered by the ETS, such as transport, construction, agriculture and waste, separate reduction targets are defined. When the agreed EU legislation is fully implemented, total greenhouse gas reductions are estimated to reach around 45% in 2030 (compared to 1990 levels). The policies put in place today have a continued impact after 2030 and with projected emissions of around 60% by 2050 (EC, 2018b).

[149] The CO_2 concentration from a point source such as a coal-powered power plants is around 12 percent, which is approximately 300 times higher than in ambient air (0.04 percent) (House, 2011).

[150] The atmosphere effectively disperses CO_2 quickly and evenly, which means that processing plants can be located anywhere (Broehm et al., 2015).

[151] Estimations for the longer-term are generally smaller than those for the short-term due to economies of scale and learning by doing. However, energy requirements are likely to remain high in the future (Breyer, 2019).

Trade

Although the total CO_2-emissions under EU ETS declined by 2.3 percent per year on average since 2013, the emissions from intra-EEA aviation increased by 4.5 percent per year (see Table 29). This indicates that the aviation sector is a net buyer of emission allowances. The power sector is the main seller of emission allowances. For power generators it is currently more cost-effective to reduce their own emissions and sell abundant allowances to other sectors where abatement costs are higher. By purchasing allowances from the power sector, the aviation sector contributes to the decarbonisation of the power sector. This shows that money flows to those investment projects that reduce emissions in the most cost-effective way.

Table 33: Verified emissions (mln CO_{2e}) (source: European Commission (2018a), analysis by authors)

	2013	2014	2015	2016	2017	2018	Y-o-Y change
Fixed installations	1,908	1,814	1,803	1,751	1,754	1,681	-2.5%
Aviation	54	55	57	62	64	67	4.5%
Total	1,962	1,869	1,860	1,813	1,818	1,748	-2.3%

In 2017, 41 percent of aviation emissions within the EEA was covered by EUAs purchased from the other sectors (see Figure 13). The remainder of the aviation emissions is covered by the aviation allowances (EUAAs). The majority of the EUAAs, 82 percent, was allocated for free to airlines over the 2013-2017 period (see Figure 13)[152]. Free allocation was introduced to limit the risk of market distortions and carbon leakage. This risk is highest for sectors that are exposed to international competition. Therefore the aviation sector obtains a relatively large share of its allowances for free. The system of free allocation remains in place during the next trading period. The remainder of the EUAAs, 18 percent, was auctioned or reserved for fast-growing airlines and new entrants.

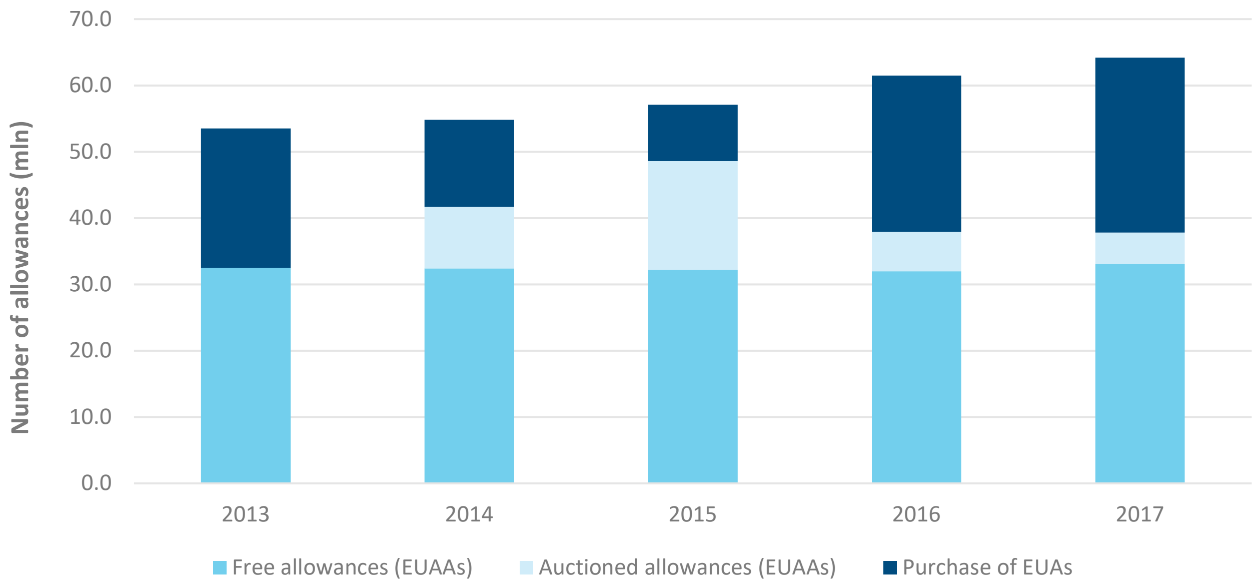

Figure 13: Aviation emissions covered by EUAAs and EUAs (source: European Commission (2018), analysis by authors)

[152] The European Commission estimates that 57 percent of allowances are auctioned over the 2013-2020 trading period. Power generators in principle do not receive any free allowances under the current trading period, although Article 10c of the ETS Directive allows for free allocation to modernise the power sectors in lower-income Member States. The heavy industry received around 80 percent of the allowances for free at the beginning of the trading period, which has been gradually decreased to 30 percent in 2020.

The auctioning revenues accrue to the Member States.[153] Member States report that they spend 80 percent of auctioning revenues on climate and energy purposes (ERCST, et al., 2019)[154]. Most of the revenues go to national and EU purposes, while a smaller share goes to international purposes (EC, 2019g). Data on the spending of the revenues is provided by the individual Member States. It is not clear to what extent the expenditures are additional and to what extent they lead to actual CO_2 reductions.

Member States can compensate producers for part of the costs incurred to a maximum of 25 percent of the auctioning revenues. The amount of compensation paid is partial and regressive and subject to state-aid guidelines. In 2018 producers could be compensated for 80 percent of their costs, this was reduced to 75 percent in 2019. In 2017, a total of € 694 million was paid out in compensation by ten Member States (EC, 2018a).

Several funding mechanisms are linked to the EU ETS to stimulate investments in low-carbon technologies (EC, 2019g):

- **Innovation fund:** The innovation fund supports the development of innovative technologies and breakthrough innovation in sectors covered by the EU ETS. The fund was established by the revised ETS directive. The amount of funding available corresponds to the market value of at least 450 million allowances. Depending on the allowance price the fund may amount to € 10 billion. The fund will be supplemented by any unused budget from the New Entrants Reserve (NER) 300[155] and up to 50 million allowances when these are not needed for free allocation (EC, 2018a);
- **Modernisation fund:** The modernisation fund supports low-carbon investments in the energy systems of 10 low-income Member States. The fund will be sourced with allowances corresponding to 2 percent of the total quantity in phase 4. At a carbon price of € 20 tCO2, around € 14 billion will be available over the coming decade.

Historic price development

The 2008 economic crisis and the widespread use of international credits in the second and third trading periods led to a surplus of emission allowances. As a short-term measure the European Commission postponed the auctioning of part of the allowances in 2014. This back-loading did not reduce the total number of allowances available during the third trading period, but only the timing at which new allowances became available. The introduction of the Market Stability Reserve (MSR) in January 2019 addressed the surplus of allowances in a more structural way. It makes the system more resilient to shocks by adjusting the supply of auctionable allowances[156].

The price of EUA allowances peaked at almost €30 per tCO_2e just before the economic crisis hit in 2008. The surplus of allowances that followed depressed the price to less than €5 per tCO_2e in 2013. The back-loading of allowances led to a modest price increase, but prices on average remained relatively low. In 2017 EUA prices averaged €5.80 per tCO_2 and the allowance costs represented around 0.3% of total operating costs for airlines within the scope of the ETS (EEA, EASA & EUROCONTROL, 2019). Since 2018 prices have risen sharply as market participants anticipated on the supply squeeze of the MSR and the post-2020 reforms that would come into effect from 2021. In 2019 EUA prices averaged almost €25 per tCO_2 (see Figure 14). The corona crisis had a sharp, but short-lived impact on the EUA price, which is currently back on the pre-crisis level. The EUAA prices showed a similar development.

[153] Two auctioning platforms are in place. The European Energy Exchange (EEX) is used by most participating countries. The ICE Futures Europe (ICE) acts as the platform for the United Kingdom. In 2017, the EEX-platform auctioned 89 percent of the total volume on behalf of 27 Member States. The ICE-platform was responsible for the remainder 11 percent (EC, 2018a).
[154] Article 10 of the EU-ETS Directive requires that at least 50 percent of the auctioning revenues are used by Member States for climate and energy related purposes.
[155] The NER 300 is one of the world's largest funding programme for innovative low-carbon energy demonstration projects. It is funded from the revenues of 300 million EU ETS emission allowances.
[156] Between 2019 and 2023, the amount of allowances put in the reserve will double to 24% of the allowances in circulation. The regular feeding rate of 12% will be restored as of 2024. As a long-term measure to improve the functioning of the EU-ETS, and unless otherwise decided in the first review of the MSR in 2021, from 2023 onwards the number of allowances held in the reserve will be limited to the auction volume of the previous year. Holdings above that amount will lose their validity.

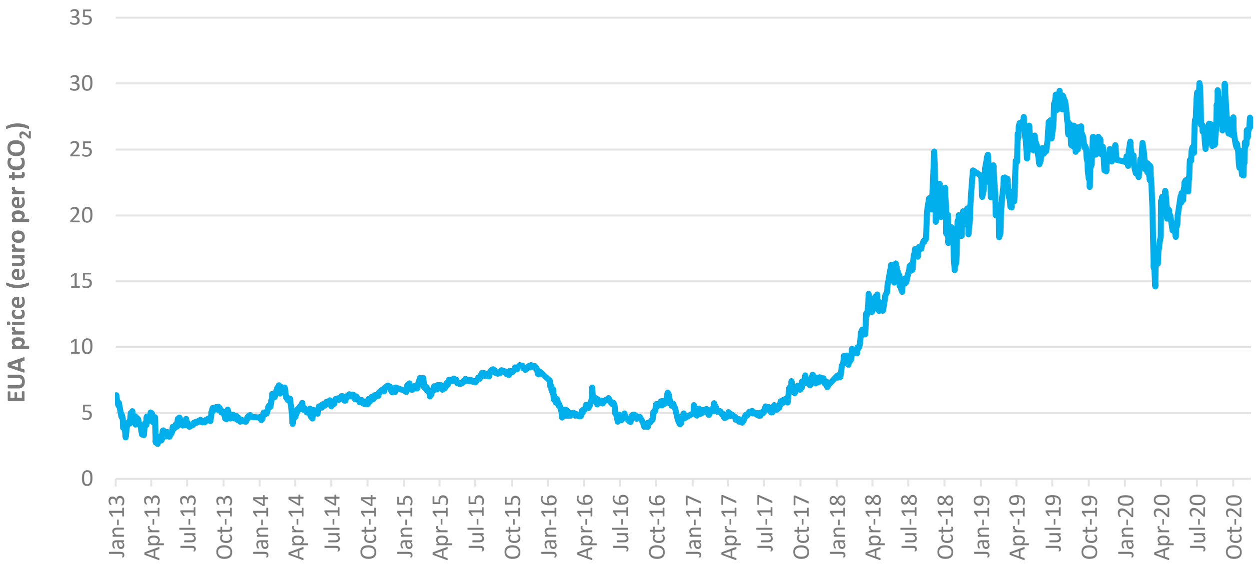

Figure 14: Development of ETS allowance prices in Phase 3 (EEX, n.d., analysis by authors)

The price increases lead to higher auctioning revenues for Member States. Figure 15 shows that the revenues from auctioning EUA and EUAA allowances increased from almost €4 billion in 2013 to over €16 billion in 2019. The additional revenues allow Member States to increase funding for climate and energy purposes as mentioned above. Over the 2013-2019 period, an estimated € 52 billion was raised by the auctioning of emission allowances. Almost € 0.5 billion was paid for by the aviation sector through the auctioning of aviation allowances[157].

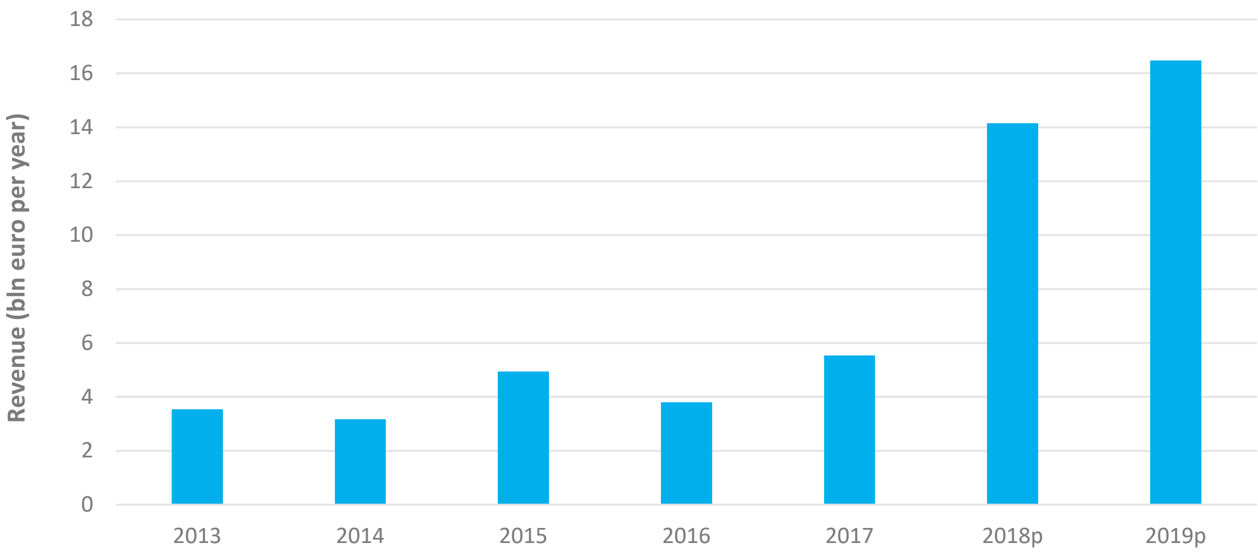

Figure 15: Development of ETS auctioning revenues in Phase 3 (analysis by authors). Note: Revenues are based on the allowance prices at the largest exchange platform, the European Energy Exchange (EEX). The number of auctioned allowances has not yet been officially published by the European Commission for 2018 and 2019. We predicted these numbers (indicated by 2018p and 2019p) based on the growth in auctioned allowances on the EEX-platform since 2017.

[157] In addition the aviation sector purchased allowances from the power and industrial sectors. The total cost of these purchases could not be calculated due to missing data for 2018 and 2019. However data for the 2013-2017 period suggests that these costs are significantly higher than the costs of the auctioned allowances. Also these costs are expected to increase more rapidly as an increasing share of allowances shall be purchased by the aviation industry.

6.3.2 CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is an offsetting scheme. This global market-based measure was agreed upon at the 2016 ICAO Assembly to address CO_2-emissions from international aviation.

CORSIA aims to stabilize net CO_2-emissions from international flights from 2020 onwards. CORSIA requires airlines to offset any emissions above the 2019 threshold by purchasing carbon credits generated by projects that reduce emissions in other sectors. This should ensure that the ICAO target of carbon-neutral growth from 2020 onwards (CNG2020) is being met. No further targets have been specified for the period after 2020.

International carbon credits are financial instruments that represent a tonne of CO_2 reduced or removed from the atmosphere as a result of an emissions reduction project. The credits are generated by emission reduction projects and are available through various offsetting programs. The Kyoto Protocol set the basis for two of such programs, the Clean Development Mechanism (CDM) and the Joint Implementation (JI) in 1997. The most widely used programs today are the Verified Carbon Standard (VCS) and the Gold Standard.[158]

In October 2020, 88 states (including all EU Member States) representing 77 percent of international aviation activity applied to voluntarily participate in the pilot phase (2021-2023) and first phase (2024-2046) of CORSIA. The second phase (2027-2035) is mandatory, although exemptions exist for states with a small aviation industry, Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs). These states may however still participate on a voluntary basis.

Initially the price of carbon credits developed in line with the price of EU-ETS allowances, as they could be used for compliance within the EU-ETS system. Prices plummeted after the financial crisis. But where the EU-ETS prices recovered when the oversupply of allowances was addressed, the prices of credits remained low due to oversupply and the fact that they could only be used to a limited extent during the third trading period of the EU-ETS (2013-2020). In early February 2020, carbon credits were traded for as little as € 0.23, roughly 100 times less than the price of EU-ETS allowances. Projects that adhere to higher quality standards regarding environmental and social integrity generate more expensive credits and could trade at up to $ 70 per tCO_{2e} (Energies Nouvelles, 2017). However, around half of the credits is sold below $ 1 per tCO_{2e} (World Bank Group, 2019). CORSIA might lead to a large increase in demand for carbon credits. The more stringent the criteria for the credits, the more expensive these credits will eventually be.

> **QUALITY OF OFFSET CREDITS**
> There is a general consensus that offset programs may in principle generate credible credits. The major offsetting programs follow equivalent, if not the same, procedures and methodologies. Therefore the environmental and social integrity of the carbon credits mainly depends on the type of projects that are being offered through the programs.
>
> The quality of carbon credits is generally measured by the following criteria:
> - Additionality: credits generated by a project represent greenhouse gas reductions or carbon sequestration or removals that would not have occurred without the project;
> - Measurable: greenhouse gas reductions should be measurable to confirm that they are real;
> - Permanence: credits should represent greenhouse gas reductions or removals that are permanent, i.e. have a low risk that the reductions or removals are reversed;
> - No leakage: the projects generating credits should not lead to increased emissions elsewhere;
> - Prevent double counting: the greenhouse gas reductions or removals may only be counted once;

[158] Offset credits may also be used by companies and organisations to voluntarily offset (part of) their carbon footprint. The size of the voluntary carbon market is much smaller than the compliance markets. Over the 2005-2018 period around 2,000 projects worldwide had issued over 430 MtCO2e of voluntary credits. This is relatively modest compared to the 11 GtCO2 covered each year by emission trading schemes and carbon taxes (Energies Nouvelles, 2017).

- Do no net harm: the projects generating credits should not cause any negative environmental or social externalities.

Several studies suggest that claims made by projects regarding environmental integrity often appear unrealistic and exaggerated. The majority of available carbon credits on the market is therefore of questionable quality with respect to their environmental integrity. A study commissioned by the European Commission concluded that 85% of the CDM projects and 73% of the credits issued under the mechanism had a low likelihood that emission reductions were actually additional and were not overestimated. Only 2% of the projects and 7% of the credits had a high likelihood of additionality and low likelihood of overestimation (Ökö-Institut e.V., 2016). Despite the fact that CDM standards have been improved, the performance of the scheme has not improved due to a shift in the project portfolio to more questionable project types.

Furthermore, the low prices of carbon credits generally does not reflect the actual cost of avoiding or reducing a tonne of CO_2. The projects often receive additional funding such as grants or subsidies from NGOs and governments. This means that the buyer of the credits is not fully responsible for the emission reductions achieved. When both the buyer and the NGO and/or government claim the same emission reduction, there is a risk of double counting the same reduction.

This suggests that there are many credits available in the market that might not actually represent additional, permanent and real emission reductions. Companies may however only rightfully claim emission reductions from projects that adhere to high standards regarding the environmental and social integrity.

In 2018 the ICAO Council adopted standards and recommended practices (SARPs) for CORSIA. In 2019 ICAO invited offsetting programmes to apply for assessment by the Technical Advisory Body (TAB) based on its eligibility criteria (ICAO, 2019c). It received 14 responses, which included the aforementioned Clean Development Mechanism (CDM), Verified Carbon Standard (VCS) and the Gold Standard. Although the Ökö-Institut e.V. (2019) concluded that many programs did not guarantee environmental integrity, 6 out of the 14 programs were approved in March 2020.
The implementation of the scheme is ongoing and not yet complete. Uncertainties remain regarding its coverage, robustness and compliance policy. Certain countries with a large aviation industry might not participate or delay the implementation of CORSIA into national law.

As mentioned above, carbon removal projects may lead to the issuance of allowances or carbon credits which can be used by the aviation sector to compensate for a part of its emissions that cannot be mitigated before 2050. This means that even under a net zero target, there may still be allowances and credits available stemming from carbon removal projects.

6.3.3 Comparison

The previous sections detailed EU-ETS and CORSIA. Table 34 summarizes the main differences between the two schemes. These relate to:

- **Ambition level:** EU-ETS aims to reduce absolute GHG emissions by 43 percent (compared to 2005) levels in 2030 for the sectors covered by the system (power generation, heavy industry and aviation). The European Green Deal may lead to a more ambitious target. CORSIA is less ambitious as it aims to stabilize net CO_2-emissions at the 2019 level;
- **Certainty on reaching emission target:** In EU-ETS the number of available allowances (cap) is fixed and corresponds to the target. This ensures that the target is met under full compliance. As mentioned before compliance levels are high due to the fact that the system is legally binding and penalties apply in case of non-compliance. For CORSIA much is still uncertain. The quality of the carbon credits greatly determines its efficiency. Furthermore, the system is not legally binding until countries have implemented it into national law. If CORSIA is not implemented in all countries at the same time, this could lead to market distortions (EC, 2017). Also it is yet unclear how compliance will eventually be enforced;
- **Geographic coverage and timing:** EU-ETS covers CO_2-emissions from intra-EEA flights until the end of 2023, after which it reverts to its full scope unless there will be a revision in light of CORSIA. CORSIA has a global reach and

covers the growth in CO_2-emissions of international flights between participating states after 2020. The global scope of CORSIA limits the risk of market distortions and carbon leakage. However, emissions from domestic flights are not covered by CORSIA.[159] This allows airlines with a large domestic network to pass-through part of the costs to their domestic routes. This gives them a competitive advantage on international routes. The same holds for airlines that serve international markets through indirect flights whereby one of the flights is domestic. This means that they only need to offset their emissions for the non-domestic flight leg, whereas competitors that operate direct need to offset emissions on the entire route. This introduces new risks of market distortions and carbon leakage. Both systems are in place at least during the 2021-2023 period. Over these years the growth in CO_2-emissions of intra-EEA flights between two EEA states is covered by both systems, unless the EU ETS is being revised. However, CO_2-emissions from the EEA states to states not participating in CORSIA (and vice versa) are neither covered by ETS nor CORSIA;

- **Use of international credits:** EU-ETS is based on emission allowances that can be traded among sectors in the EU. The system only allows operators to cover a small part of their obligations through the use of international credits until 2020. Thereafter such credits are no longer allowed. This means that as of 2021, all of the emission reductions achieved will occur within the EU. The offsetting under CORSIA is based on international credits. These credits will to a large extent stem from projects outside the EU. This means that CORSIA mainly offsets emissions through reductions outside the EU and thus has only a limited potential to contribute to the EU GHG reduction targets.
- **Exceptions for SAF:** The EU-ETS attributes zero emissions to SAFs that comply with the sustainability criteria defined in the RED. The purchase of SAF thereby reduces an aircraft operator's reported emissions, and the number of ETS allowances required (EEA, EASA & EUROCONTROL, 2019). Under CORSIA airlines can reduce their offsetting requirements by claiming emissions reductions from the use of CORSIA eligible fuels (CEF)[160]. The emission reduction that can be claimed depends on the life-cycle emissions of the specific SAFs used compared to the life-cycle emissions of conventional fuels. When the life-cycle emissions of a SAF are for instance 70 percent lower than those of conventional fuels, airlines only need to offset the remaining 30 percent of the emissions resulting from the combustion of the SAF through CORSIA. Excluding emissions from the combustion of SAFs partly or completely acts as a financial incentive for airlines to use SAF (EEA, EASA & EUROCONTROL, 2019).

Table 34: Main differences between EU-ETS and CORSIA

	EU-ETS	CORSIA
Scheme	Cap and trade	Offsetting
	Caps the level of emissions. Operators reduce their emissions or buy EU Allowances in the market (trade). International credits (CERs and ERUs) can be used to offset up to 1.5% of emissions (until 2020)	Operators buy international carbon credits to offset their emissions above 2020 levels. Conditions apply to offsetting programs.
Applicability	'12-'23	'21-'26 (voluntary), '27-'35 (mandatory)
	Reverts to full-scope in '24 unless there is a revision in light of CORSIA	
Target	2020: -5% compared to '04-'06 2030: -43% compared to '05	Carbon-neutral growth from 2020 (CNG2020)
	From 2021-2030 general and aviation caps are reduced by 2.2% each year	Cap remains fixed at 2019 level
Certainty on reaching target	Available allowances (cap) correspond to target, ensuring that target is met under full compliance	Depends on the quality of the carbon credits and compliance level
	Legally binding system, penalties in case of non-compliance	Only legally binding when implemented in national law. Uncertain how compliance is enforced

[159] Reducing these emissions is a responsibility of individual states. Domestic emissions are covered by the Nationally Determined Contributions (NDCs) that States have to meet under the Paris Agreement. The ambition levels of the NDCs differs per state and are not legally binding. Around two thirds of all flights is domestic and 40 percent of aviation emissions can be attributed to domestic flights (ICCT, 2019).
[160] Specific certification processes determine whether a SAF meets the CORSIA eligibility criteria.

	EU-ETS	CORSIA
Coverage	Intra-EEA flights and within Outermost Regions	International flights between participating states
	Initially all flights to and from EEA airports. 'Stop the clock decision' limited the scope in 2013 to give ICAO time to develop a global MBM (CORSIA). Reverts to full-scope in '24 unless there is a revision in light of CORSIA	In June 2019, 80 states representing 76.63% of RTKs, announced their intention to participate from the outset . Exemptions apply for domestic flights, least developed countries, small island states, landlocked developing countries, small operators and aircraft, flights with public purpose
SAFs	SAF are attributed zero emissions if matching RED requirements	Reduced offsetting obligation for 'eligible fuels' depending on life-cycle emissions

6.4 Approach

This section describes what is assumed regarding the development of market-based measures and associated prices in the report.

Development of carbon prices

The impacts of market-based measures on traffic and CO_2 emissions depend to a large extent on the price development of emission allowances and/or carbon credits. Future carbon prices depend on a range of factors, such as (1) economic growth, (2) international climate targets, (3) exceptions and freely allocated emission rights, (4) improvements in energy efficiency in different sectors, (5) availability of lower carbon-intensive generation capacity, (6) development of commodity prices, (7) coal phase-outs regulation, (8) timing of investments (9) linking of market-based measures[161] and (10) whether prices are based on damage costs or prevention costs (Carbon Tracker, 2018; ICIS, 2019; IPCC, 2018a; IMF, 2019a). This makes it difficult to predict how prices develop over time.

Based on recent literature we make a reasoned assumption on how market prices[162] may develop over time. The literature provides a large range of values, reflecting the uncertainty in the estimations (see box). According to the High-Level Commission on Carbon Prices, studies predicting relatively low prices assume a large reliance on complementary measures, whereas higher prices make pessimistic assumptions regarding technological change, supportive policies and mitigation through complementary measures. Although complementary measures have a reducing impact on the price, it is not always clear to what extent such measures have been taken into account in the various studies.

> **Literature on market prices for carbon**[163]
> The UK Department for Business, Energy & Industrial Strategy (2019) projected the prices of EU-ETS emission allowances in a high, central and low economic growth scenarios. Prices are determined based on trends in futures prices, projected emissions, abatement costs and the EU-ETS emissions target in 2030. In the central scenario prices increase from €15.64 (13.84 pounds) per tCO_2e in 2020 to €48.21 (42.66 pounds) per tCO_2e in 2030. Prices increase at a slower pace until 2025 as it is assumed that there will still be a surplus of allowances. From 2025 onwards the MSR has addressed the surplus and prices rise faster.
>
> IHS Markit (2017) estimated that the EU-ETS price would increase from around €8 per tCO_2 in 2020 to €32 per tCO_2 in 2030 and €47 per tCO_2 in 2040.

[161] The more systems are linked, the more emission reduction projects are available and the more cost-effective emission reduction becomes. This shall also reduce the risk of market distortion and carbon leakage. However, uniform pricing may give rise to equity concerns, especially with respect to emerging and developing economies. These can be solved by international transfers, although these may be politically difficult or infeasible at a large scale (Guivarch, 2017).

[162] Market prices should not be confused with the social cost of carbon. Market prices reflect the marginal abatement costs of mitigating emissions, whereas the social cost of carbon reflect the societal costs of allowing emissions to continue. The societal costs from damages caused by sea-level rise, food insecurity, loss of ecosystems et cetera are very difficult to predict (Synapse Energy, 2016).

[163] All prices found in the literature have been converted to the same currency (euro) and price level (2018) to make them comparable.

Thomson Reuters (2014) considered various price scenarios which differ in terms of the design of the MSR and emission targets. In the scenario that most closely resembles the MSR and the EU reduction target for 2030, the price of ETS allowances increases from around €18 per tCO_2 in 2020 to €52 per tCO_2 in 2030.

In 2018 Carbon Tracker expected that the supply squeeze caused by the MSR over the 2019-2023 period would create a significant gap for the power and aviation sectors. Fuel-switching from coal to gas in the power sector is considered the most cost-effective short and medium term solution to reduce emissions in the ETS. Therefore it is assumed that carbon prices rise to fuel-switching levels. Carbon Tracker (2018) forecasted that prices would reach to € 25 per tCO_2 in 2018 as producers and speculators anticipated the upcoming MSR supply squeeze. Thereafter prices would increase to fuel-switching levels: €35 per tCO_2 in 2019 and €40 per tCO_2 in 2020 and 2021. For 2022 prices were estimated to return to €35 per tCO_2 as the impact of the MSR on auctioning volumes would soften.[164] Over the longer term the emissions of the power sector are expected to decline as the cost of renewable and energy-storage technologies falls and coal plants are phased-out. The aviation sector shall become an increasingly important source of demand for allowances.

ICIS (2019) predicts that the EU-ETS allowances prices increase to more than €40 tCO_2 in 2023 to 2025 as a result of the introduction of the MSR and the post-2020 reforms. Over the short term prices are expected to remain relatively stable.

Global carbon prices under a Paris climate scenario
EDF (2018) estimated the price of emission reduction units in CORSIA using a modelling framework which explicitly takes competing demand from other sectors into account. Various scenarios were analysed including a scenario which is consistent with a 2°C scenario in which credits from Reduced Emissions from Deforestation and forest Degradation (REDD+) are eligible. The prices in this scenario increase by 5 percent per year from €28.7 ($33.9) per tCO_2e in 2020 to €59.7 ($70.4) per tCO_2e in 2035.

The High-Level Commission on Carbon Prices[165] (2017) was tasked with identifying price corridors that, combined with other policies and international collaboration could deliver on the Paris target. Based on evidence from the literature, industry and policy experience and taking into account the limitations of the various information sources, the Commission concluded that the explicit carbon price should be at least €36-72 ($40-80) per tCO_2 in 2020 and €45-90 ($50-100) per tCO_2 in 2030 to deliver the temperature objective of the Paris Agreement, provided that pricing policy is complemented with target actions and a supportive investment climate. In the absence of these elements, the carbon price range is likely higher. The prices suggested by the High-Level Commission are used by various organisations such as the International Finance Cooperation (IFC) of the World Bank and the European Bank for Reconstruction and Development (EBRD).

The IPCC (2018a) provides ranges for carbon prices under a 2° C and a 1.5° C scenario based on different models. In a 2° C scenario, prices per tCO_2e range between €13-185 ($15-220) in 2030 and €38-881 ($45-1,050) in 2050. In a 1.5° C scenario, the prices range between €113-5,078 ($135-6,050) in 2030 and €206-12,003 ($245-14,300) in 2050. The wide range of values is explained by differences in methodologies, and assumptions on fuel prices and technological developments. Models that allow more flexibility regarding mitigation options and assume perfect foresight in prices lead to lower carbon prices. Models that do not assume other ambitious measures lead to higher prices (World Bank Group, 2019). Also, the timing of investments is relevant. Delayed action increases mitigation costs and corresponding carbon prices, because more action is needed later to counterbalance the higher emissions in the short-term.

Implicit carbon prices
Companies and investors increasingly incorporate the future costs of climate related policies into their decision making. The costs are proxied by assuming an (implicit) future carbon price (Synapse Energy, 2016). EDF (2018) asked market players in the power sector which carbon prices were needed to meet the 2° C scenario in the Paris Agreement. For 2020 the carbon price runs from $24-39 per tCO_2e, increasing to $30-60 tCO_2e in 2025 and $30-100 tCO_2e in 2030.

2030

EU-ETS allowance prices are expected to range between €20-100 per tCO_2 in 2030 with most estimations ranging between €30-60 per tCO_2. The Thomson Reuters (2014) forecast, although the least recent, has been most accurate in predicting the EU-ETS allowance prices over the past years. This forecast estimates an allowance price of almost € 60 per tCO_2 for 2030, slightly higher than the central estimation of the UK Department for Business, Energy & Industrial Strategy (2019).

Global market prices for carbon might be a better proxy for credits used in CORSIA. EDF (2018) estimates a carbon price of just under €50 per tCO_2 in a 2° C scenario in 2030, which falls in the lower ends of the bandwidths provided by CDP (2017), the High-Level Commission on Carbon Prices (2017) and the 2° C scenario of the IPCC (2018a). A higher

[164] Although allowances prices might trade up to €50 tCO2 for limited time periods, Carbon Tracker (2018) expects that such levels are politically difficult to sustain over longer periods. In such circumstance the EU might increase the supply of allowances (under Articles 29a and 10c of the EU-ETS Directive) to depress the price.
[165] The Commission was initiated in 2016 at the 22nd Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) and is chaired by Joseph Stiglitz, a Nobel Laureate in Economics.

price therefore corresponds better with these bandwidths and a more ambitious net zero target. We consider the estimates from the High-level Commission on Carbon Prices most appropriate as these prices are based on delivering the temperature objective of the Paris Agreement and explicitly take the impacts of complementary measures into account.

As mentioned above, the cost-effectiveness of market-based increases with the size of the market both in terms of sectoral and geographical coverage. The larger the market, the broader the scope for emission reduction projects. This ensures that investments flow to the most cost-effective emission reduction projects. Prices in a global scheme (such as CORSIA) are therefore unlikely to be higher than under a regional scheme (such as EU ETS).

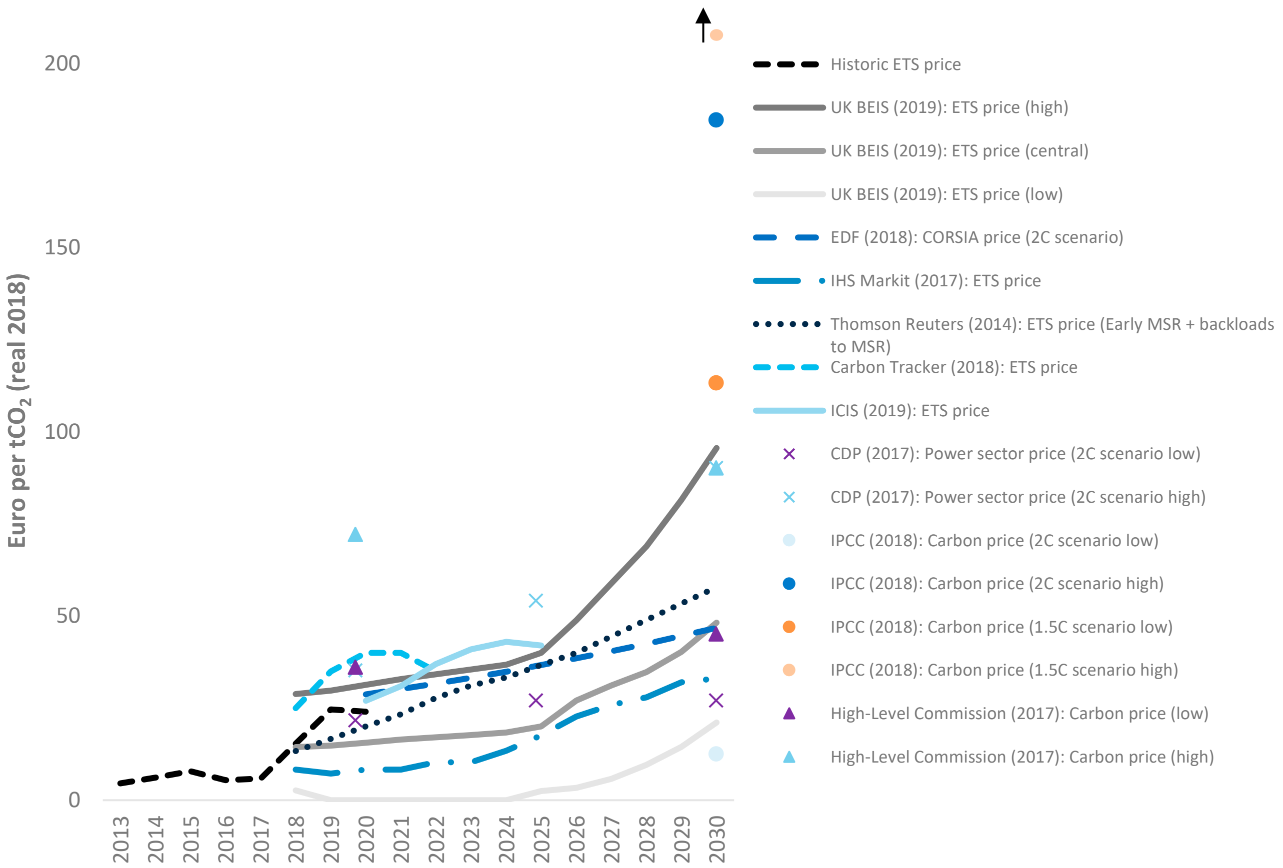

Figure 16: Estimated market prices for carbon emissions from the literature (Euros, real 2018). Note: The price estimations have been converted to the same currency (Euros) and price level (2018) to make them comparable

2050

Few studies provide price estimates until 2050. Only the IPCC provides price estimates for 2050, ranging between €40 and €12,000. Due to the lack of literature and the large bandwidth in the IPCC forecast, the price developments over the 2030-2050 period are based on the price developments over the 2020-2030 period. The studies forecasting EU-ETS allowance prices predict price increases ranging between 11-15 percent per year over the next decade, increasing to 10-19 percent in the second half of the century when allowances become increasingly scarce (see Figure 17). Under a net zero target, there will be very few allowances left when the EU-ETS remains in place. However, as mentioned above, additional allowances may be issued by carbon removal projects to balance residual emissions in 2050.

The studies forecasting global carbon prices predict smaller price increases of 2-10 percent per year until 2030. This supports our assumption that the prices of carbon credits will be lower than those of EU-ETS allowances. Apart from the fact that there is more potential for emission reduction on a global scale, not all countries outside of the EU may pursue equally ambitious climate goals for 2030 and 2050, limiting the demand for credits in other parts of the world.

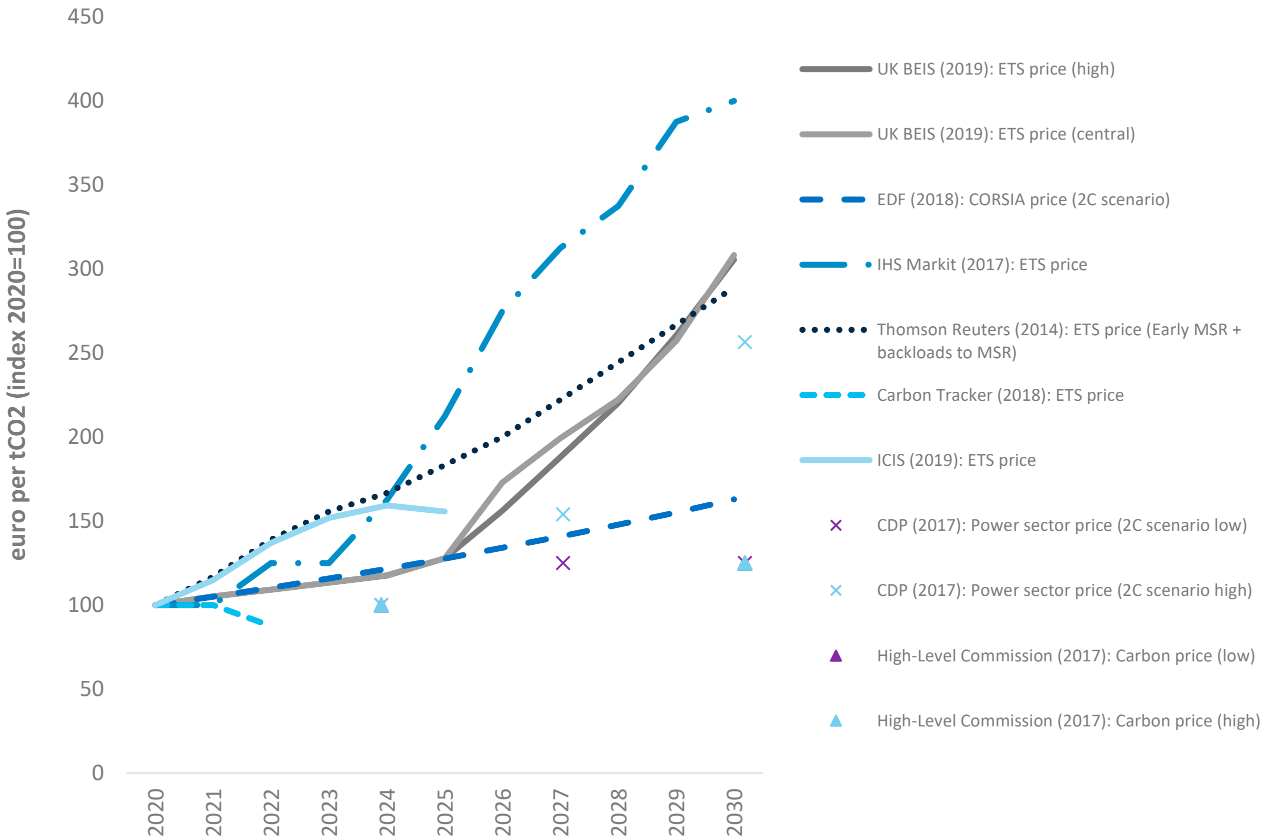

Figure 17: Relative price increases between 2020 and 2030

Assumptions

Based on the previous analysis we assume a price of €60 per tCO_2 for both the EU-ETS allowances and carbon credits in 2030. For the 2030-2050 period we assume that the prices of allowances and credits increase by 15 percent and 5 percent per year respectively. This would result in an EU-ETS allowance price of almost €1,000 per tCO_2 and a carbon credit price of around €160 per tCO_2 in 2050. However, under an efficient trading scheme the allowance prices cannot exceed the price of the most cost-effective (set of) measure(s) to achieve a specific goal. This price is also known as the efficient price. Hence, the allowance price cannot exceed the price of any of the other measures. We therefore cap the allowance price at the price of carbon removal projects and SAFs: € 315 per tCO_2 (see Figure 18).

The price for carbon credits is similar to the estimated price for carbon removals outside of Europe in 2050, i.e. € 160 per tCO_2 (see above€). This indicates that over time carbon removal projects become attractive for investors. The carbon credits issued by such projects can be used in CORSIA and represent actual carbon removals. Such credits are therefore in line with the definition of net zero.

The reference scenario already assumes a moderate carbon price. When estimating the impacts of more ambitious market-based measures we correct for the prices in the reference scenario.

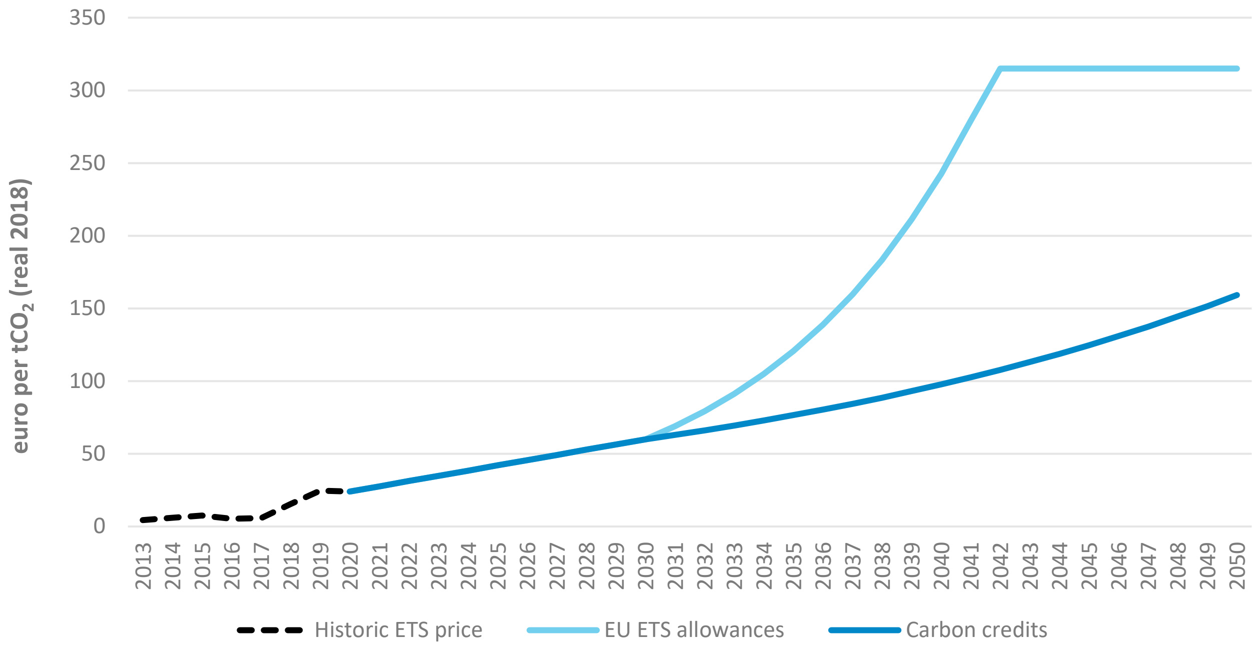

Figure 18: Price scenario

6.4.1 Development of existing measures

As mentioned above, work at ICAO is ongoing to develop the implementation rules and tools for CORSIA. Within 12 months after its adoption, the European Commission shall assess its rules, tools, ambition and environmental integrity. Based on the outcome of this assessment, the European Commission may revise the scope of EU ETS for aviation, consistent with the EU climate targets (EU, 2017). In the absence of a new revision, EU-ETS would revert back to its original full scope from 2024.

Although the EU favours a global measure, it is unlikely that it accepts CORSIA in its current form as the sole mechanism to reduce aviation emissions in the EU. First, because of its lower ambition level and the exclusion of domestic flights. With the European Green Deal the European Commission shows that it aims for more ambition instead of less. This may lead to a reinforcing of EU ETS and a further reduction of free allowances, which will further increase the difference in the level of ambition with CORSIA. Second, because of CORSIA's reliance on international credits which are generated in part by emission reduction projects outside the EU. For the EU the European ambition is key. Policy is therefore aimed at reducing intra-EU and domestic emissions.

As it is yet unclear how both measures will develop and co-exist in the future, we assume that all CO_2-emissions from intra-EEA flights are covered by some sort of smart economic measure.[166] In line with the EU climate neutrality

[166] A hybrid system is deemed most likely. Their coexistence however determines the cost to airlines, as EU allowances will be more expensive than carbon credits. In case the EEA is considered a domestic market under CORSIA or when compliance with EU ETS also counts as compliance towards CORSIA, the EU ETS system may cover all CO_2-emissions of intra-EEA flights. As the prices of EUAs and EUAAs are likely higher than those of carbon credits, this will lead to higher costs than in a scenario in which international flights in the EEA would be covered by CORSIA. For the modelling exercise we need to make an assumption on whether and how both systems eventually co-exist.
We assume that all intra-EEA emissions are covered by EU ETS. We assume that number of issued aviation allowances (EUAAs) is reduced in line with the emission targets of the EU. For the fourth trading period (2021-2030) this means a yearly reduction of 2.2 percent per year. Thereafter we assume a linear reduction factor to reach net zero in 2050. The aviation sector likely needs more allowances to cover its emissions and therefore needs to acquire EUAs on the market as indicated. Furthermore, we assume that the rate of free allocation of aviation allowances is reduced from 85 to 0 percent in 2030. This means that airlines need to buy an increasing amount of allowances on the market, which increases the cost of compliance. Finally, it is also assumed that the auction revenues are invested in projects that yield a net 50 percent CO_2 reduction in 2030. These emission reductions are ascribed to the aviation industry.

objective, it is assumed that any allowances/credits available to aircraft operators in 2050 are issued as a result of DACCS based carbon removal projects in the EU.

For extra-EEA flights we assume that the growth in CO_2-emissions from 2020 onwards is covered by CORSIA. Furthermore we assume that all states will eventually participate in CORSIA and that it will be continued (or replaced by an equivalent) scheme after 2035, with a heightened ambition level: net zero CO_2-emissions in 2050.[167] Here we also assume that any credits used by aircraft operators in 2050 stem from carbon removal projects.

In the modelling we therefore distinguish between:
- **Intra-EEA** flights are fully covered by a market-based measure;
- **Extra-EEA** flights are only covered by CORSIA. Until 2035 only the emissions of these flights above the 2019 threshold are covered. After 2035 the threshold is lowered in a linear way to net zero in 2050.

6.5 Drivers and barriers

This section describes the main drivers and barriers that determine the impact of market-based measures.

6.5.1 Drivers

Economic measures are increasingly recognised as a key tool to reduce carbon emissions. Well-designed market-based measures reduce emissions in a cost-effective way and ensure that climate goals are actually being met. These benefits contribute to their acceptance and adoption on a global scale. This is important, as the adoption of a global measure yields the largest emission reduction at the lowest cost, while at the same time preventing market distortion and carbon leakage.

Compared to the other measures described in this report, market-based measures are able to yield large emission savings in the short term. Unlike the other measures, market-based measures do not require large upfront investments. However, states need to agree on their details.

6.5.2 Barriers

CORSIA being a global measure has the largest potential for emission reduction. In its current form it however also has some drawbacks . First, CORSIA's CO_2 target is less ambitious than that of EU ETS. Second, CORSIA depends on international carbon credits, the quality of which is heavily debated. The majority of credits sold in the past did not represent real emission savings. This can be solved through more stringent eligibility criteria. As shown above, the price of carbon credits eventually reaches the cost of removal projects. This means that it becomes cost-effective to

CORSIA covers the extra-EEA emissions above the 2019 threshold until 2035 after which the threshold is linearly lowered to zero in 2050. Furthermore we assume that the EU accepts the use of high quality offsets under CORSIA and that these contribute to the EU climate goals. The reason for this is that the EU signed and ratified the Paris Agreement which recognises the importance of international carbon markets. More specifically, Article 6.2 of the Paris Agreement (United Nations, 2015) provides for the use of 'internationally transferred mitigation outcomes' towards nationally determined contributions. Article 6.4 mentions a mitigation mechanism for certification of emissions reductions for use towards the nationally determined contributions which shows similarities to CDM and JI (UNFCCC, 2017).

[167] A raised ambition level for CORSIA after 2035 shall lead to an increased demand for carbon credits from the aviation industry. However, in a global market for offset credits the impact on the price of offset credits is assumed to be limited as the share of offsets demanded by the aviation industry shall be limited. Therefore we do not expect a large increase in the price for offset credits after 2035.

invest in carbon removal projects. In 2050 carbon credits may therefore be issued from carbon removal projects. These credits can be used to cover any residual emissions and attain the net zero CO_2 emissions target.

Economic measures assign a price to emissions which increase airline costs. These costs increase over time as allowances and carbon credits become increasingly scarce. This is especially the case when few other measures are being taken. In a competitive market cost increases are passed on to the end-user. For some users, air travel may become too expensive, which may translate into less demand for air travel. The compliance costs in combination with a reduction in travel demand could however reduce airline’s ability to invest in new technology and SAFs.

National or multilateral economic measures may affect airline cost levels in different ways. This will distort competition and might lead to carbon leakage. By increasing the geographical scope of an economic measure, this risk is prevented. A global approach is preferred over a national or multilateral approach.

If CORSIA and EU ETS continue to co-exist after 2023, this may lead to a situation in which emissions from international flights within the EEA that exceed the 2019 threshold are covered by both systems. This double counting of the same emissions might be suboptimal and should be prevented. Also it will increase administrative costs to airlines and might lead to a reduced acceptance.

The accounting of a state’s aviation emissions is generally based on the emissions of departing flights. Emission reductions achieved through efficiency gains of arriving flights, such as Optimized Descent Profiles (ODPs), then do not contribute towards the state’s climate targets. This may act as a disincentive for ANSPs to improve the efficiency of arriving flights.

Although economic measures lead to cost-efficient emission reductions, they are sometimes opposed because they lead to out-of-sector reductions. The aviation sector for instance shall remain a net buyer of emission allowances and carbon credits. By doing so, the aviation sector invests in emission reductions in other sectors. This generates larger overall emission savings than in a situation in which the sector would only be allowed to invest in its own assets and processes.

6.6 Policies and actions

Aviation is a global industry which requires global solutions. National economic measures, such as aviation taxes often lead to market distortions and carbon leakage. Ideally policy-makers and industry should work together towards one global all-encompassing smart economic measure which yields actual emission savings. Such a global measure not only has the largest scope for emission reduction, it will also ensure that emission reductions are achieved against the lowest cost. Compared to a situation in which multiple systems co-exit, it has the added benefits of limited administrative costs and a reduced risk of market distortion and carbon leakage. When all emissions from flights departing from EU airports are covered by a smart economic measure, national economic measures need to be reconsidered to prevent that the same external cost is priced twice.

Until an all-encompassing global measure is available, the EU should aim for a package of measures that covers the emissions from all flights departing from EU airports in order to reach the EU climate goals. This might mean revising EU ETS to complement CORSIA in such a way that ETS addresses all emissions which are not covered under CORSIA. This would prevent double counting of the same emissions. Furthermore, while both systems co-exist, it is important that the reporting mechanisms are aligned to the limit administrative costs for the airlines. When deciding on the way in which ETS and CORSIA will interact, the risk of carbon leakage and distortion of competition has to be minimised.

This will ensure the highest environmental effectiveness of the two systems, while also avoiding social and economic disadvantages for European aviation.

The EU should also try to improve the existing measures. With respect to CORSIA this means (1) striving for an ambition level that goes beyond carbon neutral growth from 2020 onwards, (2) urging third countries to also put in place economic measures that cover their domestic emissions and (3) to agree on a high standard for carbon credits, with all credits to be sourced from high-quality carbon removal projects by 2050.

There is also room for improvement regarding EU ETS. First, the number of allowances can be reduced to zero in 2050 to ensure climate neutrality is achieved. This should be complemented with a policy which allows any remaining carbon emissions to be compensated by negative emissions. For instance by allowing carbon removal projects to lead to the issuance of additional allowances. Second, to reduce the amount of freely allocated allowances. Third, enhancing the cost-effectiveness of ETS by increasing its scope through the inclusion of more sectors and/or by linking it to similar schemes elsewhere in the world. The latter might however lead to emission reductions outside the EU financed by the European aviation sector. Fourth, by requiring that Member States to invest all proceeds of the auctioned allowances in sustainability projects.

EU ETS has proven that it yields actual emissions reductions in a cost-effective way. Further improvements to the scheme (lowering the cap and the number of free allowances) will help the EU to reach its 2050 climate goals.

7 System changes and radical ideas

Having discussed the possible effects of technology, ATM and aircraft operations, sustainable aviation fuels and economic measures, this chapter discusses a number of more radical and largely system-wide innovations.

These are not considered in the modelling and impact quantification for a number of reasons. First, some invalidate the fundamental ideas of the forecast on which the present study is based (discussed in more detail in Chapter 2). Second, some of the ideas listed here are not mutually compatible, or not compatible with measures that are part of the modelling. Nevertheless, these ideas are presented here in a mostly qualitative sense in order to inspire further thought and guide associated research.

Shorter flights with smaller aircraft

Probably the most all-encompassing of all ideas presented in this chapter is a radical return to smaller aircraft and shorter stage lengths. As discussed in Section 3.3.1, electrification and hybridisation are most feasible for small and regional aircraft travelling limited distances. A larger amount of flights might be used to transport the same amount of passengers and longer distances can be traversed using one or more intermediate stops, at which batteries can be charged or swapped. Following Figure 7 and assuming an average of 120 seats for each intra-European flight, replacement with 30-seat battery-electric aircraft would yield a 4-fold increase in flights. Assuming passenger growth factors are unaffected, this would result in 38.8 million intra-European flights in 2050, compared to 9.7 million in the reference scenario. Lower aircraft utilisation due to necessary stopovers (a consequence of the limited range of battery-electric aircraft) would require a fleet growth of more than the 4-fold-increase in flights. The same might also occur with hydrogen-powered aircraft, until that technology possibly transitions to larger and longer-range aircraft.

Unsurprisingly, this yields a number of challenges. In the traffic growth forecast supporting the present research, airport capacity is an important factor constraining growth, with EUROCONTROL (2018b) estimating some 160 million unaccommodated passengers by 2040. Helped by their smaller size and likely lower environmental footprint, these battery-electric aircraft might be welcomed by local or regional airports and shift part of the traffic that way. As such airports are often located more closely to residential areas, local environmental concerns such as noise and third-party risk should be considered carefully. Also, whereas EUROCONTROL (2018b) does not assume constraints at airspace level, this assumption might not hold in case of the massive increase in flights projected here. The additional cockpit crews, ground handling personnel and air traffic control officers required means that cost to operators is likely to increase – unless this can be compensated by increased automation and autonomy.

On the other hand of these difficulties, however, are substantial gains to be realised. In 2018, intra-European flights were responsible for 45% of the emissions considered within the scope of this study, with 10% of that associated to flights below 750 kilometres. Depending on the amount of electrification and available renewable energy, these emissions might be partially or completely avoided.

Using larger aircraft will likely alleviate these issues – at least partially. On the other hand, the benefits are reduced as well: larger aircraft are heavier, and following limitations of battery energy density, these are likely to require a hybrid-electric (rather than a battery-electric) powertrain. Assuming a 70-seat aircraft with 50% lower emissions[168], the number of intra-European flights would increase by about 70% to a total of 16.6 million in 2050, while reducing CO_2 emissions by 22.5% overall[169]. Additional reductions in carbon dioxide emissions might be realised if such an

[168] Based on the difference between fuel efficiency improvements assumed for regional versus single aisle aircraft, following Table 13.
[169] 50% × 45% = 22.5%.

aircraft were to be specifically designed for a more limited range than what is currently offered in the single aisle market.

Designing aircraft for reduced cruise speeds

Current (and anticipated future) aircraft are mostly designed for and operated at cruise speeds around Mach 0.8, with turboprop-powered models flying at Mach numbers well below 0.7 a notable exception. Even with aircraft available today, some fuel savings can be achieved by operating at reduced speeds. Estimates for the potential impact vary. According to Brok, Hagstroem, Junior & Matthes (2010), a decrease in cruise Mach number yields fuel savings of 0.4 to 1.3%, consistent with Roberson, Root & Adams (2007)[170] and Edwards, Dixon-Hardy & Wadud (2015), noting that cost index changes affect fuel burn by 1%. A simulation on 200.000 domestic flights in the United States validates these numbers: full implementation of Long Range Cruise Mach numbers (LRC) would decrease CO_2 emissions by 0.89% at a negligible change in flight time[171]; using the slower Maximum Range Cruise Mach Number (MRC), emissions would decrease an additional 1.04% – at the cost of flight times 3.86% longer (Jensen, Hansman, Venuti, & Reynolds, 2013). Although the majority of sources seems to indicate a limited savings potential, two publications stand out. Schäfer, Evans, Reynolds & Dray (2015) cite studies noting benefits of 5.5% and a study by EMRC and AEA (2011) refers to work supporting ICAO CAEPs Group of Independent Experts that shows a Mach number reduction from 0.86 to 0.74 (14%) lowering fuel consumption by 11.4%. Internal NLR analyses at engine level are most consistent with Schäfer, Evans, Reynolds & Dray (2015).

Additional benefits can be unlocked by specifically designing aircraft for these lower cruise speeds. These would then require less power full engines, for example, which reduced engine weight and in turn allows for further decreasing weight elsewhere in the structure. Similarly, lower cruise Mach numbers require less wing sweep (applied to prevent drag increases found in the transonic regime), which too can save weight. These weight reductions might then warrant another reduction in required engine thrust, and so on, and so forth.

As highlighted before, the reduction in fuel burn that is a consequence of lower cruise speeds comes at cost elsewhere in the operation. The productivity (amount of passengers transported over a particular distance in a particular time) of aircraft decreases, such that more aircraft are required for a given traffic demand. Due to longer flight times, crew costs can also be expected to rise and passenger comfort might be (negatively) impacted. Overall, however, EMRC and AEA (2011, p. 60) indicate “an 8% fuel saving from a 10% speed reduction [can be achieved], until diminishing returns are reached”.

Intermediate stop operations

The amount of fuel consumed – and as such the amount of CO_2 emitted – by long-distance flight is disproportionally large compared to the share of such flight as part of total aviation traffic (also shown in Figure 9). This is a consequence of the fact that the fuel required for the final flight phases has to be carried along the entire flight. This increases the weight of the aircraft, which in turn increases the fuel consumption. This effect is also known as ‘transport loss’, ‘cost of weight’ or, more colloquially, the snowball effect.

Adding additional stop-overs might be a way in which the emissions associated to long-haul flights can be substantially reduced. Indeed, this concept has been researched by numerous scholars. Without redesigning the aircraft for shorter ranges, estimations for the potential savings of intermediate stop operations vary between 5 and 25% (Hartjes & Bos, 2015), with the majority being between 5 and 10% (Creemers & Slingerland, 2007; Brok, Hagstroem, Junior, & Matthes, 2010; Lammering, Anton, Risse, & Franz, 2011; Bergmans & den Boer, 2012; Martinez-Val, Perez, Cuerno, & Palacin, 2012; Hartjes & Bos, 2015; Linke, Grewe, & Gollnick, 2017). Most studies consider one stop-over and missions

[170] This publication adheres to the definitions of Long-Range Cruise (LRC) and Maximum Range Cruise (MRC). The speed increase from MRC to LRC is approximately 3 to 5%, at the cost of a reduction in mileage (i.e., an increase in fuel burn) of 1%. 3 to 5% of an ordinary cruise Mach number of 0.8 is 0.024 to 0.04.
[171] This improvement potential is considered to be part of the measures to improve flight planning and execution, described in Section 4.2.1.

of 5000 to 7000 kilometres and above. At shorter distances, fuel consumption might actually increase due to the larger ratio of fuel-intensive flight phases to cruise phase (Martinez-Val, Perez, Cuerno, & Palacin, 2012). Furthermore, authors note the dependency on the location of the intermediate airport (primarily in terms of detour with respect to the original great circle route, secondarily in terms of the ratio of lengths of the two flight legs). This is also shown by Langhans, Linke, Nolte & Gollnick (2013), who, using a system-level analysis of all Airbus A330 and Boeing 777 flights as operated in 2007, estimate a lower fuel-saving potential of 2.8%, likely due to non-ideal distributions of possible intermediate airports.

In case the aircraft is redesigned for a shorter mission, potential CO_2 reductions increase further. Langhans, Linke, Nolte & Gollnick (2013) see the savings potential grow to just over 10% using a design range of approximately 5500 kilometres. Creemers & Slingerland (2007) estimate reductions of more than 25% for a reduced-range Boeing 747-400 derivative.

Despite these possible benefits, there are a number of disadvantages and complexities associated to intermediate stop operations. Most obvious, flight times will increase and the number of take-offs and landings will grow. Given the fact that these flight phases are most accident-prone, care should be taken to maintain present safety levels. Furthermore, there should be airport capacity to meet the increased demand – up to 130 additional daily flights for the ten airports most often used as stop-over location, such as at the East coast of the United States and Canada (Langhans, Linke, Nolte, & Gollnick, 2013) – as well as ATC capacity related to these operations. Moreover, the stop-overs will increase noise exposure for communities surrounding airports, as well as have an impact on local air quality. On the other hand, the lower fuel weight reduces the take-off weight, which in turn reduces the required engine thrust and associated emissions (Brok, Hagstroem, Junior, & Matthes, 2010). This is of course amplified if long-haul aircraft are replaced by alternatives designed for shorter ranges.

The impact on cost was investigated by Creemers and Slinglerland (2007), Martinez-Val, Perez, Cuerno & Palacin (2012) and Hartjes and Bos (2015). Even though maintenance costs are expected to go up and the production per aircraft reduces, both publications show benefits in terms of direct operating cost. This is mainly due to the lower fuel usage (especially when uplifted in locations where fuel prices are advantageous), but also due to reduced crew costs, as there is less need for relief pilots. Depending on fuel efficiency of the aircraft use and overall flight length, savings might be as much as 10% (Martinez-Val, Perez, Cuerno, & Palacin, 2012).

Air-to-air refuelling

Customary in military aviation, but unseen in commercial air traffic is air-to-air refuelling. In terms of fuel reduction, the benefits of intermediate stop operations also apply to this concept. However, the impact on flight time, passenger comfort and airport capacity (and the associated benefits and disadvantages) do not apply, or only do so to a more limited extent. Langhans, Linke, Nolte & Gollnick (2013), however, anticipate a significant negative (rather than a minor) impact on safety and requirements for automation. As such, it is not further considered here.

8 Assumption and impact modelling

This study presents measures to reduce CO_2 emissions from aviation across four types of measures: (i) improvements in aircraft and engine technology (including hydrogen); (ii) improvements in ATM and aircraft operations; (iii) use of drop-in SAF; and (iv) economic measures. This chapter outlines the approach that is used to assess the impacts of these measures against the reference scenario.

The identified sustainability measures impact the total aviation emissions in two ways. Firstly, the amount of emissions per flight is reduced, for example through the use of more fuel-efficient aircraft. This leads to less emissions for an equal amount of flights. Secondly, some of the identified measures will incur higher costs with respect to the reference scenario, which will be (partially) passed on to the passengers. These higher costs will reduce demand, as some passengers will refrain from travelling if fares increase. Slower demand growth will result in fewer flights compared to the reference scenario, which in turn results in lower total CO_2 emissions from aviation. All cost increases are assessed at the route level, where passengers may choose to use alternative (indirect) air routes, or choose to refrain from using air travel.

Although demand reduction is inevitable if sustainability measures lead to higher costs for passengers, measures to reach climate goals should not primarily be focused on reducing demand for air travel. Aviation supports international connectivity, and enables international business activity and tourism, as also highlighted in Section 1.1. Measures should be focused at reducing emissions from aviation, while sustaining its socio-economic benefits as much as possible.

The following sections present if and how emission reductions and cost increases are estimated in each of the four pillars. For improvements in technology and operations that yield emissions reductions, impacts of cost increases are mostly assessed in a qualitative manner. For SAF, both the emissions and cost aspects are taken into account. These impacts are based on a literature review, substantiated with interviews with experts from industry. For economic measures, direct emissions impacts are only taken into account if the measure is designed to yield a one-to-one reduction of CO_2 emissions. Table 35 summarises how the aspects were taken into account in the modelling.

Table 35: Modelling of emission reduction and cost increases per pillar

Pillar	Emissions per flight modelled?		Cost increase w.r.t. reference scenario modelled?	
Improvements in aircraft and engine technology	Yes	Reduction based on reported / estimated efficiency gain.	Limited	Costs associated to fleet renewal and technology development of kerosene-powered aircraft are estimated to be offset by reduced operational expenses. For hydrogen-powered aircraft, cost increases due to technology development and hydrogen production are based on literature.
Improvements in ATM and aircraft operations	Yes	Reduction based on reported / estimated efficiency gain.	No	Cost implications are uncertain and difficult to quantify. Cost increases for passengers depend on way investments are funded. Therefore, we assume that operational improvements do not lead to cost increases for passengers or airlines.
Sustainable aviation fuels	Yes	Emission reductions based on literature; depend on type and amount of SAF used.	Yes	Cost increase based on literature study on fuel cost.

Pillar	Emissions per flight modelled?		Cost increase w.r.t. reference scenario modelled?	
Economic measures	Yes / no	Emissions per flight only reduce if receipts of the measure are used to result in a one-to-one CO_2 reduction elsewhere.	Yes	Cost increase is directly related to the proposed measure.

8.1 Improvements in aircraft and engine technology

Technological measures chiefly consider the use of more fuel-efficient aircraft and engines, that enter the market through fleet replacement. Older aircraft types – that are still in use in the base year 2018 – will be replaced by newer aircraft types, some of which are already on the market. Estimated emission reductions from such aircraft types are derived from manufacturers' publications, research projects and studies discussed in Chapter 3.

New generations of aircraft are modelled to be phased in linearly, and that over a period of 22.5 years starting from the year a new aircraft enters service all older aircraft types will have been replaced. The average retirement age of passenger aircraft is 25 years (Jiang, 2015; Forsberg, 2015). In financial reporting airlines tend to apply a linear depreciation over a period of 20 to 25 years (KPMG & IBA, 2017). Figure 19 shows that the age of EU aircraft in service is relatively evenly distributed. This supports the assumption of linear replacement of older aircraft types.

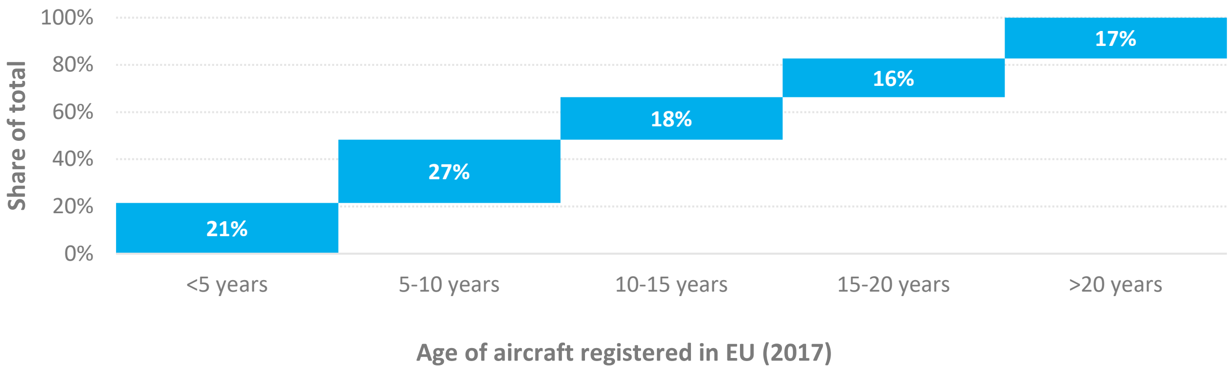

Figure 19: Age of EU aircraft fleet (eurostat, 2019)

The impacts of fleet replacement depend on the specific aircraft type being replaced, which is modelled at the aircraft type level for most aircraft. Table 36 provides an overview of the average improvement from upcoming technology, per aircraft category. This takes into account both one-to-one (per Table 5) and class-averaged (Table 6) replacements by upcoming aircraft (Section 3.2).

Table 36: Overview of average potential CO_2 emissions reduction delivered by upcoming aircraft, expressed at aircraft level (i.e., per flight) with respect to previous generation aircraft (based on Table 6). Fleet level CO_2 emissions reduction delivered by upcoming aircraft for 2030 and 2050 (i.e., taking into account fleet replacement duration)

Class (abbreviation)	Aircraft level CO_2 emissions reduction, at EIS, w.r.t. previous generation aircraft	Fleet level CO_2 emissions reduction, 2030	Fleet level CO_2 emissions reduction, 2050
Regional (R)	24.8%	13%	24.8%
Single aisle (SA)	14.8%	7%	14.8%
Small/medium twin aisle (SMTA)	17.6%	6%	17.6%

Class (abbreviation)	Aircraft level CO_2 emissions reduction, at EIS, w.r.t. previous generation aircraft	Fleet level CO_2 emissions reduction, 2030	Fleet level CO_2 emissions reduction, 2050
Large twin aisle (LTA)	19.2%	8%	19.2%

Table 37 provides an overview of the CO_2 emissions reduction potential of future technology, based on Section 3.3. This lists both the CO_2 emissions reduction at aircraft level, compared to its 'upcoming' predecessor, as well as the CO_2 emissions reduction at fleet level. The latter takes into account the time required for fleet replacement. The effects of drop-in SAF (i.e., lower carbon content per unit of fuel) is modelled in the SAF-pillar; the effects of hydrogen (i.e., zero CO_2 emissions) are included in the technology pillar.

Table 37: Overview of potential CO_2 emissions reduction delivered by future aircraft, compared to 'upcoming' aircraft expressed at aircraft level (i.e., per flight), and at fleet level (i.e., taking into account fleet replacement duration) for 2050

Class (abbreviation)	EIS	Aircraft level CO_2 emissions reduction, at EIS	Fleet level CO_2 emissions reduction, 2050
Small (S)	2030	99%	88%
Regional (R)	2035	50%, excluding effect of drop-in SAF	33.3%, excluding effect of drop-in SAF
Single aisle (SA)	2035	30%, excluding effect of drop-in SAF	20%, excluding effect of drop-in SAF
Hydrogen-powered single aisle (Hydrogen-SA)	2035	100%	66.7%
Small/medium twin aisle (SMTA)	2035	30%, excluding effect of drop-in SAF	20%, excluding effect of drop-in SAF
Large twin aisle (LTA)	2040	30%, excluding effect of drop-in SAF	13.3%, excluding effect of drop-in SAF

The total fleet level CO_2 emissions reduction delivered by upcoming and future aircraft for 2030 (only upcoming aircraft) and 2050 is presented in Table 38.

Table 38: Overview of fleet level potential CO_2 emissions reduction delivered by upcoming and future aircraft in 2030 and 2050, compared to the fleet in 2018

Class (abbreviation)	Fleet level CO_2 emissions reduction, 2030	Fleet level CO_2 emissions reduction, 2050
Small (S)	(not modelled)	88%
Regional (R)	13%, excluding effect of drop-in SAF	48%, excluding effect of drop-in SAF
Single aisle (SA)	7%, excluding effect of drop-in SAF	31%, excluding effect of drop-in SAF
Hydrogen-powered single aisle (Hydrogen-SA)		67%
Small/medium twin aisle (SMTA)	6%, excluding effect of drop-in SAF	30%, excluding effect of drop-in SAF
Large twin aisle (LTA)	8%, excluding effect of drop-in SAF	28%, excluding effect of drop-in SAF

The additional costs of fleet replacement of kerosene-powered aircraft are considered negligible with respect to the reference scenario. This assumption is substantiated using Figure 20, which lists an investment of € 5,000 billion for the acquisition of 26,000 new aircraft – meaning an average cost of € 192 million per aircraft. This is in line with recent list prices, ranging from approximately €90 million for an SA-class aircraft, through €220 million for an SMTA-type to over €300 million for an aircraft in the LTA category (Airbus, 2018a). Fleet replacement and aircraft acquisition or leasing is an important cost aspect for airlines, but these costs are also incurred in the reference scenario. Moreover, technological innovation will also lead to lower operational costs for airlines.

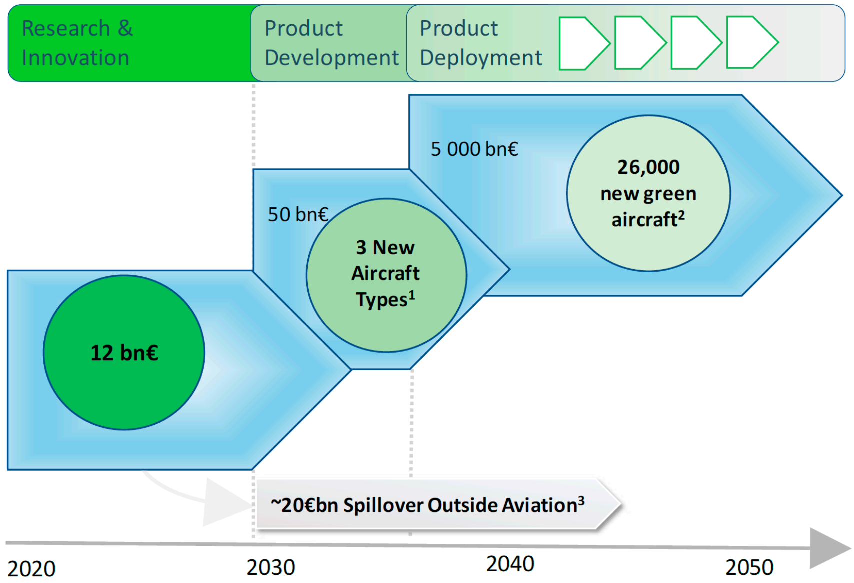

Figure 20: Cost estimation of new aircraft technology (Clean Aviation Partnership, 2020, p. 23). Product development cost based on Airbus Development (15 bn € per type); number of deliveries based on Airbus (2018b), assuming 50% market share.

A cost change is however modelled for hydrogen-powered aircraft, introduced for intra-EU+ flights of 2000 kilometres and below from 2035, as further detailed in Section 3.3.3.3. For one part, this is driven by cost increases that are a result of the characteristics of a hydrogen-powered aircraft and for another, it is a consequence of cost changes associated to the different energy carrier. Technology costs yield an increase in cost per ASK of 1.3 cents or 26% of current levels; the cost for liquid hydrogen is modelled at € 2200 per tonne. The fact that hydrogen has a notably higher (2.8 ×) energy density than kerosene suggests a rather high cost difference. Correcting for this, the energy contained in one tonne of kerosene costs €790 in the form of liquid hydrogen. This cost increase is modelled to be completely transferred to the passenger in the form of increased ticket prices.

8.2 Improvements in ATM and aircraft operations

Operational improvements lead to a general reduction in the emissions per flight, which are considered in the sustainability scenario. Cost impacts are assessed qualitatively, but are not included in the model. The cost aspects strongly depend on the exact measures defined and the way these costs impact demand for air travel in turn depends on the way such investments are funded. In general, it is assumed that any increases in acquisition or R&D cost are offset by decreases in other costs, such as fuel cost.

Table 39 provides an overview of the assumptions for the ATM and aircraft operations pillar. The underlying rationale of the figures is provided in Chapter 4. The split between short-haul (SH) and long-haul (LH) is set at 3500 kilometres; weight savings are translated into fuel burn reductions using a cost of weight factor of 3.5% per block hour, further explained in Section 4.2.2 (specifically: footnote 60 on page 56).

Table 39: Overview of potential CO_2 emissions reduction delivered by improvements in ATM and aircraft operations, compared to the reference scenario

Measure	Potential CO_2 emissions reduction	Starting year	Delivered by	Remarks
Improved flight planning	2% × 0.75 = 1.5%	2020	2025	
Flight management system updates	1%	2025	2035	
Weight reduction	10 kg / seat, 75% of flights	2020	2030	Modelled using 3.5% cost of weight
Airframe condition and maintenance	0.2%	2020	2050	
Single European Sky / SESAR – intra-EU+	5.1%	2020	2035	
Single European Sky / SESAR – extra-EU+	1.5%	2020	2035	Intercontinental departures only
Single European Sky / SESAR – further CO_2 emissions reduction potential	2%	2025	2040	
Non-European ATM efficiency improvement	2.1%	2020	2040	Intercontinental departures only
Improved NAT-efficiency	2.9% × 0.45 = 1.3%	2020	2027	Flights from Europe to North-America
Wake energy retrieval	3%	2025	2032	Flights from Europe to North-America
		2030	2040	Other flights, up to 50% combined
Reduced engine taxi – SH	0.2%	2020	2025	Intra-EU+ arrivals only
Reduced engine taxi – LH	0.1%	2020	2025	
Reduced engine taxi – SH	0.4%	2020	2025	Departures only
Reduced engine taxi – LH	0.3%	2020	2025	
Electric taxi / operational towing – SH	0.8%	2025	2035	Intra-EU+ arrivals only
Electric taxi / operational towing – LH	0.3%	2025	2035	
Electric taxi / operational towing – SH	1.2% + 175 kg weight reduction	2025	2035	Departures only, weight saving modelled using 3.5% cost of weight per block hour
Electric taxi / operational towing – LH	0.9% + 600 kg weight reduction	2025	2035	
Reduced APU usage	0.3%	2020	2025	

8.3 Sustainable aviation fuels

Increased use of SAFs will reduce CO_2 emissions per flight, but at the same time result in higher fuel costs for airlines. Both cost increases and emission reductions are taken into account in the model. The emission reductions of increased SAF uptake are based on literature and depend on the type and amount of SAF used in the years in which the sustainability scenario is evaluated.

The cost difference with respect to conventional jet fuel is sourced from literature discussed in Chapter 5. The cost difference incurred by airlines is assumed to be passed through to the passenger. According to IATA (2019a), fuel costs are on average 23% of the total airline costs in 2016. This is in line with the fuel cost share various large European airlines state in their annual reports. A full pass-through of costs to passengers is likely with measures that affect all competitors. However, if national or regional measures affect only part of the market it may lead to market distortions. For the modelling a full pass-through ensures that the demand impacts are not underestimated. Carbon pricing has an impact on the cost difference with conventional kerosene. Because SAF reduces carbon emissions, the cost difference decreases when the cost of carbon increases. This effect is taken into account when assessing cost differences.

It should be noted that the price premium of SAF compared to fossil fuels has not been analysed in terms of the business case for SAF producers. Likewise, the effects on airline business models have not been taken into account and additional costs are applied to equally all operators. An overview of model assumptions is given in Table 40, with Tables 41 and 42 detailing the situation in 2030 and 2050, respectively.

Table 40: Overall SAF percentages in 2030 and 2050

Fuel type	2030		2050	
	Amount	Percentage of fuel mix	Amount	Percentage of fuel mix
SAF	**3.2 Mt**	**6%**	**32 Mt**	**83%**
Fossil Fuels	51.8 Mt	94%	6 Mt	17%
Total	**55 Mt**	**100%**	**38 Mt**	**100%**

Table 41: Overview of model assumptions concerning SAF, 2030

Pathway and feedstocks	Amount	Percentage of SAF mix	Life-cycle CO_2 saving	Minimum selling price	CO_2 abatement costs
HEFA pathways with various waste and residue feedstocks	1.4 Mt	44%	65%	1170 €/tonne	280 €/tonne
Advanced feedstocks combined with FT, ATJ, SIP	0.6 Mt	19%	65%	2765 €/tonne	1050 €/tonne
Power to Liquid FT	1.2 Mt	37%	85%	2900 €/tonne	860 €/tonne
Total / average	**3.2 Mt**	**100%**	**72%**	**2274 €/tonne**	**640 €/tonne**

Table 42: Overview of model assumptions concerning SAF, 2050

SAF type	Amount	Percentage of SAF mix	Average life-cycle CO_2 reductions	Average minimum selling price	Average CO_2 abatement costs[172]
Biofuel (various pathways)	13 Mt	41%	95%	1790 €/tonne	366 €/tonne
Power to liquid	19 Mt	59%	100%	1557 €/tonne	274 €/tonne
Total / average	**32 Mt**	**100%**	**98%**	**1650 €/tonne**	**312 €/tonne**

8.4 Economic measures

Economic measures lead to higher costs for air passengers, and – depending on the measure – could also lead to lower (net) emissions per flight.

The cost increases resulting from measures taken are assumed to be fully passed through to the passenger. This is likely with global measures that affect all competitors. However, national or regional measures may only affect part of the market which leads to market distortions. In such cases, airlines may not be able to pass the cost increases on to

[172] Calculated as follows (SAF price – jet fuel price in 2030) / (CO2 saving × Jet A1 emission factor). Jet A1 emission factor = 3.16. Jet fuel price in 2050 = 690 €/tonne.

their customers in full in the affected markets. However, due to the small profit margins in the aviation industry, airlines shall need to recover the cost increases elsewhere in their networks. For the modelling exercise we therefore assumed a full pass-through for all measures. This also ensures that the demand impacts are not underestimated.

Economic measures may result in in-sector and out-of-sector emission reduction. Out-of-sector reductions are achieved through investing in other sectors. Through an economic measure, the aviation sector may for instance invest in carbon removal projects. In theory, if all CO_2 emissions from a flight are removed from the atmosphere, the net CO_2 impact of this flight is zero. The chapter on economic measures further elaborates on such measures and its caveats.

Economic measures act as an incentive for technological development, operational improvement and SAF uptake.

It is yet unclear how CORSIA and ETS will develop and co-exist in the future. It is therefore assumed that all CO_2-emissions from intra-EEA flights are covered by some sort of smart economic measure, whereby a hybrid system is considered most likely. For the impact modelling, the following assumptions have been made:

- EU-ETS covers CO_2-emissions from intra-EU+ flights, whereby:
  - The number of issued EU-ETS allowances is linearly reduced to zero in 2050 and freely allocated allowances are gradually phased out (EC, 2020c);
  - Revenues of auctioned allowances are invested in sustainability projects which yield a 50% CO_2 reduction in 2030;
- CORSIA covers CO_2-emissions from extra-EU+ flights:
  - From 2021-2035 airlines need to offset emissions above the 2019 threshold;
  - From 2035-2050 the threshold is gradually reduced to zero;
- Carbon removal projects are assumed to lead to the issuance of additional allowances and carbon credits.

Table 43 summarises the model inputs on amounts and prices under the mechanisms in place.

Table 43: Overview of model assumptions concerning economic measures

Year	Type of measure	Amount ($MtCO_2$)	Price (2018 €)	CO_2 reduction
2030	EU-ETS; auctioned allowances	28.3	€60	50%
	EU-ETS allowances bought from other sectors	40.7	€60	100%
	CORSIA eligible carbon credits	0.0	€60	100%
2050	EU-ETS; free allowances	0	€0	No CO_2 saving
	EU-ETS allowances bought from other sectors	0.7	€315	100% (carbon removal projects)
	CORSIA eligible carbon credits	21.2	€160	100% (carbon removal projects)

9 Destination 2050

The European aviation industry can reach the net zero CO_2 target outlined in the European Green Deal and the European Climate Law by 2050 as part of the EU's overall climate neutrality objective by implementing the measures studied in this report. Improvements in aircraft and engine technology, including the use of hydrogen-powered aircraft, contribute most to emissions reduction, followed by drop-in sustainable aviation fuels, economic measures and improved operations and ATM. Despite the fact that these measures increase the cost of air travel, passenger traffic will still be able to grow by 1.4% per year until 2050.

In 2030, net CO_2 emissions of the flights studied are reduced to 113 Mt, a reduction of 94 Mt compared to the reference scenario. Economic measures realising carbon removal make the largest contribution and ensure that the net emissions related to intra-EU+ flights are reduced to 13 Mt, 55% below their 1990 CO_2 levels. Continuous fleet renewal, improvement in ATM and aircraft operations as well as the use of 3.2 Mt of drop-in sustainable aviation fuels also help achieve this reduction.

Besides the more specific policy and action recommendations elsewhere in this report, some crucial characteristics of a long term vision for European sustainable aviation encompass this challenge in its entirety. Collaboration between stakeholders is essential and a coherent long term policy framework that reduces investment and innovation risk should be pursued. Furthermore, stakeholders should work to ensure global commitment – and joint and collaborative action – to a net zero carbon future for aviation.

9.1 Introduction

This final chapter combines all the measures in the previous chapters into a plan for achieving substantial CO_2 emissions reductions in 2030 and realising net zero CO_2 emissions in 2050. The pathway is built on four pillars: improvements in aircraft and engines (including the use of hydrogen-powered aircraft), improvements in air traffic management and aircraft operations, sustainable aviation fuels and economic measures.

All flights departing the EU+ (i.e., EU, UK and EFTA) have been included in the analyses for 2030 and 2050. Results for intermediate years are linearly interpolated and serve as a indicative pathway[173]. For each of the two horizon years, Section 9.2 present both the overall CO_2 emission reductions as well as the contributions by the various pillars to the grand total. Furthermore, the results are compared with relevant climate goals, notably the European Green Deal and proposed European Climate Law, as well as long term industry decarbonisation targets. In support of that comparison, the results for all departing flights are complemented by sub-analysis focused on flights inside and outside the EU+ region.

It is important to stress again here the status of this document, as was underlined in Chapter 0: this report shows *a* path towards decarbonisation, written to take into account the latest insights available. Nevertheless, insights might change during the timespan covered by this study. Anticipated benefits might not be realised fully, might exceed expectations, or might manifest themselves through a different measure or in a different market segment. Also, whereas the presented policies and actions for some pillars will focus on development and others on implementations, these efforts might change in the future – as the innovation cycle progresses. In any case, substantial joint and collaborative industry and government actions are required to realise the results presented here. In addition to the policies and actions listed in the various chapters, Section 9.3 lists a number of policies and outlines policy characteristics that apply to all aspects of this decarbonisation pathway.

Respecting on the one hand the uncertainties that are inherent to any study comparable to this, the consequences of inaction can on the other hand not be neglected. Indeed, as noted in Section 1.1.4, the effects of climate change on aviation and society in general are significant. As such, the results presented in the remainder of this chapter are presented as a well-supported foundation for tackling the challenge of decarbonising aviation and guiding government and industry action in the crucial following years to come.

9.2 CO_2 reduction

This section describes the net CO_2 reductions realised by 2030 and 2050. Section 9.2.1 presents and overview of the emissions reduction pathway for all flights within and departing from the EU+ region, Sections 9.2.2 and 0 zoom in on intra-EU+ flights and extra-EU+ flights. Last, Sections 9.2.4 and 9.2.5 detail the effects and the contributions of the various pillars in 2030 and 2050. Also, these sections compare the results to relevant climate goals. A comparison with the recently published ATAG-report Waypoint 2050 is included in Appendix E.

[173] This linear interpolation however takes the specific year of entry into service of future aircraft into account. Hydrogen technology, for example, is expected to be available from 2035 and accordingly, impacts are foreseen from 2035 onwards. Similarly, a

9.2.1 Overall impact

Figure 21 shows the overall impacts on CO_2 for 2030 and 2050. The dotted line shows the reference scenario, discussed in Chapter 2. The various measures treated in Chapters 3 to 6 together form the sustainability scenario. Based on these results, achieving net zero CO_2 emissions from flights departing the EU+ region in 2050 is deemed possible.

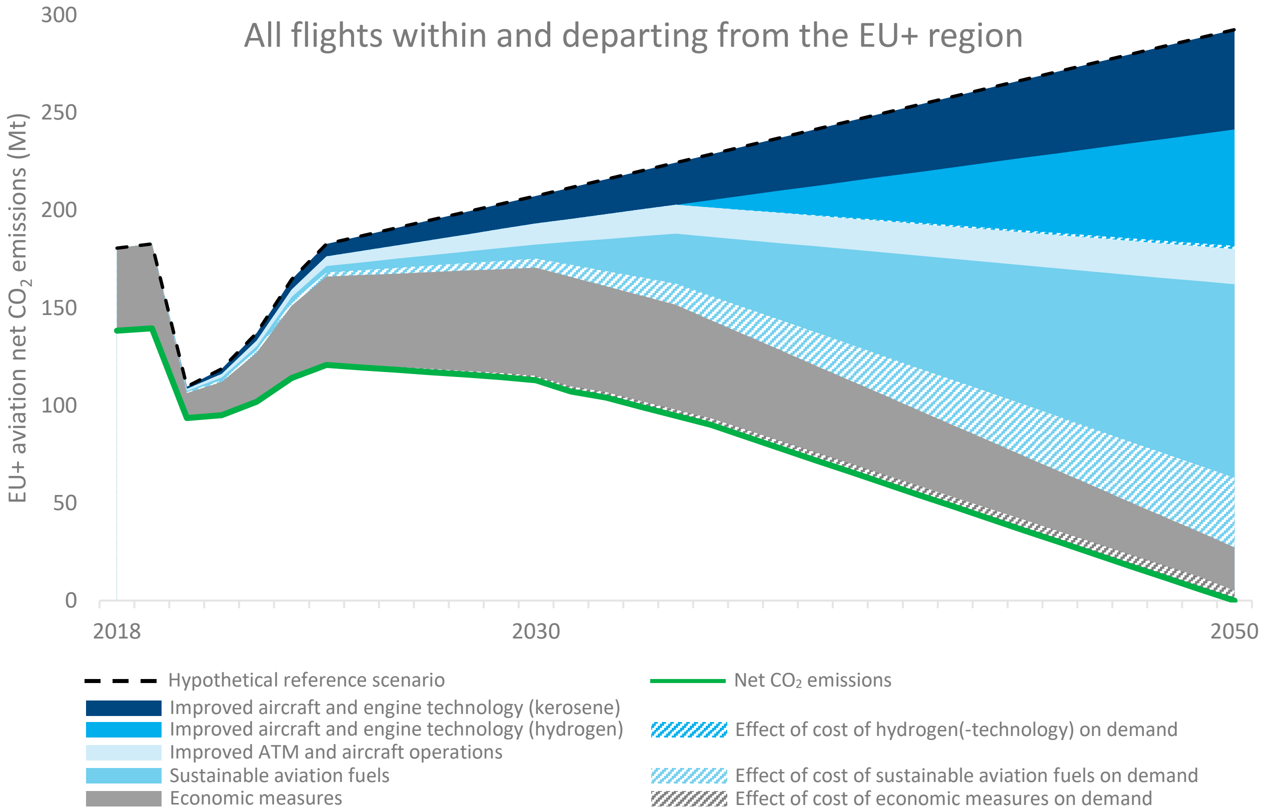

Figure 21: Overall impacts on net CO_2 emissions by flights within and departing from the EU+ region, modelled for 2030 and 2050. Linear interpolation between the years. Sustainability measures are not assessed year by year, as such pathways and contributions of individual measures may differ from the linear interpolation shown in the graph.

The graph further highlights 2019 as the peak year of absolute CO_2 emissions from EU+ aviation. Reliance on economic measures is extensive in the period up to 2030, but this is significantly reduced towards 2050. This is consistent with other projections and is caused by the fact that time is required before the most substantial emission reductions measures, in the form of new technology and sustainable aviation fuel, materialise in the market. Higher ticket prices, caused by additional costs related to sustainable aviation fuel, the introduction of hydrogen-powered aircraft and economic measures, result in lower demand for air travel. Last, the figure shows the drastic impact that the COVID-19 pandemic has on passenger numbers – although CO_2 reduction efforts are modelled to continue during the recovery period.

9.2.2 Flights within the EU+ region

Figure 22 shows how the various measures contribute to emissions reduction for intra-EU+ flights. In 2030, net CO_2 emissions are reduced to 55% of 1990 levels. The reliance on economic measures gradually reduces (used to remove the 1% CO_2 emissions from intra-EU+ aviation that remain after in-sector reductions)as new technology becomes available and SAFs become more widely available. In fact, hydrogen-powered aircraft contribute most to emission reduction after 2030. Cost increases lead to a modest decline in demand compared to the reference scenario. This can partly be explained by the lower carbon abatement cost of hydrogen, compared to that of drop-in SAF.

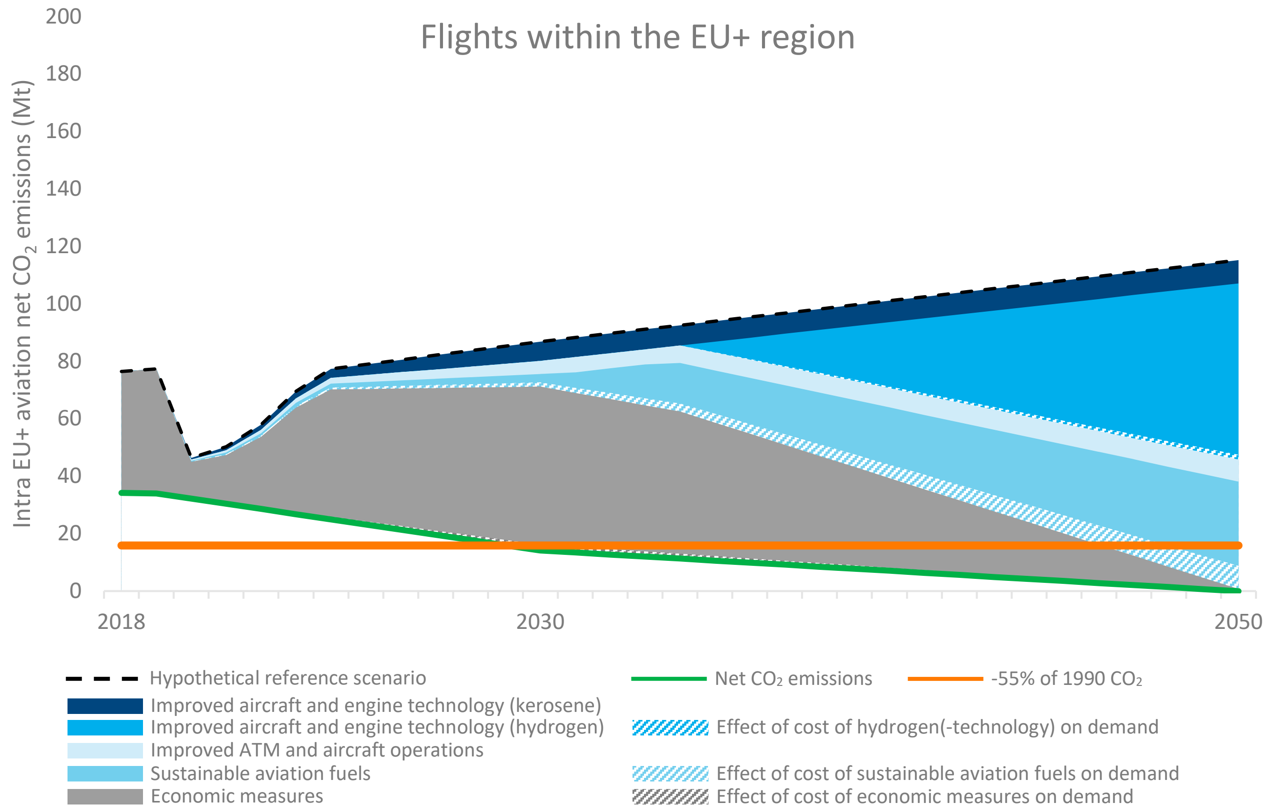

Figure 22: Impacts on net CO_2 emissions by flights within the EU+ region, modelled for 2030 and 2050. Linear interpolation between the years. Sustainability measures are not assessed year by year, as such pathways and contributions of individual measures may differ from the linear interpolation shown in the graph.

9.2.3 Flights departing from the EU+ region

Figure 23 shows the CO_2 reduction pathway for flights departing the EU+. Here the largest contribution is expected from the use of SAFs, followed by improvements in aircraft and engine technology. The higher cost of SAFs does lead to a relatively large demand impact. Over the short-term the reliance on economic measures is limited. This is due to the impact of COVID-19 on aviation demand in combination with the CORSIA 2019 baseline (ICAO, 2020d). It should be noted however that CORSIA shall be an important instrument to limit CO_2 emissions over the short-term in those parts of the world where fewer technological and operational measures are taken. This means that CORSIA shall likely play a more significant role for flights arriving in the EU, which were not included in the scope of the analysis, than for departing flights. Contrary to the situation for intra-EU+ flights, the reliance on economic measures increases slightly after 2030.

A significant share of CO_2 emission reduction (88%, including demand effects) is achieved by in-sector measures. Hydrogen-powered aircraft are not anticipated to operate on extra-EU+ routes and therefore do not contribute to CO_2 emissions reductions for intercontinental air traffic.

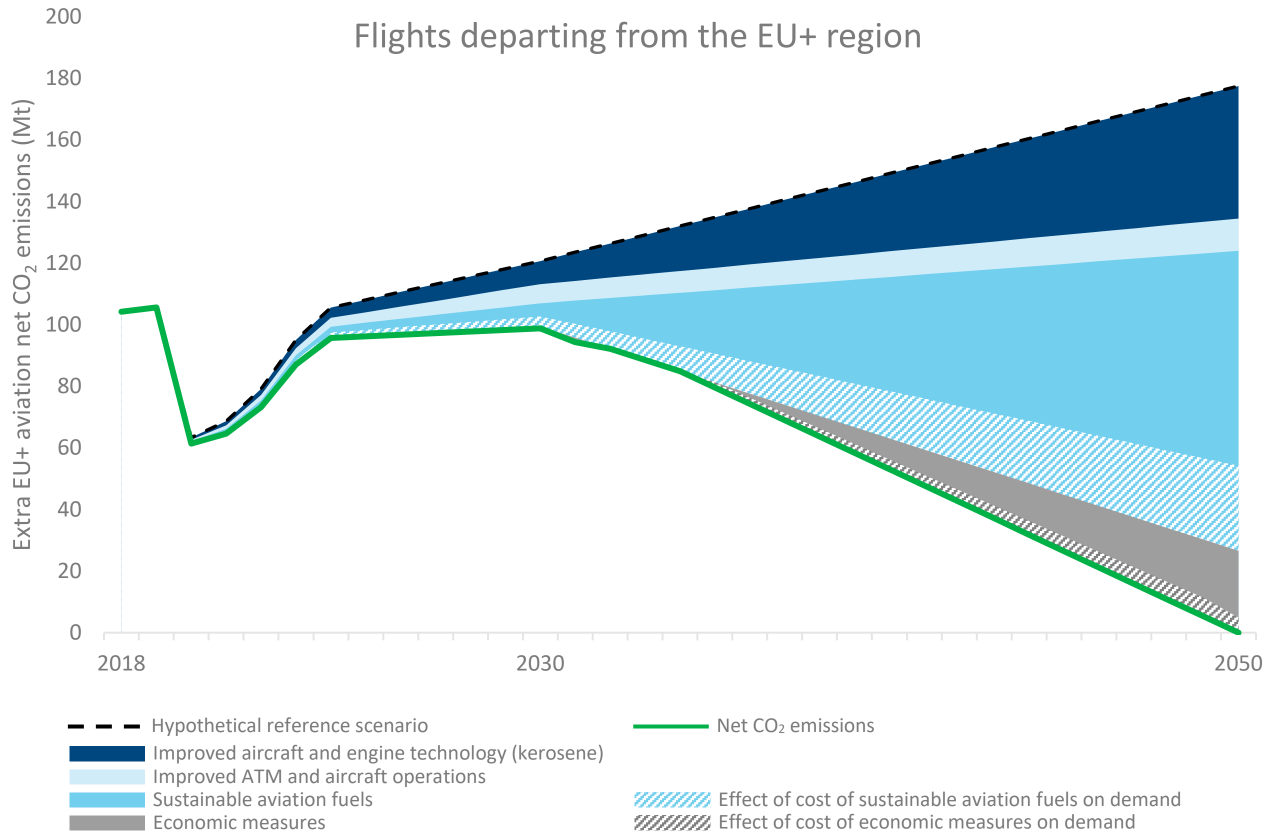

Figure 23: Impacts on net CO_2 emissions by flights departing the EU+ region, modelled for 2030 and 2050. Linear interpolation between the years. Sustainability measures are not assessed year by year, as such pathways and contributions of individual measures may differ from the linear interpolation shown in the graph.

9.2.4 2030

Table 44 shows the total and per-pillar impact on CO_2 emissions modelled for 2030, relative to the reference scenario. Overall, net CO_2 emissions are reduced to 113 Mt. The majority (100 Mt) is emitted by flights to destinations outside the EU+.

Table 44: Total and per-pillar CO_2 emissions reduction, modelled for 2030, compared to the reference scenario

Change in CO_2 emissions in 2030 compared to the reference scenario	All		Intra-EU+		Non-EU+	
	Mt	%	Mt	%	Mt	%
CO_2 emissions in the reference scenario	207		87		120	
Sustainable aviation fuels-induced demand impacts	5	2%	2	2%	3	3%
Economic measures-induced demand impacts	2	1%	2	2%	0	0%
Total CO_2 emissions reduction due to demand impacts	7	3%	4	4%	3	3%
Improvements in aircraft and engine technology, kerosene-powered aircraft	14	7%	7	8%	7	6%
Improvements in ATM and aircraft operations	11	5%	5	5%	6	5%
Sustainable aviation fuels	7	3%	3	3%	4	4%
Economic measures	55	27%	55	63%	0	0%
Total CO_2 emissions reduction due to sustainability measures	87	42%	70	79%	17	15%
Total combined CO_2 emissions reduction	**94**	**45%**	**74**	**83%**	**20**	**18%**
CO_2 emissions in the sustainability scenario	**113**		**13**		**100**	

Starting from the CO_2 emissions in the reference scenario, discussed in Section 2.3.2, demand impacts are shown first. These emissions reductions are the consequence of higher cost associated to the use of sustainable aviation fuels and economic measures, which are modelled to increase ticket prices, and thereby suppress demand. In total, these effects reduce CO_2 emissions by 7 Mt or 3% (intra-EU+: 4 Mt or 4%; non-EU+: 3 Mt or 3%).

Improvements in aircraft and engine technology yields the largest reduction in CO_2 emissions – 14 Mt or 7%. This reduction is mainly a result of a newer generation of aircraft entering the market. As more revolutionary technological improvements are expected to enter the market from 2030 onwards, the benefits delivered by these improvements lie largely beyond 2030. As hydrogen-powered aircraft are modelled to enter into service in 2035, they do not affect the results for 2030.

Improvements in ATM and aircraft operations yield a 11 Mt (5%) reduction in CO_2 emissions in 2030. By 2030, most of the foreseen measures have been implemented, or at least partially. It should be noted here that this analysis only counts the CO_2 emissions from flights departing from the EU+ (to avoid double counting), whereas some of the benefits in this pillar yield benefits on arrivals or overflights. Such benefits are only counted for intra-EU+ flights, but are out of scope for inbound intercontinental flights or en-route traffic.

The level of SAF uptake is still relatively limited in 2030, mainly due to its expected availability. Still, the efforts taken to achieve the expected CO_2 reduction of 7 Mt (3%) in 2030 are needed to yield much higher benefits of SAF beyond 2030, as production capacity will be increased and other production processes reach maturity.

Last, economic measures result in a CO_2 emissions reduction of 55 Mt (27%) outside the sector. This means that in 2030, economic measures contribute most to the overall reduction of CO_2 emissions by flights within and departing from the EU.

As 2019 was previously identified as the peak year for CO_2 emissions, the industry target of carbon neutral growth from 2020 onwards is achieved. Total CO_2 emissions in the sustainability scenario accrue to 113 Mt, which is 36% higher than the 83 Mt of CO_2 emissions observed in 1990. As such, the proposed European target of reducing CO_2 emissions across all sectors by 55% in 2030 compared to 1990-levels is not met for all flights considered in this study. Focusing on intra-EU+ flights, alignment with that 55%-reduction goal is achieved. These flights emitted a total of approximately 30 Mt of CO_2 in 1990 and are foreseen to reduce that to 13 Mt in 2030.

9.2.5 2050

Table 45 shows the total and per-pillar impact on CO_2 emissions modelled for 2050, compared to the reference scenario. This shows that for all flights departing EU+ airports, net zero CO_2 emissions are realised.

Table 45: Total and per-pillar CO_2 emissions reduction, modelled for 2050, compared to the reference scenario

Change in CO_2 emissions in 2050 compared to the reference scenario	All		Intra-EU+		Non-EU+	
	Mt	%	Mt	%	Mt	%
CO_2 emissions in the reference scenario	293		115		178	
Improvements in aircraft and engine technology-induced demand impacts (hydrogen-powered aircraft)	2	1%	2	1%	0	0%
Sustainable aviation fuels-induced demand impacts	36	12%	8	7%	28	16%
Economic measures-induced demand impacts	5	2%	0	0%	5	3%
Total CO_2 emissions reduction due to demand impacts	43	15%	10	8%	33	19%
Improvements in aircraft and engine technology, kerosene-powered or (hybrid)-electric aircraft	51	17%	8	7%	43	24%
Improvements in aircraft and engine technology, hydrogen-powered aircraft	60	20%	60	52%	0	0%
Improvements in ATM and aircraft operations	18	6%	8	7%	10	6%
Sustainable aviation fuels	99	34%	29	25%	70	39%
Economic measures	22	8%	<1	1%	22	12%
Total CO_2 emissions reduction due to sustainability measures	250	85%	105	92%	145	81%
Total combined CO_2 emissions reduction	**293**	**100%**	**115**	**100%**	**178**	**100%**
CO_2 emissions in the sustainability scenario	**0**		**0**		**0**	

Again, various demand impacts reduce CO_2 emissions by 43 Mt (15%). In addition to the demand impact of sustainable aviation fuels and economic measures, the results for 2050 include a demand impact associated to the introduction of hydrogen-powered aircraft from 2035 onwards.

Of the sustainability measures, improvements in aircraft and engine technology, including the use of hydrogen-powered aircraft, yield the highest reduction of CO_2 emissions. This is followed by application of drop-in sustainable aviation fuel, economic measures realising out-of-sector carbon removals and improvements in ATM and aircraft operations.

By 2050, aircraft and engine technology have developed such that (partially) kerosene-powered aircraft emit 51 Mt (17%) less CO_2 than currently is the case. This impact is mostly seen for intercontinental traffic, as hydrogen-powered aircraft are used for a large portion of intra-EU+ flights below 2,000 kilometres, reducing CO_2 emissions by 60 Mt (20%) while consuming a total of 3.7 Mt of hydrogen.

The further realisation of numerous improvements due to ATM and aircraft operations in the period between 2030 and 2050 result in a total contribution of CO_2 reduction equal to 18 Mt, slightly increasing its share (from 5% in 2030 to 6% in 2050). Despite this reduction, as well as those realised by the energy efficiency improvements delivered by kerosene-powered aircraft and the partial switch to hydrogen-powered aircraft, a demand for kerosene still exists in 2050. Due to upscaling of various production processes 83% of the jet fuel used is sustainable aviation fuel, reducing CO_2 emissions by 34% compared to the reference scenario. Following the introduction of hydrogen-powered aircraft on intra-EU+ flights, SAF is primarily used for non-EU+ flights (23 Mt, versus 9.5 Mt intra-EU+).

Last, economic measures are used for removing 22 Mt of CO_2 from the atmosphere, almost completely on flights outside the EU+ region. The remaining emissions on intra-EU+ flights (0.7 Mt) result from the fact that not all SAF pathways yield a 100% CO_2 reduction. These emissions need to be removed through the EU-ETS scheme, at the price of € 315 per tonne. For flights outside the EU+ regions, carbon credits are required for 22 Mt, at the price of € 160 per tonne. This yields an average cost per tonne of CO_2 of € 165.

Overall, Figure 24 shows that almost 90% of all energy used in aircraft operations in 2050 comes from a renewable source. This includes both drop-in SAF as well as the use of liquid hydrogen, the CO_2 savings of which are included in the pillar 'Improvement in aircraft and engine technology'.

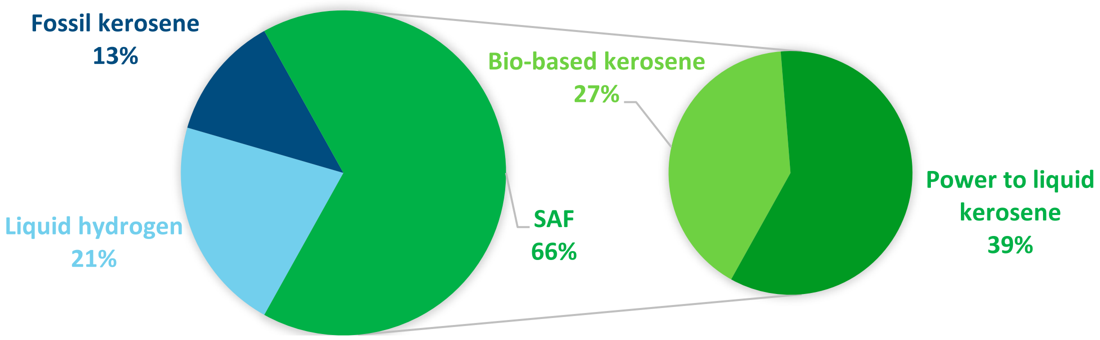

Figure 24: Breakdown of total energy and SAF demand for 2050

As net zero CO_2 is achieved for all flights within and departing from the EU+ region, these results show European aviation operations to be aligned with the European Green Deal and the proposed European Climate Law in terms of CO_2 emissions. The currently set industry goal, reducing net aviation emissions by 50% in 2050 compared to 2005-levels, is surpassed.

9.3 Overall policies and actions

In addition to the specific policies and actions described in the chapters dealing with the four pillars that this study considers, a number of recommendations encompass the entire work. This section treats these, in two categories.

First, Section 9.3.1, highlights three characteristics that are considered crucial to the development of a successful policy framework supporting European sustainable aviation. Second, Section 9.3.2, lists a number of much more concrete proposals for policies and actions, but which are nevertheless applicable to all areas of improvement considered.

9.3.1 Characteristics of a long term vision for European sustainable aviation

Three main items have been identified that are common to all pillars analysed in this study. These items form what should be the main pillars supporting a common long term vision for European aviation: setting a long term goal in combination with a coherent policy framework supported by strong collaboration between stakeholders.

Collaboration between stakeholders
A common item for all policies and actions presented in this report is collaboration and commitments between stakeholders. ACI-EUROPE, ASD Europe, ERA, A4E and CANSO have jointly commissioned this study to highlight the importance of a joint vision. The sustainability scenario requires action from all stakeholders, in the first place the five organisations that jointly commissioned this study in collaboration with governments. Stakeholders – encompassing both industry, government and non-governmental organisations – should strive for a truly collaborative effort to effectively address the decarbonisation challenge facing commercial aviation. The EU Pact for Sustainable Aviation, proposed in the recent Aviation Round Table Report on the Recovery of European Aviation (2020), that brings even more aviation stakeholders together, is another key example of the collaboration required.

Coherent long term policy framework
Decarbonizing the aviation industry requires making large capital investments for a time period of 15 up to 25 years ahead. This applies to improvements in aircraft, engines and sustainable aviation fuels. It is therefore essential for investors to know well in advance which targets should be met and in which timeframe. The policy framework should set a clear vision for the future to de-risk investment in sustainable aircraft, engine and fuels over the entire value chain from R&D to commercial deployment. This requires long-term and consistent policies, reducing uncertainty as much as possible.

Working towards global commitment to a net zero future for aviation
This study shows a pathway towards achieving net zero CO_2 emissions from all flights within and departing form the EU by 2050. Following the leadership position of the EU aviation industry and government, all should work towards ensuring a global commitment to a net zero future for aviation, supported by effective policies and realised by joint and collaborative action. This would align aviation worldwide to the Paris Agreement and the 1.5 °C scenario of the IPCC, and thereby mitigate an important negative climate effect of aviation. The current ICAO work on defining a global long term aspirational goal, which is anticipated to be set in 2022 (ICAO, n.d.), is a key opportunity to realising this ambition. If a global net zero target cannot be agreed upon, global and European goals should at least be brought closer together.

9.3.2 Cross-pillar policies and actions

The policies and actions described in the various chapters of this report address specific pillars. A number of policies and actions, however, are shared between these pillars. As such, they are treated separately in this section.

Enabling customers to make a sustainable choice

The policies and actions mentioned in this report are aimed at governments and industry stakeholders. Nevertheless, customers can also play an important role in the sustainability transition. Providing consumers with information on the sustainability of various travel options allows them to make sustainable choices. Various online calculators that estimate CO_2 emissions per flight exist, but show widely varying results, do not all accurately capture all factors that contribute to a particular footprint and neglect airport sustainability efforts. Addressing these problems is one of the possible ways that might help make aforementioned environmental decision making by consumers easier.

Increasing sustainability awareness across industry

A key point raised in various chapters, and reiterated in Section 9.3.1, is the need for the aviation community to work together on the decarbonisation challenge ahead. Besides awareness at management and executive level, this requires awareness with operational employees. Pilots and air traffic control officers are a straightforward example, but maintenance personnel, ground handling agents, airport personnel and many others can each contribute.

Coupled to increasing awareness across the organisation comes the responsibility to recognise sustainability as a full-fledged part of the business. It should not be regarded as something different or extra – but part of the working activities of all involved.

Nurturing and stimulating new and disruptive ideas – inside and outside

Also stressed earlier in this chapter, a study as this should be updated regularly to make sure the latest insights are included. It is recommended to continuously gather these and to stimulate their development.

Idea generation contests, business accelerators and support for or participation in start-up programmes should be considered to that effect. Such can be done within an organisation, but also cross-industry, or open to a more general audience of possibly interested minds. Even though not all ideas might be mature enough to directly apply into practice, they might provide a refreshing new perspective. Bringing together entrepreneurial spirits often found in start-ups or spin-offs with seasoned aviation professionals is a not to be missed opportunity.

References

ACI Europe. (2019, June 26). European Airports Committing to Net-Zero Carbon Emissions by 2050. *ACI Europe Resolution*. ACI Europe 29th Annual Congress & General Assembly. Retrieved from https://www.aci-europe.org/component/downloads/downloads@/6030.html

ACI Europe. (2020a). *COVID-19 & airports. Traffic Forecast & financial impact. 3rd Updated Forecast.* Brussels: Airport's Council International.

ACI Europe. (2020b). *Information on the use of modulations of airport charges for environmental reasons.* Retrieved from https://www.aci-europe.org/downloads/resources/ACI%20EUROPE%20Paper%20on%20Environmental%20Modulations%20of%20Charges.pdf

ACI World. (2020a). *Airports' Resilience and Adaptation to a Changing Climate.* 2018. Airports Council International. Retrieved from https://store.aci.aero/wp-content/uploads/2018/10/Policy_brief_airports_adaption_climate_change_V6_WEB.pdf

ACI World. (2020b). *The impact of COVID-19 on the airport business.* Montreal: Airport's Council International.

AIN Online. (2019, June 20). *Rolls-Royce Lines Up Greener Future With UltraFan*. Retrieved from Paris Air Show: https://www.ainonline.com/aviation-news/air-transport/2019-06-20/rolls-royce-lines-greener-future-ultrafan

Air France. (2019, October 1). *Air France to proactively offset 100% of CO2 emissions on its domestic flights as of January 1st, 2020.* Retrieved January 9, 2020, from Air France - Corporate: https://corporate.airfrance.com/en/press-release/air-france-proactively-offset-100-co2-emissions-its-domestic-flights-january-1st-2020

Airbus. (2013, December 18). *Airbus signs MoU with Honeywell and Safran to develop electric taxiing solution for the A320 Family*. Retrieved January 10, 2020, from Airbus - Commercial Aircraft: https://www.airbus.com/newsroom/press-releases/en/2013/12/airbus-signs-mou-with-honeywell-and-safran-to-develop-electric-taxiing-solution-for-the-a320-family.html

Airbus. (2018a, January 15). *Airbus 2018 Price List Press Release*. Retrieved June 14, 2020, from Media: https://www.airbus.com/newsroom/press-releases/en/2018/01/airbus-2018-price-list-press-release.html

Airbus. (2018b). *Global Market Forecast. Global Networks, Global Citizens. 2018-2037.* Retrieved from https://www.airbus.com/content/dam/corporate-topics/publications/media-day/GMF-2018-2037.pdf

Airbus. (2019a, November 18). *Airbus inspired by nature to boost aircraft environmental performance*. Retrieved January 10, 2020, from Airbus - Commercial Aircraft: https://www.airbus.com/newsroom/press-releases/en/2019/11/airbus-inspired-by-nature-to-boost-aircraft-environmental-performance.html

Airbus. (2019b, June 17). *Airbus launches longest range single-aisle airliners: the A321XLR*. Retrieved January 8, 2020, from Commercial Aircraft: https://www.airbus.com/newsroom/press-releases/en/2019/06/airbus-launches-longest-range-singleaisle-airliner-the-a321xlr.html

Airbus. (2019c, December). Family Figures - December 2019 Edition.

Airbus. (2019d, November 11). *fello'fly: A flight demonstrator inspired by nature*. Retrieved from YouTube: https://www.youtube.com/watch?v=D2Ag6HGrB_0

Airbus. (2020a). *A321neo*. Retrieved January 7, 2020, from A320 Family: https://www.airbus.com/aircraft/passenger-aircraft/a320-family/a321neo.html#details

Airbus. (2020b). *A321XLR: Efficiency and extra-long range*. Retrieved May 27, 2020, from A321neo: https://www.airbus.com/aircraft/passenger-aircraft/a320-family/a321neo.html#a321xlr

Airbus. (2020c, September 21). *Airbus reveals new zero-emission concept aircraft*. Retrieved November 24, 2020, from Airbus Innovation: https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html

Airbus. (2020d, September). *ZEROe: Towards the world's first zero-emission commercial aircraft*. Retrieved November 4, 2020, from Innovation: https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html

Aircraft Commerce. (2009). Owner's & Operator's Guide: CRJ Family. *Aircraft Commerce*(66), 9-32.

Airfleets. (2020). *Fleet WestJet Airlines*. Retrieved February 19, 2020, from Airfleets.net: https://www.airfleets.net/flottecie/WestJet%20Airlines.htm

Airliner World. (2009, August 20). *Queen of its time*. Retrieved January 8, 2020, from Airliner World: https://airlinerworld.keypublishing.com/2009/08/queen-of-its-time/

Ang, A., Gangoli Rao, A., Kanakis, T., & Lammen, W. (2019). Performance analysis of an electrically assisted propulsion system for a short-range civil aircraft. *Journal of Aerospace Engineering*, 1490-1502. doi:10.1177/0954410017754146

Antcliff, K., & Capristan, F. (2017). Conceptual Design of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept. *18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conferenece / AIAA AVIATION Forum.* Denver, Colorado, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2017-4001

Antcliff, K., Guynn, M., Marien, T., Wells, D., Schneiderr, S., & Tong, M. (2016). Mission Analysis and Aircraft Sizing of a Hybrid-Electric Regional Aircraft. *54th AIAA Aerospace Sciences Meeting / AIAA SciTech Forum.* San Diego, California, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2016-1028

ATAG. (2015). *Aviation Climate Solutions.*

ATAG. (2017, November 3). Beginner's Guide to Sustainable Aviation Fuel.

ATAG. (2018, October). *Facts & figures*. Retrieved January 13, 2020, from https://www.atag.org/facts-figures.html

ATAG. (2019). *Aviation Benefits Report 2019.*

ATAG. (2020a). *Climate change*. Retrieved January 12, 2020, from ATAG: https://www.atag.org/our-activities/climate-change.html

ATAG. (2020b). *Waypoint 2050.* Air Transport Action Group.

ATR. (2018). *Connecting the future: Turboprop market forecast 2018-2037.*

ATR. (2020, July). ATR 72-600. Retrieved from http://1tr779ud5r1jjgc938wedppw-wpengine.netdna-ssl.com/wp-content/uploads/2020/07/Factsheets_-_ATR_72-600.pdf

Aviation Round Table. (2020). *Aviation Round Table Report on the Recovery of European Aviation.* A4E; ACA; ACI-EUROPE; ARC; ASA; ASD; BEUC; CANSO; CPMR; EBAA; ECA; ECTAA; EEA; EFFAT; ERA; ETC; ETRC; EUACA; EU TRAVEL TECH; GAMA; INDUSTRIALL EUROPE; UNI EUROPA; T&E. Retrieved from https://a4e.eu/wp-content/uploads/aviation-round-table-report-16-11-2020.pdf

Aviation Week & Space Technology. (2007, October 29). *Aviation Week & Space Technology*.

AviationPros. (2011, December 6). *Iberia Airlines Taxiing Program To Reduce Emissions At ORD*. Retrieved January 10, 2020, from AviationPros: https://www.aviationpros.com/airports/airports-municipalities/article/10467486/singleengine-taxi-program-will-reduce-emissions-and-save-fuel

Babikian, R., Lukachko, S., & Waitz, I. (2002). The historical fuel efficiency characteristics of regional aircraft from technological, operational, and cost perspectives. *Journal of Air Transport Management, 8*, 389-400.

Bachman, J. (2012, June 8). *IPads Help Some Airlines Cut Costs*. Retrieved February 19, 2020, from Bloomberg: https://www.bloomberg.com/news/articles/2012-06-06/ipads-help-some-airlines-cut-costs

Baker, P., Chartier, O., Haffner, R., Heidecke, L., van Hussen, K., Meindert, L., & et al. (2017, November). Research and Innovation perspective of the mid - and long-term Potential for Advanced Biofuels in Europe. European Commission.

Bakx, K. (2015, August 7). *What's behind WestJet's new Connect Wi-Fi system*. Retrieved February 19, 2020, from CBC News: https://www.cbc.ca/news/business/what-s-behind-westjet-s-new-connect-wi-fi-system-1.3180349

Barclays. (2020). *Travel survey - 12-17 percent of business trips at risk of being substituted. 21 May 2020.*

Bauhaus Luftfahrt. (2017). *Conceptual studies of a future hybrid-electric regional aircraft*. Retrieved January 12, 2020, from Bauhaus Luftfahrt: https://www.bauhaus-luftfahrt.net/en/research/systems-aircraft-technologies/conceptual-studies-of-a-future-hybrid-electric-regional-aircraft/

BBC. (2019, October 2). *'Flight shame' could halve growth in air traffic*. Retrieved January 9, 2020, from BBC News: https://www.bbc.com/news/business-49890057

Becken, S., & Pant, P. (2020). *Airline initiatives to reduce climate impact - Ways to accelerate action.*

Bentsen, N. S., & Felby, C. (2012). Biomass for energy in the European Union - a review of bioenergy resource assessments. *Biotechnology for Biofuels*.

Bergmans, D., & den Boer, M. (2012). *Duurzame luchtvaart 2050.* Netherlands Aerospace Centre. Amsterdam: NLR.

Berton, J., & Haller, W. (2014). A Noise and Emissions Assessment of the N3-X Transport. *52nd Aerospace Sciences Meeting - AIAA SciTech* (p. 594). National Harvor, Maryland, United States of America: American Institute of Aeronautics and Astronautics.

Bijewitz, J., Seitz, A., Hornung, M., & Isikveren, A. (2017). Progress in Optimizing the Propulsive Fuselage Aircraft Concept. *Journal of Aircraft, 54*(5), 1979-1989.

Biofuel International. (2019, June 4). *Finnish government targets 30% biofuels share in aviation fuel*. Retrieved from Biofuel international: https://biofuels-news.com/news/finnish-government-targets-30-biofuels-share-in-aviation-fuel/

BLUE MED, G.A.R.S, Universita di Bologna, & FABEC. (2020, October 26). *Interdependency within ATM Performance in the Context of a Dynamic Environment.* Retrieved from https://www.fabec.eu/others/download_file.htm?ITEM_ID=19488&dltype=ITEMPDF&readdirect=1

Boeing. (1998). *777-200/300 Airplane Characteristics for Airport Planning.* Retrieved from http://www.boeing.com/assets/pdf/commercial/airports/acaps/777_23.pdf

Boeing. (2005). *767 Airplane Characteristics for Airport Planning.* Retrieved from http://www.boeing.com/assets/pdf/commercial/airports/acaps/767.pdf

Boeing. (2007). Interior arrangements. *757 Passenger*. Retrieved from http://www.boeing.com/resources/boeingdotcom/company/about_bca/startup/pdf/historical/757_passenger.pdf

Boeing. (2009). *The Boeing 777 Program Background*. Retrieved June 8, 2009, from 777 Family: http://www.boeing.com/commercial/777family/background.html

Boeing. (2013). *737 Airplane Characteristics for Airport Planning.* Boeing. Retrieved from http://www.boeing.com/assets/pdf/commercial/airports/acaps/737.pdf

Boeing. (2014, October 31). *Boeing, Monarch Airlines Finalize Order for 30 737 MAX 8s*. Retrieved January 7, 2020, from Boeing Mediaroom: boeing.mediaroom.com/2014-10-31-Boeing-Monarch-Airlines-Finalize-Order-for-30-737-MAX-8s

Boeing. (2015). *777-200LR / -300ER / -Freighter Airplane Characteristics for Airport Planning.* Retrieved from http://www.boeing.com/assets/pdf/commercial/airports/acaps/777_2lr3er.pdf

Boeing. (2018). *787 Airplane Characteristics for Airport Planning.* Retrieved from https://www.boeing.com/resources/boeingdotcom/commercial/airports/acaps/787.pdf

Boeing. (2019a). *737 MAX Airplane Characteristics for Airport Planning.* Retrieved from https://www.boeing.com/resources/boeingdotcom/commercial/airports/acaps/737MAX_RevE.pdf

Boeing. (2019b). *Commercial Market Outlook 2019-2038.*

Boeing. (2020). *Commercial Market Outlook 2020-2039.*

Boeing. (n.d. - a). *777*. Retrieved January 7, 2020, from Boeing: http://www.boeing.com/commercial/777#/design-highlights/unmatched-capabilities/profitability/fuel-efficiency

Boeing. (n.d. - b). *787 Dreamliner*. Retrieved January 7, 2020, from Boeing: https://www.boeing.com/commercial/787/#/by-design

Boeing. (n.d. - c). *The Boeing 767 Family*. Retrieved August 21, 2011, from Boeing Commercial Airplanes: http://www.boeing.com/commercial/767family/background.html

Bombardier. (2015). C Series. Retrieved from https://web.archive.org/web/20150908154642/http://commercialaircraft.bombardier.com/content/dam/Websites/bca/literature/cseries/Bombardier-Commercial-Aircraft-CSeries-Brochure-en.pdf.pdf

Booz Allen Hamilton. (2018). State of the Industry Report on Air Quality Emissions from Sustainable Alternative Jet Fuels. National Academy of Sciences.

Bradley, M., & Droney, C. (2011). *Subsonic Ultra Green Aircraft Research: Phase I Final Report.* Hampton, Virginia, United States of America: NASA. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20110011321

Bradley, M., & Droney, C. (2015). *Subsonic Ultra Green Aircraft Research: Phase II - Volume II - Hybrid Electric Design Exploration.*

Brady, C. (2019, January 1). *Boeing 737 Orders and Deliveries*. Retrieved January 17, 2020, from The Boeing 737 Technical Site: http://www.b737.org.uk/sales.htm

Brain, D., & Voorbach, N. (2019). ICAO's Global Horizontal Flight Efficiency Analysis. In ICAO, *2019 Environmental Report* (pp. 138-144). Montréal.

Brelje, B. J., & Martins, J. R. (2019). Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches. *Progress in Aerospace Sciences*(104), 1-19.

Breyer, C. F. (2019). Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitigation and Adaptation Strategies for Global Change*(25), 43-65.

British Airways. (2019, October 10). *British Airways to Become First UK Airline to Offset Carbon Emissoins on Flights Within the UK from 2020*. Retrieved January 9, 2020, from British Airways Media Centre: https://mediacentre.britishairways.com/pressrelease/details/86/2019-319/11662

Broderick, S. (2018, July 16). *Airbus A220 Order Boosts 'Mini-Narrowbody' Market*. Retrieved July 16, 2018, from Aviation Week: http://aviationweek.com/aviation-week-space-technology/airbus-a220-order-boosts-mini-narrowbody-market

Broderick, S., Massy-Beresford, H., Schofield, A., Flottau, J., & Goldstein, J. (2020, October 29). *Airlines Revamping Fleets With Little Insight On Future*. Retrieved November 24, 2020, from Aviation Week: https://aviationweek.com/air-transport-month/airlines-revamping-fleets-little-insight-future

Broehm et al. (2015). Techno-Economic Review of Direct Air Capture Systems for Large Scale Mitigation of Atmospheric CO2. 1-26.

Brok, P., Hagstroem, M., Junior, A., & Matthes, S. (2010). *Research Roadmap on Green Flight.* Amsterdam, The Netherlands: National Aerospace Laboratory NLR.

Bruce, A., & Spinardi, G. (2018). On a wing and hot air: Eco-modernisation, epistemic lock-in, and the barriers to greening aviation and ruminant farming. *Energy Research & Social Science, 40*, 36-44.

Bruce, S., Temminghoff, M., Hayward, J., Palfreyman, D., Munnings, C., Burke, N., & Creasey, S. (2020). *Opportunities for hydrogen in commercial aviation.* CSIRO. Retrieved from https://www.csiro.au/~/media/Do-Business/Files/Futures/Boeing-Opportunities-for-hydrogen-in-commercial-aviation.pdf?la=en&hash=C8C20FB36BEA73EFA6F722F48FCEE9E2C8EDF831

Buxton, D., Farr, R., & Maccarthy, B. (2006). The aero-engine value chain under future business environments: using agent-based simulation to understand dynamic behaviour. *Proceedings of MITIP.* The Modern Information Technology in the Innovation Processes of the Industrial Enterprises.

CAAFI. (2020, June 05). *Commercial Aviation Alternative Fuels Initiative*. Retrieved from Fuel Qualification: http://caafi.org/focus_areas/fuel_qualification.html#approved

Cames, M., Graichen, J., Siemons, A., & Cook, V. (2015). *Emission Reduction Targets for International Aviation and Shipping.* Öko-Institut. Brussels: European Parliament, Policy Department A: Economic and Scientific Policy. Retrieved from https://www.europarl.europa.eu/RegData/etudes/STUD/2015/569964/IPOL_STU(2015)569964_EN.pdf

CANSO. (2012). *ATM Global Environment Efficiency Goals for 2050.*

Carbon Tracker. (2018). *Carbon Countdown. Prices and Politics in the EU-ETS.*

Carrillo Pineda, A., & Faria, P. (2019). *Towards a Science-Based Approach to Climate Neutrality in the Corporate Sector (Discussion paper, Draft for initial feedback - Version 1.0).* Science Based Targets Initiative. Retrieved from https://sciencebasedtargets.org/wp-content/uploads/2019/10/Towards-a-science-based-approach-to-climate-neutrality-in-the-corporate-sector-Draft-for-comments.pdf

CDP. (2017). *Carbon Pricing Corridors.*

CE Delft & SEO Amsterdam Economics. (2019). *Taxes in the field of Aviation and their impact. Directorate-General for Mobility and Transport.* European Commission, Directorate Aviation.

CENTRELINE. (2017). *Objectives*. Retrieved January 8, 2020, from CENTRELINE: https://www.centreline.eu/project/objectives/

Cihlar, J., Villar Lejarreta, A., Wang, A., Melgar, F., Jens, J., & Rio, P. (2020). *Hydrogen generation in Europe - Overview of costs and key benefits.* Directorate-General for Energy. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1

Cirium. (2020, March 9). *Finnair lays out ambitious new sustainability strategy*. Retrieved June 8, 2020, from FlightGlobal: https://www.flightglobal.com/strategy/finnair-lays-out-ambitious-new-sustainability-strategy/137148.article

Clean Aviation Partnership. (2020). *Strategic research and innovation agenda.* The Proposed European Partnership on Clean Aviation.

Clean Sky. (n.d.). *Aviation*. Retrieved January 12, 2020, from Clean Sky: https://www.cleansky.eu/aviation

Clean Sky JU. (2015). *Clean Sky 2 Joint Technical Programme.*

Clean Sky JU. (2018, March 1). *BLADE wins 2018 Laureate Award for Technology*. Retrieved from https://www.cleansky.eu/news/blade-wins-2018-laureate-award-for-technology#:~:text=Under%20the%20Clean%20Sky%20research,emissions%20by%20up%20to%205%25.

Clean Sky JU. (n.d.). *Go with the flow: Clean Sky's Hybrid Laminar Flow Control Demo*. Retrieved from https://www.cleansky.eu/go-with-the-flow-clean-skys-hybrid-laminar-flow-control-demo

Committee on Climate Change. (2019, September 24). Net-zero and the approach to international aviation and shipping emissions. London, United Kingdom. Retrieved from https://www.theccc.org.uk/publication/letter-international-aviation-and-shipping/

Compensaid. (2020). *Compensaid - fly CO2-neutral*. Retrieved from Compensaid: https://compensaid.com/

CPB & PBL. (2016). *Kansrijk Mobiliteitsbeleid.* The Hague, Netherlands.

Creemers, W., & Slingerland, R. (2007). Impact of intermediate stops on long-range jet-transport design. *7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)* (p. 7849). Belfast, Northern Ireland: American Institute of Aeronautics and Astronautics.

Da Silva, S. (2012, May). Trajectory-Based Operations (TBO). *ANConf/12*. Bangkok, Thailand: International Civil Aviation Organisation.

Dahlmann, K., Matthes, S., Yamashita, H., Unterstrasser, S., Grewe, V., & Marks, T. (2020). Assessing the Climate Impact of Formation Flights. *Aerospace, 7*, 172.

de Jong, S., Hoefnagels, R., van Stralen, J., Londo, M., Slade, R., Faaij, A., & Junginger, M. (2017). *Renewable Jet Fuel in the European Union – Scenarios and Preconditions for Renewable Jet Fuel Deployment towards 2030.* Copernicus Institute of Sustainable Development - Utrecht University.

Deonandan, I., & Balakrishnan, H. (2010). Evaluation of strategies for reducing taxi-out emissions at airports. *10th AIAA Aviation Technology, Integration, and Operations Conference.* American Institute of Aeronautics and Astronautics.

Department for Transport. (2017). *UK Aviation Forecasts.*

DisPURSAL. (n.d.). *Outcome*. Retrieved January 9, 2020, from DisPURSAL Project: http://dispursal.eu/index.html?Page=outcome

Doganis, R. (2010). *Flying Off Course - Airlines Economics and Marketing.* New York, United States of America: Routledge.

Drela, M. (2010). *D8.x Aircraft Development - Update.*

Dubois, T. (2019, December 4). *Airbus ends Safran collaboration on A320 eTaxi*. Retrieved January 10, 2020, from Aviation Week: https://aviationweek.com/air-transport/aircraft-propulsion/airbus-ends-safran-collaboration-a320-etaxi

Dumont, J. (2020, September 9). Aviation CO2 Reductions - Stocktaking Seminar 2020. *Air Operations: Airbus fello'fly*. ICAO. Retrieved from https://www.icao.tv/stocktaking-seminar-on-aviation-in-sector-co2-emissions-reductions/videos/stocktaking-2020-day-2

E4tech (UK) Ltd, & studio Gear Up. (2019). *Study on the potential effectiveness of a renewable energy obligation for aviation in the Netherlands.* London: E4tech (UK) Ltd.

EASA. (2020). *Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4).* Brussels, Belgium: European Commission. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD:2020:277:FIN

easyJet. (2019, November 19). *easyJet to become the world's first major airline to operate net-zero carbon flights*. Retrieved January 9, 2020, from easyJet Media Centre: https://mediacentre.easyjet.com/story/13474/easyjet-to-become-the-world-s-first-major-airline-to-operate-net-zero-carbon-flights

EC. (2000). *Single European sky - Report of the high-level group.* Luxembourgh.

EC. (2011). *Flightpath 2050 - Europe's Vision for Aviation.* Brusssels, Belgium: European Commission.

EC. (2013a, June 11). Accelerating the implementation of the Single European Sky. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*. Strasbourg, France. Retrieved from https://ec.europa.eu/transport/sites/transport/files/modes/air/single_european_sky/doc/ses2plus/com%282013%29408_en.pdf

EC. (2013b, June 11). Proposal for a regulation of the European Parliament and of the Council amending Regulation (EC) No 216/2008 in the field of aerodromes, air traffic management and air navigation services. Strasbourg, France. Retrieved from https://ec.europa.eu/transport/sites/transport/files/modes/air/single_european_sky/doc/ses2plus/com%282013%29409_en.pdf

EC. (2014, September 26). *Commission Implementing Regulation (EU) No 1028/2014 of 26 September 2014 amending Implementing Regulation (EU) No 1207/2011 laying down requirements for the performance and the interoperability of surveillance for the single European sky Text with EEA re.* Retrieved January 6, 2020, from Publications Office of the EU: https://op.europa.eu/en/publication-detail/-/publication/42561ef7-486e-11e4-a0cb-01aa75ed71a1

EC. (2017). *Impact assessment SWD(2017) 473 final.*

EC. (2018a). *Report on the functioning of the European carbon market.* Brussels: European Commission.

EC. (2018b, November 28). A Clean Planet for all. *A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. Brussels: European Commission.

EC. (2018c, November 28). A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. *In-Depth Analysis in Support of the Commission Communication COM(2018) 773*. Brussels, Belgium. Retrieved from https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

EC. (2019a, February 11). *Commission implementing regulation (EU) 2019/317 on 11 February 2019 laying down a performance and charging scheme in the single European sky and repealing Implementing Regulations (EU) No 390/2013 and (EU) No 391/2013.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0317&from=EN

EC. (2019b, January 11). *Energy.* Retrieved from Renewable energy directive: https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive/overview

EC. (2019c, January 11). *Energy - biofuels*. Retrieved from Sustainability criteria: https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/sustainability-criteria

EC. (2019d, January 11). *EU Science Hub - Joint Research Centre, EUCAR and Concawe*. Retrieved from Renewable Energy – Recast to 2030 (RED II): https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

EC. (2019e). *Evaluation of the Council Directive 2003/96/EC of 27 October 2003 restructuring the Community framework for taxation of energy prodducts and electricity.* Brussels, Belgium.

EC. (2019f, August 19). *Natural laminar flow for fuel-efficient airplanes*. Retrieved from Cordis EU research results: https://cordis.europa.eu/article/id/394834-natural-laminar-flow-for-fuelefficient-airplanes

EC. (2019g). *Preparing the ground for raising long-term ambition - EU Climate Action Progress Report 2019.* Brussels: European Commission.

EC. (2019h, December 11). Sustainable mobility. *The European Green Deal*. doi:10.2775/395792

EC. (2019i, December 11). The European Green Deal. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*. Brussels, Belgium. Retrieved from https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

EC. (2020a, September 22). A fresh look at the Single European Sky. *Commission Staff Working Document*. Brussels, Belgium. Retrieved from https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=SWD:2020:187:FIN

EC. (2020b, July 8). A hydrogen strategy for a climate-neutral Europe. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*. Brussels, Belgium: European Commission. Retrieved from https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

EC. (2020c, October 29). Amendment of the EU Emissions Trading System (Directive 2003/87/EC). *Inception Impact Assessment*. European Commission. Retrieved from https://ec.europa.eu/cf747897-59c3-4b68-9624-4233d3192c4f

EC. (2020d, March 4). Proposal for a Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). Brussels, Belgium: European Commission. Retrieved from https://ec.europa.eu/info/sites/info/files/commission-proposal-regulation-european-climate-law-march-2020_en.pdf

EC. (2020e, July 8). *Questions and answers: A Hydrogen Strategy for a climate neutral Europe*. Retrieved November 25, 2020, from https://ec.europa.eu/commission/presscorner/detail/en/QANDA_20_1257

EC. (2020f, March 24). ReFuelEU Aviation - Inception impact assessment. *Ref. Ares(2020)1725215*.

EC. (2020g, June 02). *Renewable Energy – Recast to 2030 (RED II)*. Retrieved from JEC: https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

EC. (2020h, February 24). *Single European Sky II*. Retrieved February 24, 2020, from Mobility and Transport: https://ec.europa.eu/transport/modes/air/single_european_sky/ses_2_en

EC. (2020i, December 9). Sustainable and Smart Mobility Strategy - putting European transport on track for the future. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. Brussels, Belgium: European Commission.

EC. (2020j, November 24). *Updated analysis of the non-CO2 effects of aviation*. Retrieved December 10, 2020, from Climate Action: https://ec.europa.eu/clima/news/updated-analysis-non-co2-effects-aviation_en

EC. (2020k, March 19). *Voluntary schemes*. Retrieved from Biofuels: https://ec.europa.eu/energy/topics/renewable-energy/biofuels/voluntary-schemes_en

ECA. (2017). *Single European Sky: a changed culture but not a single sky.* Luxembourgh: European Union. Retrieved from https://op.europa.eu/webpub/eca/special-reports/single-european-sky-18-2017/en/

Economist Intelligence Unit. (2015). *Long-term macroeconomic forecasts. Key trends to 2050.*

EDF. (2018). *Carbon prices under carbon market scenarios consistent with the Paris Agreement: Implications for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).* Environmental Defense Fund.

Edwards, H., Dixon-Hardy, D. W., & Wadud, Z. (2015). Optimisation of Aircraft Cost Indices to Reduce Fuel Use. *TRB 94th Annual Meeting.* Washington, D.C., United States of America: Transportation Research Board.

EEA. (2017). *Climate change, impacts and vulnerability in Europe 2016. An indicator-based report.*

EEA. (2019, December 19). *Recent trends and projections in EU greenhouse gas emissions*. Retrieved January 13, 2020, from European Environment Agency: https://www.eea.europa.eu/themes/climate/approximated-greenhouse-gas-emissions/approximated-greenhouse-gas-emissions-in-2017

EEA. (2020, January 31). *Final energy consumption by sector and fuel in Europe*. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-10/assessment

EEA, EASA & EUROCONTROL. (2019). *European Aviation Environmental Report 2019.* doi:10.2822/309946

EEX. (n.d.). *European Energy Exchange AG*. Retrieved from https://www.eex.com/en/

Embraer. (2016, Marh). Fuel Burn Improvements. *Investor Relations*.

EMRC; AEA. (2011). *A Marginal Abatement Cost Curve Model for the UK Aviation Sector.* Department for Transport.

Energies Nouvelles. (2017). *Overview of economic carbon pricing tools worldwide. Economic Outlook.*

Energy Transitions Commission. (2019). *Mission Possible - Sectoral Focus: Aviation.*

EP & CEU. (2009, October 21). Regulation (EC) No 1070/2009 of the European Parliament and of the Council of 21 October 2009 amending Regulations (EC) No 549/2004, (EC) No 550/2004, (EC) No 551/2004 and (EC) No 552/2004 in order to improve the performance and sustainability of the Euro. Publications Office of the European Union. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32009R1070

ERA. (2020). *Green and sustainble connectivity - ERA's first sustainability report.* Retrieved from https://www.eraa.org/sites/default/files/era_green_and_sustainable_connectivity_v1.pdf

Erbach, G. (2018). *CO2 emissions from aviation.* European Parliament, European Parliamentary Research Service. Retrieved from https://www.europarl.europa.eu/RegData/etudes/BRIE/2017/603925/EPRS_BRI(2017)603925_EN.pdf

ERCST, Center, Wegener, ICIS, I4CE, & Ecoact. (2019). *2019 State of the EU-ETS Report.*

EU. (2017). *Regulation (EU) 2017/2392 of the European Parliament and The Council of 13 December 2017 amending Directive 2003/87/EC to continue current limitations of scope for aviation activities and to prepare to implement a global market-based measure from 2021.*

EUROCONTROL. (2013). *Challenges of Growth 2013. Task 7: European Air Traffic in 2050.*

EUROCONTROL. (2017, August 4). *North Atlantic Operations - Organised Track System*. Retrieved January 6, 2020, from SKYbrary Aviation Safety: https://www.skybrary.aero/index.php/North_Atlantic_Operations_-_Organised_Track_System

EUROCONTROL. (2018a). *Challenges of Growth. Annex 2 Adapting to Changing Climate.*

EUROCONTROL. (2018b). *European Aviation in 2040. Challenges of Growth. Annex 1: Flight Forecast to 2040.*

EUROCONTROL. (2018c). *Specification for Collaborative Environmental Management (CEM).* EUROCONTROL.

EUROCONTROL. (2019a, June 21). *Fuel Tankering: economic benefits and environmental impact.* Retrieved from EUROCONTROL: https://www.eurocontrol.int/publication/fuel-tankering-european-skies-economic-benefits-and-environmental-impact

EUROCONTROL. (2019b). *Performance Review Report - An Assessment of Air Traffic Management in Europe during the Calendar Year 2018.* Brussels, Belgium.

EUROCONTROL. (2019c, September 10). *The aviation network - Decarbonisation issues.* Retrieved January 9, 2020, from EUROCONTROL: https://www.eurocontrol.int/sites/default/files/2019-09/decarbonisation-eurocontrol-think-paper-v4.pdf

EUROCONTROL. (2020a). *Environmental Assessment: European ATM Network Fuel Inefficiency Study.*

EUROCONTROL. (2020b). *Five-year forecast 2020-2024. European flight movements and service units. Three scenarios for recovery from COVID-19.*

EUROCONTROL. (n.d.). *Advanced flexible use of airspace* . Retrieved January 6, 2020, from EUROCONTROL: https://www.eurocontrol.int/concept/advanced-flexible-use-airspace

eurostat. (2019, September 25). *Commercial aircraft fleet by age of aircraft*. Retrieved January 6, 2020, from Data explorer: https://appsso.eurostat.ec.europa.eu/nui/show.do?query=BOOKMARK_DS-054094_QID_10FAFB62_UID_-

3F171EB0&layout=TIME,C,X,0;GEO,L,Y,0;AGE,L,Z,0;INDICATORS,C,Z,1;&zSelection=DS-054094AGE,TOTAL;DS-054094INDICATORS,OBS_FLAG;&rankName1=AGE_1_2_-1_2&rankName2=INDIC

eurostat. (2019, June). *Greenhouse gas emission statistics - emission inventories*. Retrieved from Eurostat - Statistics Explained: https://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics

eurostat. (2019, January). *Labour market and Labour force survey (LFS) statistics*. Retrieved January 13, 2020, from Statistics Explained: https://ec.europa.eu/eurostat/statistics-explained/index.php/Labour_market_and_Labour_force_survey_(LFS)_statistics

FAA & EUROCONTROL. (2019). *Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe.*

FAA. (2020, January 2). *Airspace*. Retrieved January 6, 2020, from NextGen - Equip ADS-B: https://www.faa.gov/nextgen/equipadsb/research/airspace/

Faggiano, F., Vos, R., Baan, M., & van Dijk, R. (2017). Aerodynamic Design of a Flying V Aircraft. *17th AIAA Aviation Technology, Integration, and Operations Conference.* Denver, Colorado, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2017-3589

Fala, N., Uday, P., Le, T., & Marais, K. (2014). Surface Performance of End-around Taxiways. *Air Traffic Control Quarterly, 22*(4), 327-351. doi:10.2514/atcq.22.4.327

Falcus, M. (2020, August 10). *Aircraft Fleets and Types Retired During Covid-19*. Retrieved November 24, 2020, from Airport Spotting: https://www.airportspotting.com/aircraft-fleets-and-types-retired-during-covid-19/

Fehrm, B. (2017, November 2). *Why is Airbus A330-800 not selling?* Retrieved January 7, 2020, from Leeham News and Analysis: https://leehamnews.com/2017/11/02/airbus-a330-800-not-selling/

Felder, J. (2014, November 17). NASA N3-X with Turboelectric Distributed Propulsion. Cleveland, Ohio, United States of America: NASA. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20150002081

Ferro, S. (2014, November 8). *Airlines Are Tossing Seat-Back Screens. Here Is Why That's A Great Design Move*. Retrieved February 19, 2020, from Fast Company: https://www.fastcompany.com/3034196/airlines-are-tossing-seat-back-screens-here-is-why-thats-a-great-design-mo

Flanzer, T. C., Bieniawski, S. R., & Brown, J. A. (2020). Advances in Cooperative Trajectories for Commercial Applications. *AIAA SciTech 2020 Forum.* Orlando, Florida, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2020-1257

Fleuti, E., & Maraini, S. (2017). *Taxi-Emissions at Zurich Airport.* Zurich Airport.

Flottau, J. (2015, January 13). *Airbus Launches Long-Range A321neo Version*. Retrieved June 12, 2017, from Aviation Week: http://aviationweek.com/commercial-aviation/airbus-launches-long-range-a321neo-version

Forsberg, D. (2015). *Aircraft Retirement and Storage Trends. Economic Life Analysis Reprised and Expanded.* Avolon.

Gambhir, A. T. (2019). Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation. *One Earth*(1), 405-409.

Gangoli Rao, A., Yin, F., & van Buijtenen, J. (2014). A hybrid engine concept for multi-fuel blended wing body. *Aircraft Engineering and Aerospace Technology: An International Journal, 86*(6), 483-493. doi:10.1108/AEAT-04-2014-0054

German Environment Agency. (2016, September). Power-to-Liquids. *Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*. German Environment Agency.

Gerzanics, M. (2018, July 17). *ANALYSIS: With E2 series, Embraer closes the loop*. Retrieved January 7, 2020, from FlightGlobal: https://www.flightglobal.com/analysis/analysis-with-e2-series-embraer-closes-the-loop/128584.article

Goldmann, A., Sauter, W., Oettinger, M., Kluge, T., Schröder, U., Seume, J. R., . . . Dinkelacker, F. (2018). A Study on Electrofuels in Aviation. *Energies, 11*(392).

Goold, I. (2018, July 18). *Airbus 'BLADE Runner' Exceeds Expectations*. Retrieved January 16, 2020, from AINonline: https://www.ainonline.com/aviation-news/air-transport/2018-07-18/airbus-blade-runner-exceeds-expectations

Gosnell, G., List, J., & Metcalfe, R. (2016, June). A New Approach to an Age-Old Problem: Solving Externalities by Incenting Workers Directly. *NBER Working Paper Series*. Cambridge, Massachusetts, United States of America: National Bureau of Economic Research. Retrieved from www.nber.org/papers/w22316

Graham, W., Hall, C., & Vera Morales, M. (2014). The potential of future aircraft technology for noise and pollutant emissions reduction. . *Transport Policy, 34*, 36-51. doi:10.1016/j.tranpol.2014.02.017

Graver, B., Rutherford, D., & Zheng, S. (2020). *CO2 emissions from commercial aviation: 2013, 2018, and 2019.* ICCT. Retrieved from https://theicct.org/publications/co2-emissions-commercial-aviation-2020

Graver, B., Zhang, K., & Rutherford, D. (2019, September 19). *CO2 emissions from commercial aviation, 2018.* Retrieved January 13, 2020, from International Council on Clean Transportation: https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf

GreenAir Communications. (2018, March 20). *IAG implements Honeywell fuel efficiency software across its airlines and reports 2.6% fuel burn improvement*. Retrieved January 10, 2020, from GreenAir Online: https://www.greenaironline.com/news.php?viewStory=2461

Greenair Communications. (2019, March 7). *Proposal for Sweden to follow Norway's lead and mandate use of sustainable aviation fuels from 2021.* Retrieved from Green Air Online: https://www.greenaironline.com/news.php?viewStory=2574

Greenair Communications. (2020, January 27). *French government announces launch of roadmap and deployment targets for a national sustainable aviation fuel industry.* Retrieved from Green Aironline: https://www.greenaironline.com/news.php?viewStory=2659

Grewe, V. (2019, February 12). Addressing non-CO2 effects of aviation. *ICSA Aviation Decarbonization Forum*. Montreal, Canada.

Grewe, V., Bock, L., Burkhardt, U., Dalhmann, K., Gierens, K., Hüttenhofer, L., . . . Levy, Y. (2016). Assessing the climate impact of the AHEAD multi-fuel blended wing body. *Meteorologische Zeitschrift*. doi:10.1127/metz/2016/0758

Grewe, V., Dahlmann, K., Flink, J., Frömming, C., Ghosh, R., Gierens, K., . . . Ziereis, H. (2017). Mitigating the Climate Impact from Aviation: Achievements and Results of the DLR WeCare Project. *Aerospace, 4*(34), 1-50. doi:10.3390/aerospace4030034

Gubisch, M. (2011, March 28). *Balancing it out: weight savings in the passenger cabin*. Retrieved January 10, 2020, from FlightGlobal: https://www.flightglobal.com/balancing-it-out-weight-savings-in-the-passenger-cabin/99050.article

Guivarch, C. R. (2017). *Carbon price variations in 2C scenarios explored.*

Hansen, K., Breyer, C., & Lund, H. (2019). Status and perspectives on 100% renewable energy systems. *Energy*, 471-480.

Harrison, P., Malins, C., Searle, S., Baral, A., Turley, D., & Hopwood, L. (2014). Wasted: Europe's untapped resource. ICCT.

Hartjes, S., & Bos, F. (2015). Evaluation of intermediate stop operations in long-haul flightst. *Transportation Research Procedia, 10*, 951-959.

Heinemann, P., Panagiotou, P., Vratny, P., Kaiser, S., Hornung, M., & Yakinthos, K. (2017). Advanced Tube and Wing Aircraft for Year 2050 Timeframe. *55th AIAA Aerospace Sciences Meeting - AIAA SciTech Forum.* Grapevine, Texas, United States of America: American Institute for Aeronautics and Astronautics. doi:10.2514/6.2017-1390

Hemmerdinger, J. (2016, April 18). *P&W fix will cut PW1100G start-up delay in half*. Retrieved April 7, 2020, from FlightGlobal: https://www.flightglobal.com/pandw-fix-will-cut-pw1100g-start-up-delay-in-half/120323.article

Hemmerdinger, J. (2019, April 15). *Embraer's E195-E2 receives type certification*. Retrieved January 7, 2020, from FlightGlobal: https://www.flightglobal.com/systems-and-interiors/embraers-e195-e2-receives-type-certification/132309.article

Hepher, T. (2013, July 3). *Elbows fly in Airbus and Boeing battle over mini-jumbos*. Retrieved January 7, 2020, from Reuters: https://www.reuters.com/article/us-airbus-boeing-minijumbo-insight-idUSBRE9620TJ20130703

High-Level Commission on Carbon Prices. (2017). *The European carbon market. The impact of higher carbon prices on utilities and industries.* Washington DC.

Honeywell. (2019, September 25). *Honeywell Advanced Software Saving Nippon Cargo Airlines, Kuwait Airways Up To 3% In Fuel Costs*. Retrieved January 10, 2020, from CISION PR Newswire: https://www.prnewswire.com/news-releases/honeywell-advanced-software-saving-nippon-cargo-airlines-kuwait-airways-up-to-3-in-fuel-costs-300924920.html

Hornung, M., Isikveren, A., Cole, M., & Sizmann, A. (2013). Ce-Liner - Case Stuy for eMobility in Air Transportation. *2013 Aviation Technology, Integration, and Oprations Conference.* Los Angeles, California, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2013-4302

House, K. B. (2011). Economic and energetic analysis of capturing CO2 from ambient air. *PNAS*(108 (51)), 20428-20433.

IAG. (2019). Flightpath net zero. Retrieved from https://www.iairgroup.com/sustainability/flightpath-net-zero

IATA. (2013). *Technology Roadmap, 4th Edition.*

IATA. (2015). *IATA Sustainable Aviation Fuel Roadmap.* IATA.

IATA. (2019a). Retrieved from ACMG Data Toolset FY2018.: https://www.iata.org/contentassets/3b5a413027704ce08976fe1890fb43e2/acmg-data-toolset.xls

IATA. (2019b). *ACMG Data Toolset FY2019.* Retrieved November 4, 2020, from Airline Cost Management Group (ACMG): https://www.iata.org/en/programs/workgroups/airline-cost-mgmt/

IATA. (2019c). *Economic Performance of the Airline Industry. June 2019.*

IATA. (2020a). *Air Passenger Forecasts. July Update.*

IATA. (2020b). *Climate Change*. Retrieved June 12, 2020, from Policy: https://www.iata.org/en/policy/environment/climate-change/

IATA. (2020c). *COVID-19 June data and revised air travel outlook.*

IATA. (2020d). *IATA*. Retrieved January 12, 2020, from Climate Change: https://www.iata.org/en/policy/environment/climate-change/

IATA; AEA & ERA. (2013). *A Blueprint for the Single European Sky.*

ICAO. (2006). *Convention on International Civil Aviation.* Retrieved from https://www.icao.int/publications/Documents/7300_cons.pdf

ICAO. (2013). *2013 Environmental Report - Destination Green.*

ICAO. (2014a). *Air Navigation Report.* Montréal, Canada. Retrieved from https://www.icao.int/airnavigation/Documents/ICAO_AN%20Report_EN_final_30042014.pdf

ICAO. (2014b). *Operational Opportunities to Reduce Fuel Burn and Emissions.*

ICAO. (2015). An introduction to market-based measures (MBMs).

ICAO. (2016). On Board A Sustainable Future. Retrieved from https://www.icao.int/environmental-protection/Documents/ICAOEnvironmental_Brochure-1UP_Final.pdf

ICAO. (2018a). *Climate Adaptation Synthesis.*

ICAO. (2018b). *The World of Air Transport in 2018*. Retrieved November 5, 2020, from Annual Report 2018: https://www.icao.int/annual-report-2018/Pages/the-world-of-air-transport-in-2018.aspx

ICAO. (2019, June). *CORSIA Eligible Fuels.* Retrieved from CORSIA supporting document — Life cycle assessment methodology: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

ICAO. (2019a). *2019 Environmental Report.* Montréal: ICAO.

ICAO. (2019b, October 8). *Call for long-term aviation emissions target; CORSIA support, and new CAEP supersonics study among key environmental protection outcomes at 40th ICAO Assembly*. Retrieved April 15, 2020, from ICAO Newsroom: https://www.icao.int/Newsroom/Pages/Call-for-long-term-aviation-emissions-target-CORSIA-support.aspx

ICAO. (2019c). *CORSIA Emissions Unit Eligibility Criteria.*

ICAO. (2020d, June 30). *ICAO Council agrees to the safeguard adjustment for CORSIA in light of COVID-19 pandemic*. Retrieved November 26, 2020, from ICAO Newsroom: https://www.icao.int/Newsroom/Pages/ICAO-Council-agrees-to-the-safeguard-adjustment-for-CORSIA-in-light-of-COVID19-pandemic.aspx

ICAO. (n.d.). *Feasibility of a long term global aspirational goal for international aviation*. Retrieved November 26, 2020, from ICAO Environment: https://www.icao.int/environmental-protection/Pages/LTAG.aspx

ICB. (2019). *ICB Vision for a Single European Sky (2nd edition).* Industry Consultation Body. Retrieved from http://www.icb-portal.eu/index.php/publications/formal-icb-outputs/category/6-icb-positions?download=121:icb-vision-2019-issue

ICCT. (2017, January). The European Commission's renewable energy proposal for 2030. ICCT.

ICCT. (2018). Sustainability challenges of lignocellulosic bioenergy crops.

ICCT. (2019). *CO2 emissions from commercial aviation. Working paper 2019-16.*

ICF, & Petchenik. (2020, June 26). *How airlines have managed their fleet mix during the COVID-19 pandemic*. Retrieved November 24, 2020, from FlightRadar24: https://www.flightradar24.com/blog/how-airlines-have-managed-their-fleet-mix-during-the-covid-19-pandemic/

ICIS. (2019). *The European carbon market. The impact of higher carbon prices on utilities and industries.*

IEA. (2020). Energy Technology Perspectives. Special Report on Carbon Capture Utilisation and Storage.

IHS Markit. (2017). *EU-ETS - Carbon Price Increase: Will it last?*

IMF. (2019a). *Fiscal policies for Paris climate strategies from principle to practice.* Washington, DC: International Monetary Fund.

IMF. (2019b, April). *Report for Selected Country Groups and Subjects*. Retrieved January 13, 2020, from World Economic Outlook Database:

https://www.imf.org/external/pubs/ft/weo/2019/01/weodata/weorept.aspx?pr.x=59&pr.y=14&sy=2017&ey=2021&scsm=1&ssd=1&sort=country&ds=.&br=1&c=998&s=NGDPD%2CPPPGDP%2CPPPPC%2CPCPIPCH&grp=1&a=1

Integra A/S; ECORYS Nederland BV; Winsland Consulting & Combitech. (2017). *Study on Functional Airspace Blocks: Final Report.* European Commission / DG Move.

International Energy Agency. (2020). *Energy Technology Perspectives.* IEA.

IPCC. (2006). *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanebe K. (eds).* Japan: IGES.

IPCC. (2018a). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,.*

IPCC. (2018b). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. Shukla, . . . T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,.* Geneva, Switzerland: World Meteorological Organisation. Retrieved January 9, 2020, from IPCC: https://www.ipcc.ch/sr15/chapter/spm/

IRENA. (2019). *Global energy transformation: The REmap transition pathway (Background report to 2019 edition).* Abu Dhabi: Renewable Energy Agency International.

Isikveren, A., Seitz, A., Bijewitz, J., Mirzoyan, A., Isyanov, A., Grenon, R., . . . Stückl, S. (2015, November). Distributed Propulsion and Ultra-high By-Pass Rotor Study at Aircraft Level. *Aeronautical Journal, 119*(1221), 1237-1276. doi:10.1017/S0001924000011295

Ithnan, M., Selderbeek, T., Beelaerts van Blokland, W., & Lodewijks, G. (2013). Aircraft Taxiing Strategy Optimization. *TRAIL Internal Congress.*

Jensen, L., Hansman, R., Venuti, J., & Reynolds, T. (2013). Commercial Airline Speed Optimiztion Strategies for Reduced Cruise Fuel Consumption. *AIAA AVIATION Forum / 2013 Aviation Technology, Integration, and Operations Conference.* Los Angeles, United States of America: American Institute of Aeronautics and Astronautics.

Jiang, H. (2015). *Trends in Fleet and Aircraft Retirement.* Boeing Commercial Airplanes.

Johansson, C. (2014). Managing Uncertainty and Ambiguity in Gates: Decision Making in Aerospace Product Development. *International Journal of Innovation and Technology Management, 11*(2).

Kaminski-Morrow, D. (2019, September 18). *SAS offers passengers option to purchase biofuel*. Retrieved from Flight Global: https://www.flightglobal.com/safety/sas-offers-passengers-option-to-purchase-biofuel/134363.article

Karatzos, S., McMillan, J., & Saddler, J. (2014). *The Potential and Challenges of Drop-in Biofuels.* IEA Bioenergy Task 39.

Khalilpo, K. R. (2019). Chapter 5 - Interconnected Electricity and Natural Gas Supply Chains: The Roles of Power to Gas and Gas to Power.

Kharina, A., & Rutherford, D. (2015, September 3). *Fuel efficiency trends for new commercial jet aircraft: 1960 to 2014.* Retrieved from The International Council on Clean Transportation: https://theicct.org/publications/fuel-efficiency-trends-new-commercial-jet-aircraft-1960-2014

Khawaja, C., & Janssen, R. (2014). Sustainable supply of non-food biomass for a resource efficient bioeconomy - A review paper on the state-of-the-art. WIP - Renewable Energies.

KiM. (2011). *Effecten van de vliegbelasting. Gedragsreacties van reizigers, luchtvaartmaatschappijen en luchthavens.* Den Haag: Kennisinstituut voor Mobiliteitsbeleid.

KLM. (2017, March 24). *KLM Media App vervangt kranten aan boord*. Retrieved January 10, 2020, from KLM Newsroom: https://nieuws.klm.com/klm-media-app-vervangt-kranten-aan-boord/

Koopmans, C., & Lieshout, R. (2016). Airline cost changes: To what extent are they passed through to the passenger? *Journal of Air Transport Management*(53), 1-11.

Koudis, G., Hu, S., Majumdar, A., Ochieng, W., & Stettler, M. (2018, December). The impact of single engine taxiing on aircraft fuel consumption and pollutant emissions. *The Aeronautical Journal, 122*(1258), 1967-1984. doi:10.1017/aer.2018.117

KPMG & IBA. (2017). *Depreciation, residual values and useful economic lives.*

Lafage, R., Aubry, S., & Junior, A. (2016). The Clean Sky Technology Evaluator: review and results of the environmental impact assessment at mission level. *16th AIAA Aviation Technology, Integration and Operations Conference.* Washington, D.C., United States of America: American Institute for Aeronautics and Astronautics. doi:10.2514/6.2016-3745

Lammen, W., & Vankan, J. (2019). Electrification studies of single aisle aircraft: a 'retrofit' investigation including parallel hybrid electric propulsion. *International Symposium on Sustainable Aviation 2019.* Budapest, Hungary.

Lammering, T., Anton, E., Risse, K., & Franz, K. (2011). Gains in Fuel Efficiency: Multi-Stop Missions vs. Laminar Aircraft. *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference* (p. 6885). Virginia Beach, United States of America: American Institute of Aeronautics and Astronautics.

Lamontagne, J., Reed, P., Marangoni, G., Keller, K., & Garner, G. (2019). Robust abatement pathways to tolerable climate futures require immediate global action. *Nature Climate Change, 9*, 290-294. doi:10.1038/s41558-019-0426-8

Langhans, S., Linke, F., Nolte, P., & Gollnick, V. (2013). System Analysis for an Intermediate Stop Operations Concept on Long Range Routes. *Journal of Aircraft, 50*(1), 29-37.

Lawson, C. (2016, October 17). eTaxi Fuel Cell System - Feasibility for Low Cost Carriers.

Leahy, J. (2007, June 19). Commercial update. Paris: Airbus S.A.S.

Leahy, J. (2016, February). Annual Press Conference. *2015 commercial review*.

Leahy, J. (n.d.). The A330neo - Powering into the future. Retrieved from http://www.ausbt.com.au/files/A330neo%20Launch%20Presentation.pdf

Learmount, D. (2019a, May 13). *ATM makeover takes on ad-hoc post-Brexit uncertainty*. Retrieved January 6, 2020, from FlightGlobal: https://www.flightglobal.com/analysis/atm-makeover-takes-on-ad-hoc-post-brexit-uncertainty/132411.article

Learmount, D. (2019b, October 25). *How the busiest oceanic airspace manages safety in a world first*. Retrieved February 26, 2020, from FlightGlobal: https://www.flightglobal.com/in-depth/how-the-busiest-oceanic-airspace-manages-safety-in-a-world-first-/134804.article

Lee, D. (2018). *The current state of scientific understanding of the non-CO2 effects of aviation on climate.* UK Department for Transport. Retrieved from https://www.gov.uk/government/publications/aviation-2050-the-future-of-uk-aviation-consultation-sustainable-growth-carbon-reports

Lee, D., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C., Lim, L. L., . . . Sausen, R. (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment, 44*(22-23), 3520-3537.

Lee, D., Fahey, D., Skowron, A., Allen, M., Burkhardt, U., Chen, Q., . . . Wilcox, L. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*.

Lee, D., Pitari, G., Grewe, V., Gierens, K., Penner, J., Petzold, A., . . . Sausen, R. (2010, December). Transport impacts on atmosphere and climate: Aviation. Elsevier Ltd.

Leeham News. (2014, February 3). *Updating the A380: the prospect of a neo version and what's involved*. Retrieved January 7, 2020, from Leeham News and Analysis: https://leehamnews.com/2014/02/03/updating-the-a380-the-prospect-of-a-neo-version-and-whats-involved/

Leguijt, C., van der Veen, R., van Grins, A., Nieuwenhuijse, I., Broeren, M., Kampman, B., . . . Pronk, I. (2020). *Bio-Scope.* CE Delft.

Linke, F., Grewe, V., & Gollnick, V. (2017). The Implications of Intermediate Stop Operations on Aviation Emissions and Climate. *Metereologische Zeitschrift*. doi:10.1127/metz/2017/0763

Liu, Y., Elham, A., Horst, P., & Hepperle, M. (2018, January). Exploring Vehicle Level Benefits of Revolutionary Technology Progress via Aircraft Design and Optimization. *Energies, 11*(166). doi:10.3390/en11010166

Mace, M. (2019, October 18). *UK airline industry calls on government to spur sector to net-zero*. Retrieved January 9, 2020, from EURACTIV.com: https://www.euractiv.com/section/aviation/news/uk-airline-industry-calls-on-government-to-spur-sector-to-net-zero/

Madavan, N. (2016, November 9). NASA Investments in Electric Propulsion Technologies for Large Commercial Aircraft. Mountain View, California, United States of America.

Martinez, V. (2018, December 20). *Sánchez planea imponer a las aerolíneas una cuota verde pionera del 2% en el uso de biocarburantes*. Retrieved from El Mundo: https://www.elmundo.es/economia/2018/12/20/5c1a972421efa0af7d8b45d8.html

Martinez-Val, R., Perez, E., Cuerno, C., & Palacin, J. (2012). Cost-range trade-off of intermediate stop operations of long-range transport airrplanes. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 227*(2), 394-404.

McKinsey & Company. (2020). *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050.* Clean Sky 2 JU; FCH 2 JU.

Miller, S. (2019, April 11). *JetBlue plans 140 seats, Boston base for A220 launch*. Retrieved May 27, 2020, from PaxEx.Aero: https://paxex.aero/2019/04/jetblue-a220-interior-layout/

Ministry of Infrastructure and Water Management. (2020a, March 3). Bijmengverplichting Luchtvaart en andere ontwikkelingen duurzame brandstoffen. Government of the Netherlands.

Ministry of Infrastructure and Water Management. (2020b). *Verantoord vliegen naar 2050: Ontwerp-Luchtvaartnota 2020-2050.* Government of the Netherlands. Retrieved from https://luchtvaartindetoekomst.nl/ontwikkeling+luchtvaart/documenten+ontwerp+luchtvaartnota+2020-2050/default.aspx#folder=1663196

MIT. (2010, April 23). MIT Team Final Review. *NASA N+3*. Hampton, Virginia, United States of America.

Morgan, S. (2020, February 27). *Heathrow airport expansion is unlawful, says UK court*. Retrieved April 16, 2020, from EURACTIV: https://www.euractiv.com/section/aviation/news/heathrow-airport-expansion-is-unlawful-says-uk-court/1435413/

Munich Re. (2018). *Natural catastrophes 2017. A stormy year. Topics Geo.*

NASA. (2020, January 9). *The Effects of Climate Change*. Retrieved January 12, 2020, from Global Climate Change: Vital Signs of the Planet: https://climate.nasa.gov/effects/

Nickol, C., & Haller, W. (2016). Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project. *54th AIAA Aerospace Sciences Meeting / AIAA SciTech Forum.* San Diego, California, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2016-1030

Norris, G. (2012, June 26). *Operators Reporting Positive 787 Fuel-Burn Results*. Retrieved from Aviation Week: https://aviationweek.com/air-transport/operators-reporting-positive-787-fuel-burn-results

Norris, G. (2014, February 26). *Rolls-Royce Reveals Next-Gen Engine Plan*. Retrieved January 6, 2016, from Aviation Week: https://aviationweek.com/commercial-aviation/rolls-royce-reveals-next-gen-engine-plan

Norris, G. (2019, December 10). *Boeing, FedEx 777F Tests Confirm Wake Fuel Burn Benefit*. Retrieved January 10, 2020, from Aviation Week: https://aviationweek.com/air-transport/boeing-fedex-777f-tests-confirm-wake-fuel-burn-benefit

Norris, G. (2020, February 4). *Boeing 777X Flight-Test Campaign Takes Off*. Retrieved February 19, 2020, from Aviation Week: https://aviationweek.com/aerospace/boeing-777x-flight-test-campaign-takes

Norris, G., & Anselmo, J. (2016, October 31). *777X Production Investments Bolster Boeing*. Retrieved from Aviation Week: http://aviationweek.com/commercial-aviation/777x-production-investments-bolster-boeing

Northrop Grumman. (2010, April 21). Silent, Efficient, Low-Emissions Commercial Transport (SELECT) - Program Final Review. Brook Park, Ohio, United States of America.

Norwegian Government. (2019, January 17). *Luftfarten skal bruke 0,5 prosent avansert biodrivstoff fra 2020*. Retrieved from Norwegian Government: https://www.regjeringen.no/no/aktuelt/biodrivstoff-i-luftfarten/id2613122/

OECD. (2018a). *Effective Carbon Rates 2018: Pricing Carbon Emissions Through Taxes and Emissions Trading.* Paris: OECD Publishing.

OECD. (2018b). *The Long View: Scenarios for the World Economy to 2060.*

Official Airline Guide. (2019). Schedules Analyser.

Ökö -Institut e.V. (2019). *Lessons learned from the first round of applications by carbon-offsetting programs for eligibility under CORSIA.*

Ökö-Institut e.V. (2016). *How additional is the Clean Development Mechanism?* . Berlin.

oneworld. (2020, September 11). *oneworld member airlines commit to net zero carbon emissions by 2050* . Retrieved November 24, 2020, from oneworld: https://www.oneworld.com/news/2020-09-11-oneworld-member-airlines-commit-to-net-zero-carbon-emissions-by-2050

Osborne, T. (2019, September 16). *Transatlantic Surveillance From Space Is Making Flights Greener*. Retrieved January 6, 2020, from Aviation Week: https://aviationweek.com/air-transport/transatlantic-surveillance-space-making-flights-greener

Pallini, T. (2020, May 15). *Iconic planes are disappearing from the sky earlier than planned as coronavirus wreaks airline havoc not seen since 9/11*. Retrieved November 24, 2020, from Business Insider: https://www.businessinsider.nl/coronavirus-havoc-forces-airlines-to-retire-iconic-planes-sooner-2020-3?international=true&r=US

Pavlenko, N., Searle, S., & Christensen, A. (2019, March). The cost of supporting alternative jet fuels in the European Union. ICCT.

Peerlings, B. (2020, May 11). *Terug naar de toekomst: op naar een duurzame luchtvaart*. Retrieved November 24, 2020, from Netherlands Aerospace Centre : https://www.nlr.nl/nlr-blog/terug-naar-de-toekomst-op-naar-een-duurzame-luchtvaart/

Perrett, B. (2020, October 30). *Mitsubishi Heavy Industries Suspends SpaceJet Development*. Retrieved November 25, 2020, from Aviation Week: https://aviationweek.com/air-transport/aircraft-propulsion/mitsubishi-heavy-industries-suspends-spacejet-development

Pidcock, R., & Yeo, S. (2016, August 8). *Analysis: Aviation could consume a quarter of 1.5C carbon budget by 2050*. Retrieved April 14, 2020, from Carbon Brief: https://www.carbonbrief.org/aviation-consume-quarter-carbon-budget

Polek, G. (2015, January 13). *Airbus Launches Long-Range A321neo*. Retrieved May 27, 2020, from AINonline: https://www.ainonline.com/aviation-news/air-transport/2015-01-13/airbus-launches-long-range-a321neo

Pornet, C., & Isikveren, A. (2015). Conceptual design of hybrid-electric transport aircraft. *Progress in Aerospace Sciences, 79*, 114-135. doi:10.1016/j.paerosci.2015.09.002

Pornet, C., Kaiser, S., Isikveren, A., & Hornung, M. (2014). Integrated fuel-battery hybrid for a narrow-body sized transport aircraft. *Aircraft Engineering and Aerospace Technology: An International Journal, 86*(6), 568-574. doi:10.1108/AEAT-05-2014-0062

Presidency of the Council of the European Union. (2019, November 8). The future of the Single European Sky - Policy debate. Brussels: Council of the European Union. Retrieved from http://data.consilium.europa.eu/doc/document/ST-13782-2019-INIT/en/pdf

Raymer, D. (2002). Enhancing Aircraft Conceptual Design using Multidisciplinary Optimization. Stockholm, Sweden: Royal Institute of Technology.

Realmonte, G. D. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*.

Reals, K. (2014, March 31). *ANALYSIS: How airlines are losing weight in the cabin*. Retrieved January 16, 2020, from FlightGlobal: https://www.flightglobal.com/analysis-how-airlines-are-losing-weight-in-the-cabin/112695.article

RINGO. (2020). *RINGO Final Report - What aviation research infrastructures does Europe need to meet Flightpath 2050 challenges?*

Roberson, W., Root, R., & Adams, D. (2007). Fuel Conservation Strategies: Cruise Flight. *AERO*, 22-27.

Rockland Dutton. (2020). *Air Traveler Response to COVID-19. An 11-Country Survey: Wave III.*

Roskam, J. (1985). *Airplane Design.* Ottawa, Kansas, United States of America: Roskam Aviation and Engineering Corporation.

Royal Schiphol Group, KLM, NLR, Rotterdam The Hague Airport, Eindhoven Airport, Lelystad Airport, . . . Dutch Aviation Group. (2018). Slim én duurzaam. Luchtvaart Nederland.

Russell, E. (2018, November 14). *United sends the 787-10 to Europe from Newark in 2019*. Retrieved January 7, 2020, from FlightGlobal: https://www.flightglobal.com/strategy/united-sends-the-787-10-to-europe-from-newark-in-2019/130291.article

Ryerson, M. S., & Hansen, M. (2010). The potential of turboprops for reducing aviation fuel consumption. *Transportation Research Part D, 15*, 305-314.

Ryerson, M., Hansen, M., & Bonn, J. (2014). Time to burn: Flight delay, terminal efficiency, and fuel consumption in the National Airspace System. *Transportation Research Part A, 69*, 286-298. doi:10.1016/j.tra.2014.08.024

Sadraey, M. (2013). *Aircraft Design.* Chichester, West Sussex, United Kingdom: John Wiley & Sons, Ltd.

Saeed, S. (2020, June 3). *Airbus CEO: EU should adopt 'cash for clunkers' airplane scheme*. Retrieved November 24, 2020, from Politico: https://www.politico.eu/article/airbus-ceo-eu-should-adopt-clash-for-clunkers-airplane-scheme/

Schäfer, A., Evans, A., Reynolds, T., & Dray, L. (2015, November 23). Costs of mitigating CO2 emissions from passenger aircraft. *Nature Climate Change, 6*, 412-417. doi:10.1038/nclimate2865

Schmidt, P., & Weindorf, W. (2016). *Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel.* German Environment Agency.

Searle, S., Pavlenko, N., Kharina, A., & Giuntoli, J. (2019, January). Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities. ICCT.

SeatGuru. (2020). *Embraer E-190 (E90)*. Retrieved May 27, 2020, from JetBlue Seat Maps: https://www.seatguru.com/airlines/JetBlue_Airways/JetBlue_Airways_Embraer_190.php

Seitz, A., Nickl, M., Stroh, A., & Vratny, P. C. (2018). Conceptual study of a mechanically integrated parallel hybrid electric turbofan. *Journal of Aerospace Engineering, 232*(14), 2688-2712. doi:10.1177/0954410018790141

SEO Amsterdam Economics. (2009). *Implicaties van de invoering van de ticket-tax.* Amsterdam: SEO.

SEO Amsterdam Economics. (2019). *Effecten van een nationale vliegbelasting.* Amsterdam: SEO.

SESAR. (2019, December 18). *Deployment View - Implementation Objectives (Monitoring)*, 1.0.70.15.3435 (LDB). Retrieved January 6, 2020, from eATM Portal: https://www.atmmasterplan.eu/depl/essip_objectives/monitoring

SESAR 3 JU. (2020, November). SESAR 3 Joint Undertaking. *Joint Memorandum of Understanding*. Retrieved from https://www.sesarju.eu/sites/default/files/documents/reports/SESAR%203%20JU%20-%20Memorandum%20of%20Understanding.pdf

SESAR DM. (2020, Ocobter 27). *ADS-B Implementation Status*. Retrieved from Automatic Dependent Surveillance – Broadcast: https://ads-b-europe.eu/

SESAR DM. (2020, November 23). SESAR Deployment Delivers Benefits. SESAR Deployment Manager. Retrieved from https://assets.ctfassets.net/krj50g99u3hm/6II655qUqUnLfcDxdgY8XJ/3ca7ea5836e26198ccba4bc1e9cb8e7e/Factsheet-A4-Update_23112020.pdf

SESAR JU. (2019a). *A proposal for the future architecture of the European airspace.* Luxembourgh: Publications Office of the European Union. doi:10.2829/309090

SESAR JU. (2019b). *Benefits: Environment*. Retrieved January 6, 2020, from SESAR Joint Undertaking: https://www.sesarju.eu/approach/environment

SESAR JU. (2019c). *Discover SESAR*. Retrieved January 6, 2020, from SESAR Joint Undertaking: https://www.sesarju.eu/discover-sesar

SESAR JU. (2019d). *European ATM Master Plan | Digitalising Europe's Aviation Infrastructure - Executive view (2020 edition).* Luxembourgh: Publications Office of the European Union. doi:10.2829/10044

SESAR JU. (2019e). *European ATM Master Plan Edition 2020 - Master Plan Companion Document on the Performance Ambitions and Business View.* Retrieved from https://www.atmmasterplan.eu/downloads/286

SESAR JU. (2019f). *Objectives*. Retrieved January 6, 2020, from SESAR Joint Undertaking: https://www.sesarju.eu/approach/objectives

SESAR JU. (2019g). *SESAR Solutions Catalogue 2019.* Luxembourg: SESAR Joint Undertaking.

Shell. (2018). *The road to sustainable fuels for zero emissions mobility: status of, and perspectives for, power-to-liquids fuels*. Retrieved from https://www.concawe.eu/wp-content/uploads/E-fuels-article.pdf

Sheppard, I. (2019, November 26). *Thales Reveals Next-generation FMS, PureFlyt*. Retrieved January 10, 2020, from Aerospace News: Aviation International News: https://www.ainonline.com/aviation-news/aerospace/2019-11-26/thales-reveals-next-generation-fms-pureflyt

Simon, F. (2019, 12 12). *EU Commission unveils 'European Green Deal': The key points*. Retrieved October 9, 2020, from EURACTIV.com: https://www.euractiv.com/section/energy-environment/news/eu-commission-unveils-european-green-deal-the-key-points/

Simon, F. (2020a, September 16). *'We can do it!': EU chief announces 55% emissions reduction target for 2030*. Retrieved November 24, 2020, from EURACTIV.com: https://www.euractiv.com/section/climate-environment/news/we-can-do-it-eu-chief-announces-55-emissions-reduction-target-for-2030/

Simon, F. (2020b, October 7). *EU Parliament votes for 60% carbon emissions cut by 2030*. Retrieved November 24, 2020, from EURACTIV.com: https://www.euractiv.com/section/energy-environment/news/eu-parliament-votes-for-60-carbon-emissions-cut-by-2030/

Squadrin, G., & Schmit, F. (2020, September 30). *Europe makes legislative push for aviation transition*. Retrieved from Argus Media group: https://www.argusmedia.com/en/news/2145902-europe-makes-legislative-push-for-aviation-transition

Sridhar, B., Chen, N., Ng, H., Rodionova, O., Delahaye, D., & Linke, F. (2015). Strategic Planning of Efficient Oceanic Flights. *ATM Seminar 2015, 11th USA/EUROPE Air Traffic Management R&D Seminar.* Lisbo, Portugal.

Srivastava, A. (2018, July 20). *'TaxiBots' will tow planes at Delhi airport to save fuel, cut pollution*. Retrieved January 10, 2020, from Hindustan Times: https://www.hindustantimes.com/delhi-news/semi-robotic-taxibots-will-tow-aircraft-at-delhi-airport-cut-pollution/story-x8KnwklZofINuNA6pGXTBL.html

Strack, M., Chiozzotto, G. P., Iwanizki, M., Plohr, M., & Kuhn, M. (2017). Conceptual Design Assessment of Advanced Hybrid Electric Turboprop Aircraft Configurations. *17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum.* Denver, Colorado: AIAA.

Stückl, S., van Toor, J., & Lobentanzer, H. (2012). VoltAir - The all electric propulsion concept platform - A vision for atmospheric friendly flight. *ICAS2012 - 28th International Congress of the Aeronautical Sciences*, (pp. 1-11).

Sustainable Aviation. (2017). *Inter-dependencies between emissions of CO2, NOx & noise from aviation - Policy Discussion Paper.*

Sustainable Aviation. (2020a). *Decarbonisation Road-Map: A Path to Net Zero.*

Sustainable Aviation. (2020b). Sustainable Aviation Fuels Road-Map - Fueling the future of UK aviation.

Sustainable Aviation UK. (2012). *Sustainable Aviation CO2 Road-Map.*

Sustainable Aviation UK. (2016). *Sustainable Aviation CO2 Road-Map.*

Swiss Re. (2018). *Natural catastrophes and man-made disasters in 2017 - A year of record-breaking losses.* Retrieved from https://www.swissre.com/dam/jcr:1b3e94c3-ac4e-4585-aa6f-4d482d8f46cc/sigma1_2018_en.pdf

Synapse Energy. (2016). *Spring 2016 National Carbon Dioxide Price Forecast.* Cambridge.

The Economist. (2012, December 5). *Saving weight the Wi-Fi way*. Retrieved February 18, 2020, from The Economist: https://www.economist.com/gulliver/2012/12/05/saving-weight-the-wi-fi-way

Thisdell, D. (2019, May 20). *ANALYSIS: Rolls-Royce's vision of a hybrid future*. Retrieved from FlightGlobal: https://www.flightglobal.com/analysis/analysis-rolls-royces-vision-of-a-hybrid-future/132585.article

Thisdell, D. (2020, January 12). *Industry must grasp 'technology shift'*. Retrieved February 18, 2020, from Flight Global: https://www.flightglobal.com/flight-international/industry-must-grasp-technology-shift/136159.article

Thomson Reuters. (2014). *The MSR: Impact on market balance and prices.*

Thomson, R. (2020, January 15). *Electrically propelled aircraft developments exceed 200 for the first time*. Retrieved December 11, 2020, from Roland Berger: https://www.rolandberger.com/en/Point-of-View/Electric-propulsion-is-finally-on-the-map.html

Topham, G. (2019, October 17). *'Flight-shaming' could slow growth of airline industry, says Iata* . Retrieved January 9, 2020, from The Guardian: https://www.theguardian.com/business/2019/oct/17/flight-shaming-could-slow-growth-of-airline-industry-says-iata

Trimble, S. (2014, November 14). *ANALYSIS: After three years in service, how is 787 performing?* Retrieved January 7, 2020, from FlightGlobal: https://www.flightglobal.com/analysis-after-three-years-in-service-how-is-787-performing/115069.article

Trinomics. (2020). Opportunities arising from the inclusion of Hydrogen Energy Technologies in the National Energy & Climate Plans. Fuel Cells and Hydrogen 2 Joint Undertaking.

TU Delft. (n.d.). *Flying-V*. Retrieved January 9, 2020, from https://www.tudelft.nl/en/ae/flying-v/

Turgut, E., Cavcar, M., Usanmaz, O., Ozan Canarslanlar, A., Dogeroglu, T., Armutlu, K., & Yay, O. (2014). Fuel flow analysis for the cruise phase of commercial aircraft on domestic routes. *Aerospace Science and Technology, 37*, 1-9.

UK Department for Business, Energy & Industrial Strategy. (2019). *Updated short-term traded carbon values. Used for modelling purposes.*

UNEP. (2018). *The Emissions Gap Report 2018.* Nairobi: United Nations Environment Programme.

UNFCC. (2015, December 12). Adoption of the Paris Agreement. United Nations. Retrieved from https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

UNFCCC. (2017). *CER Demand, CDM Outlook and Article 6 of the Paris Agreement. CDM Training Workshop for DNAs and Stakeholders in Pakistan.* Islamabad.

UNFCCC. (n.d.). *Time Series - Annex I*. Retrieved January 13, 2020, from Greenhouse Gas Inventory Data: https://di.unfccc.int/time_series

United States Government Publishing Office. (2011, January 1). *14 CFR 91.225 Automatic Dependent Surveillance-Broadcast (ADS-B) Out equipment and use.* Retrieved January 6, 2020, from govinfo: https://www.govinfo.gov/app/details/CFR-2011-title14-vol2/CFR-2011-title14-vol2-sec91-225/summary

Uslu, A. (2017, September 1). Market analysis - RESfuels in transport sector.

van Nuffel, L., Gorenstein Dedecca, J., Smit, T., & Rademarkers, K. (2018). *Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?* Brussels: Policy Department for Economic, Scientific and Quality of Life Policies - European Parliament.

van Wijk, A., & Chatzimarkakis, J. (2020, March). Green Hydrogen for a European Green Deal A 2x40 GW Initiative. Hydrogen Europe.

Veldhuis, L., & Voskuijl, M. (2016). Exloration of Hybrid Electric Propulsion in Regional Aircraft. *The Electric and Hybrid Aerospace Technology Symposium 2016*. Cologne, Germany: Delft University of Technology.

Voskuijl, M. (2017). Cruise Range in Formation Flight. *Journal of Aircraft, 54*(6), 2184-2191. doi:10.2514/1.C034246

Voskuijl, M., van Bogaert, J., & Rao, A. (2017, March). Analysis and design of hybrid electric regional turboprop aircraft. *CEAS Aeronautical Journal, 9*(1), 15-25. doi:10.1007/s13272-017-0272-1

Vranjkovic, P., & Brain, D. (2020, September 9). Aviation CO2 Reductoins - Stocktaking Seminar 2020. *Air Operations*. ICAO. Retrieved from https://www.icao.tv/stocktaking-seminar-on-aviation-in-sector-co2-emissions-reductions/videos/stocktaking-2020-day-2

Wall, T., & Meyer, R. (2017). A Survey of Hybrid Electric Propulsion for Aircraft. *53rd AIAA/SAE/ASEE Joint Propulsion Conference - AIAA Propulsion and Energy Forum.* Atlanta, Georgia, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2017-4700

Warwick, G. (2019a, October 15). *NASA Takes Wraps Off Electrical Propulsive Fuselage Concept*. Retrieved January 8, 2020, from Aviation Week: https://aviationweek.com/aerospace/aircraft-propulsion/nasa-takes-wraps-electrical-propulsive-fuselage-concept

Warwick, G. (2019b, November 25). *The Week In Technology, Nov. 25-29, 2019*. Retrieved January 13, 2020, from Aviation Week: https://aviationweek.com/aerospace/week-technology-nov-25-29-2019

Warwick, G. (2020, February 14). *Airbus And Boeing Working On Next Steps For Fuel-saving Wake Surfing*. Retrieved February 18, 2020, from Aviation Week Intelligence Network: https://aviationweek.com/air-transport/airbus-boeing-working-next-steps-fuel-saving-wake-surfing

Warwick, G., & Norris, G. (2020, January 10). *Mild Hybridization A Potential Path To Near-Term Electrification Of Propulsion*. Retrieved June 12, 2020, from Aviation Week: https://aviationweek.com/air-transport/mild-hybridization-potential-path-near-term-electrification-propulsion

Welstead, J., & Felder, J. (2016). Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion. *54th AIAA Aerospace Sciences Meeting - AIAA SciTech Forum.* San Diego, California, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2016-1027

Wise Persons Group on the Future of the Single European Sky. (2019). *Report of the Wise Persons Group on the Future of the Single European Sky.*

WMO. (2019). *Statement on the State of the Global Climate in 2018. WMO-no. 1233.*

World Bank Group. (2019). *State and Trends of Carbon Pricing.*

World Economic Forum. (2020). *Joint Policy Proposal to Accelerate the Deployment of Sustainable Aviation Fuels in Europe.* World Economic Forum.

Yang, S., Page, M., & Smetak, E. (2018). Achievement of NASA New Aviation Horizons N+2 Goals with a Blended-Wing-Body X-Plane Designed for the Regional Jet and Single-Aisle Jet Markets. *2018 AIAA Aerospace Sciences Meeting.* Kissimmee, Florida, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2018-0521

Yin, F., Gangoli Rao, A., Bhat, A., & Chen, M. (2018). Performance assessment of a multi-fuel hybrid engine for future aircraft. *Aerospace Science and Technology, 77*, 217-227. doi:10.1016/j.ast.2018.03.005

Zamboni, J., Vos, R., Emeneth, M., & Schneegans, A. (2019). A Method for the Conceptual Design of Hybrid Electric Aircraft. *AIAA SciTech Forum.* San Diego, California, United States of America: American Institute of Aeronautics and Astronautics. doi:10.2514/6.2019-1587

Zheng, X., & Rutherford, D. (2020). *Fuel burn of new commercial jet aircraft: 1960 to 2019.* Washington D.C., United States of America: ICCT. Retrieved from https://theicct.org/sites/default/files/publications/Aircraft-fuel-burn-trends-sept2020.pdf

Zill, T., Iwanizki, M., Schmollgruber, P., Defoort, S., Döll, C., Hoogreef, M., . . . Lammen, W. (2020). An Overview of the Conceptual Design Studies of Hybrid Eletric Propulsion Air Vehicles in the Frame of Clean Sky 2 Large Passenger Aircraft. *Aerospace Europe Conference.* Bordeaux.

Zschocke, A., Scheuermann, S., & Ortner, J. (2012). High Biofuel Blends in Aviation. *ENER/C2/2012/ 420-1 Final Report*.

Appendix A Abbreviations

ACRONYM	DESCRIPTION
/A	With aromatics
A4E	Airlines for Europe
ACARE	Advisory Council for Aviation Research and Innovation in Europe
ACI	Airports Council International
ADS-B	Automatic Dependent Surveillance - Broadcast
AFUA	Advanced flexible use of airspace
AI	Artificial intelligence
AIAA	American Institute of Aeronautics and Astronautics
AMAN	Arrival management
ANSP	Air navigation service provider
APR	Aqueous phase reforming
APU	Auxiliary power unit
AR	Aspect ratio
ASD Europe	AeroSpace and Defense Industries Association of Europe
ASK	Available seat kilometre
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
ATCO	Air traffic control officer
ATJ	Alcohol to jet
ATM	Air traffic management
BLI	Boundary layer ingestion
BPR	Bypass ratio
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAEP	Committee on Aviation Environmental Protection
CANSO	Civil Air Navigation Services Organisation
CASK	Cost per ASK
CDM	Clean development mechanism
CER	Certified emission reduction
CfD	Contract for difference
CFRP	Carbon fibre reinforced plastics
CH	Catalytic hydrothermolysis
CNG	Carbon-neutral growth
CNG2020	Carbon-neutral growth at 2020 levels
CNS	Communication, navigation and surveillance
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent

ACRONYM	DESCRIPTION
CoP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CROR	Contra-rotating open rotor
DAC	Direct air capture
DG MOVE	Directorate-General for Mobility and Transport
DSHC	Direct sugars to hydrocarbons
EASA	European Union Aviation Safety Agency
ECA	European Court of Auditors
ECAC	European Civil Aviation Conference
EEA	European Environment Agency
EEX	European Energy Exchange
EFTA	European Free Trade Association
e-GPU	Electrical ground power unit
EIS	Entry into service
EJ	Exajoule (10^{18} Joules)
ER	Extended range
ERA	European Regions Airline Association
ETC	Energy Transitions Committee
ETD	Energy Taxation Directive
ETS	Emissions Trading Scheme
EU, EU+	European Union *Unless explicitly stated otherwise, to be interpreted as EU + UK + EFTA, also referred to as EU+.*
EU ATM MP	European Air Traffic Management Master Plan
EUA	European Union Allowance
EUAA	European Union Aviation Allowance
FAA	Federal Aviation Administration
FAB	Functional airspace block
FEGP	Fixed electrical ground power
FMS	Flight management system
FOG	Fats, oils and greases
FQD	Fuel Quality Directive
FRA	Free route airspace
FT	Fischer-Tropsch
FUA	Flexible use of airspace
GDP	Gross domestic product
GHG	Greenhouse gases
GMF	Global Market Forecast *Airbus industry forecast*
GPU	Ground power unit

ACRONYM	DESCRIPTION
GSE	Ground service equipment
H_2	Hydrogen
HDCJ	Hydrotreated depolymerised cellulosic jet
HEFA	Hydro-processed esters and fatty acids
HT	Horizontal tailplane
HTL	Hydrothermal liquefaction
HVO	Hydrotreated Vegetable Oil
IAG	International Airlines Group
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
ILUC	Indirect land use change
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	Intermediate stop operations
IUCN	International Union for Conservation of Nature
JI	Joint implementation
JU	Joint undertaking
KPI	Key performance indicator
LCA	Life-cycle assessment
LH_2	Liquid hydrogen
LHV	Lower heating value
LR	Long range
LTA	Large twin aisle *Aircraft class*
LULUCF	Land use, land use change and forestry
MEA	More electric aircraft
MFN	Mid-fuselage nacelle
MSR	Market Stability Reserve
MSW	Municipal solid waste
Mtoe	Mega-tonne oil equivalent
NASA	National Aeronautics and Space Administration
NAT	North-Atlantic tracks
NAT-OTS	North-Atlantic Organised Track System
NDC	Nationally determined contribution
NECP	National Energy & Climate Plan
neo	New engine option
NLR	Netherlands Aerospace Centre

ACRONYM	DESCRIPTION
nm	Nautical mile (1.842 kilometres)
NO_X	Oxides of nitrogen
NRDC	Natural Resources Defence Council
O&D	Origin and destination
OAG	Official Airlines Guide
ODP	Optimized Descent Profile *Formerly often referred to as Continuous Descent Operations (CDO) or Continuous Descent Approach (CDA)*
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
OPR	Overall pressure ratio
OTS	*See: NAT-OTS*
OWN	Over-wing nacelle
PCA	Pre-conditioned air
PCP	Pilot Common Project
PIP	Performance improvement package / programme
PPP	Public-private partnership
PtL	Power to liquid
R	Regional *Aircraft class*
R&D	Research and development
R&I	Research and innovation
RDT&E	Research, development, testing and evaluation
RED	Renewable Energy Directive
REDD	Reduced Emissions from Deforestation and forest Degradation
RLAT	Reduced lateral separation minima
RPK	Revenue passenger kilometre
RSB	Roundtable on Sustainable Biomaterials
RSS	Relaxed static stability
RTK	Revenue tonne kilometre
RVSM	Reduced vertical separation minima
S	Small *Aircraft class*
SA	Single aisle *Aircraft class*
SAF	Sustainable aviation fuel
SAK	Synthetic aromatic kerosene
SCR	Shortest constrained route
SEO	SEO Amsterdam Economics
SES	Single European Sky
SESAR	Single European Sky ATM Research

ACRONYM	DESCRIPTION
SESAR DM	SESAR Deployment Manager
SESAR JU	SESAR Joint Undertaking
SIP	Synthesised isoparaffins
SK	Synthetic kerosene
SKA	Synthetic kerosene with aromatics
SMTA	Small/medium twin aisle *Aircraft class*
SPK	Synthetic paraffinic kerosene
SUGAR	Subsonic Ultra-Green Aircraft Research
SWD	Staff Working Document
TBO	Trajectory Based Operations
TE	Trailing edge
TMA	Terminal control area / terminal manoeuvring area
TR	Technology readiness
TRL	Technology readiness level
UHBR	Ultra-high bypass ratio
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
VLA	Very large aircraft
VT	Vertical tailplane
WTP	Well to pump
WTWa	Well to wake
WWF	Worldwide Wildlife Fund
XMAN	Cross-border arrival management

Appendix B Consulted parties

Throughout the process of developing Destination 2050, numerous industry and research parties provided valuable input in interviews and workshops.

From Airports Council International – Europe (ACI-EUROPE)

- Avinor
- Groupe ADP
- Heathrow Airport
- Manchester Airports Group
- Royal Schiphol Group

From Airlines for Europe (A4E)

- Air France
- British Airways
- easyJet
- International Airlines Group
- KLM – Royal Dutch Airlines

From European Regional Airlines Association (ERA)

- Air Nostrum
- Euroairlines
- Widerøe

From AeroSpace and Defence Industries Association of Europe (ASD)

- Airbus
- ATR
- Avio Aero
- DLR / German Aerospace Center
- Honeywell
- Leonardo
- MTU Aero Engines
- Rolls-Royce
- Safran
- Sustainable Aviation UK

From Civil Air Navigation Services Organisation – Europe (CANSO Europe)

- AustroControl
- DFS
- ENAIRE
- IAA
- NATS
- Skeyes
- Skyguide

Other

- International Council on Clean Transportation
- Neste
- SkyNRG

Appendix C Class-averaged improvement potential of upcoming aircraft

Section 3.2 discusses the potential fuel efficiency improvements of upcoming aircraft. These aircraft are types that have entered service recently (or are about to do so), but have not fully materialised in the European fleet. In some cases, upcoming aircraft form a direct replacement of legacy aircraft and are replaced one-to-one. For legacy aircraft types without a direct replacement, a class-averaged improvement potential is used. This appendix details how that value – as presented in Table 6 – is computed for the various classes.

Table 5 specifies various upcoming aircraft in the regional, single aisle, small/medium twin aisle and large twin aisle classes. Table 35 up to and including Table 49 repeat the relevant data, extended with the improvement per flight and class-averaged values. These are subsequently used in Table 6 in Section 3.2.

Table 46: Improvement potential and entry into service of upcoming aircraft types in the regional class

Upcoming			Reference		Improvement	
Type	***Subtype***	***EIS***	***Type***	***EIS***	***Per ASK***	***Per flight***
ATR72		2011	CRJ700	2001	47.7%	46.3%
Embraer E2	E175-E2	2021	E175	2005	16%	10.7%
Embraer E2	E190-E2	2018	E190	2005	17.3%	17.3%
Entire class	***Average***	***2017***		***2004***		***24.8%***

Given the much larger share of Boeing 737NG aircraft with winglets than without, a reference model with winglets is assumed. Following Table 5, the Boeing 737MAX then realises a 14% improvement (assumed per flight, following footnote 28 on page 29) over late Boeing 737NG models, which entered into service in 2004.

Table 47: Improvement potential and entry into service of upcoming aircraft types in the single aisle class

Upcoming			Reference		Improvement	
Type	***Subtype***	***EIS***	***Type***	***EIS***	***Per ASK***	***Per flight***
A220	A220-100	2016	E190	2005	20%	6.8%
A220	A220-300	2016	E190	2005	40%	6.8%
Embraer E2	E195-E2	2021	E195	2006	25.4%	5.4%
A320neo	A319neo	2019	A319	1996	19%	16.4%
A320neo	A320neo	2016	A320	1988	20%	15.0%
A320neo	A321neo	2016	A321	1994	23%	13.9%
A320neo	A321neoLR	2018	757-200	1983	30%	27.0%
A320neo	A321neoXLR	2023	757-200	1983	30%	30.0%
B737MAX	B737MAX7	2021	737 NG	2004		14%
B737MAX	B737MAX8	2017				
B737MAX	B737MAX9	2018				
B737MAX	B737MAX10	2020				
Entire class	***Average***	***2018***		***2003***		***14.8%***

Table 48: Improvement potential and entry into service of upcoming aircraft types in the small/medium twin aisle class

Upcoming			Reference		Improvement	
Type	*Subtype*	*EIS*	*Type*	*EIS*	*Per ASK*	*Per flight*
A330neo	A330-800	2020	A330-200	1998	14.2%	12.6%
A330neo	A330-900	2018	A330-300	1994	14%	12.6%
B787	B787-8	2011	767-300ER	1988	20%	27.3%
B787	B787-9	2014	767-400ER (est.)	2000	20%	22.0%
B787	B787-10	2018			25%	13.5%
Entire class	***Average***	***2016***		***1996***	***18.6%***	***17.6%***

Table 49: Improvement potential and entry into service of upcoming aircraft types in the large twin aisle class

Upcoming			Reference		Improvement	
Type	*Subtype*	*EIS*	*Type*	*EIS*	*Per ASK*	*Per flight*
A350	A350-900	2015	777-200ER	1995	30%	25.7%
A350	A350-1000	2018	777-300ER	2004	25%	22.5%
B777X	B777-8	2023	777-200ER	1995	21.7%	27.0%
B777X	B777-8	2023	777-200LR	2006	20.8%	8.8%
B777X	B777-9	2021	777-300ER	2004	20%	11.8%
Entire class	***Average***	***2020***		***2001***	***23.5%***	***19.2%***

Appendix D Future aircraft concept studies

This appendix provides an overview of future concept aircraft studies, ranging from academic efforts to conceptual studies presented by manufacturers. These studies show which technologies have been considered promising for integration into an aircraft concept. As the fuel efficiency improvements published for such concepts are sometimes criticised as “an unrealistically optimistic view of technological potential” (Graham, Hall, & Vera Morales, 2014, p. 34), this appendix does not include such estimates.

The remainder of this appendix presents the results obtained from literature. Fitting the split made in Section 3.3, the results distinguish between studies looking at aircraft powered by drop-in fuels (Appendix D.1) and non-drop-in fuels (Appendix D.2).

Appendix D.1 Aircraft with drop-in fuels

Tables 50 up to and including 53 show concept studies of future aircraft using drop-in fuels, starting with the regional class before moving on to the single aisle, small/medium twin aisle and large twin aisle classes.

Table 50: Future aircraft concept studies with drop-in fuels in the regional class showing main technologies

Name	Technology	Source(s)
T+W98-DD	Two under- (T+W) or over-wing (OWN) direct-drive turbofans, BPR 9.7, OPR 35. Hybrid laminar flow control (wing, HT, VT, nacelles), riblets, stitched resin-infused composites, adaptive compliant TE, winglets (T+W)	Nickol & Haller (2016)
OWN98-DD		

Table 51: Future aircraft concept studies with drop-in fuels in the single aisle class showing main technologies

Name	Technology	Source(s)
CENTRELINE		CENTRELINE (2017)
CS SMR	Tube and wing with two CROR-engines between H-tails and natural laminar flow wing.	Lafage, Aubry & Junior (2016)
D8.1	Double-bubble lifting aluminium fuselage with twin T-tails and three flush-mounted direct-drive turbofans with BPR 6 and centerbody BLI. Straight wing with AR 17.3 (D8.1) or strut-braced wing with AR 25.9 (SD8.1). No LE slats. *Minimal technology insertion*.	MIT (2010) and Drela (2010)
SD8.1		
D8.5	Double-bubble lifting composite fuselage with twin T-tails and two high-efficiency BLI fans (BPR 20) with advanced combustor, distortion tolerant fan, variable area nozzle and advanced engine materials. Natural laminar flow, reduced secondary structure weight, advanced structural materials, health and usage monitoring, active load alleviation. AR 24.85 (D8.5) or 33.92 with strut-braced wing (SD8.5). Operational modifications w.r.t. cruise Mach number and altitude.	
SD8.5		
DZYNE Ascent 1000	Advanced composite blended wing body (w/ aerodynamic and structural advantages) with two upper-fuselage geared turbofans (BPR 9) and hybrid-electric wake filling fans, reduced-size landing gear, multifunctional wing movables (incl. load alleviation and stability augmentation)	Yang, Page & Smetak (2018)
DZYNE BWB-165		
ESAero ECO-150	Two turbogenerators and 16 motor driven fans (all possibly superconducting) in (relatively high AR) split wing with V-tail	Madavan (2016)

Name	Technology	Source(s)
SELECT	Two three shaft turbofans, ultra-high BPR 18, cooled cooling air turbine, shape memory alloy nozzle, laminar flow, ultrahigh performance fibre	Northrop Grumman (2010)
Refined SUGAR	Two under-wing two-spool turbofans, BPR 9.2, OPR 66 with a.o. an advanced 3D aero composite fan ultra-high pressure recovery compressor, advanced low-emissions combustor, integrated thrust reverser/variable fan nozzle, CMC turbine blades/vanes, next-generation component aerodynamics and nacelle technology, improved shaft material. Natural laminar flow wing, fuselage riblets, multi-functional structures, gapless movables, c.g. control, RSS, advanced composites. *Incremental development of existing technologies.*	Bradley & Droney (2011) and Welstead & Felder (2016)
SUGAR High	High-wing high-AR (23.1) truss-braced wing (High) or hybrid-wing-body (Ray) with two under-wing (High) or upper-fuselage (Ray) two-spool turbofans, BPR 13, OPR 59, improved w.r.t. Refined SUGAR. Natural and active laminar flow wing and VT (High), fuselage and wing riblets, multi-functional structures, gapless movables, c.g. control, RSS, advanced composites, advanced supercritical airfoil, adaptive camber, spanload control, low drag nacelle and strut.	Bradley & Droney (2011)
SUGAR Ray		
STARC-ABL	Two under-wing turbofans (BPR 6.4, OPR 58) and generators with a rear fuselage axisymmetrical BLI-fan and propulsor (OPR 1.25). Updated concept (2019) with smaller distributed rear fuselage BLI fans.	Welstead & Felder (2016), Warwick (2019a) and Madavan (2016)
T+W160-GTF	Two under- (T+W) or over-wing (OWN) 2nd gen. geared turbofans, ultra-high BPR 23.45, OPR 35. Hybrid laminar flow control (wing, HT, VT, nacelles), riblets, stitched resin-infused composites, adaptive compliant TE, winglets (T+W).	Nickol & Haller (2016)
OWN160-GTF		
T+W216	Tube and wing (T+W) or hybrid-wing-body (HWB) with two under wing (T+W) or upper-fuselage (HWB) 2nd gen. geared turbofans, ultra-high BPR 21.75, OPR 50. Hybrid laminar flow control (wing, HT [T+W only], VT, nacelles), riblets, stitched resin-infused composites, adaptive compliant TE (T+W), winglets (T+W)	Nickol & Haller (2016)
HWB216		

Table 52: Future aircraft concept studies with drop-in fuels in the small/medium twin aisle class showing main technologies

Name	Technology	Source(s)
2035R	Tube and wing (AR 12.4 – 12.6) with two advanced geared turbo fans (BPR 18) and aft-fuselage propulsive fan using BLI (PFC), fully electric subsystems (fuel-cell based APU), advanced wing (AR 12.6), shock contour bumps, fuselage riblets, omnidirectional carbon fibres, advanced bonding techniques.	DisPURSAL (Outcome, n.d.), Isikveren et al. (2015) and Bijewitz, Seitz, Hornung & Isikveren (2017)
PFC		
DMFC	Hybrid-wing-body (BPR 6.9) with six upper-fuselage mounted distributed fans (BPR 20) using BLI, fully electric subsystems (fuel-cell based APU), advanced wing (AR 12.6), shock contour bumps, fuselage riblets, omnidirectional carbon fibres, advanced bonding techniques.	
CS LR	Tube and wing with two advanced three-shaft turbofan engines, new FMS functions.	Lafage, Aubry & Junior (2016)
Flying V	“Tailless, V-shaped flying wing with two cylindrical pressurized cabins placed in the wing leading edge” with two over-wing turbofans.	Faggiano, Vos, Baan & van Dijk (2017) and TU Delft (Flying-V, n.d.)
HWB301-DD	Hybrid-wing-body with two upper-fuselage (HWB) or tube and wing with mid-fuselage over-wing (MFN) direct-drive (-DD, BPR 12.85) or 2nd gen. geared turbofan (-GTF, BPR 17.65), OPR 60. Hybrid laminar	Nickol & Haller (2016)
HWB301-GTF		

Name	Technology	Source(s)
MFN301-GTF	flow control (wing, HT [MFN only] VT, nacelles), riblets, stitched resin-infused composites.	
T+W301-DD	Tube and wing with two under wing direct-drive (-DD, BPR 14.65) or 2nd gen. geared turbofan (-GTF, BPR 20.6), OPR 60. Hybrid laminar flow control (wing, HT, VT, nacelles), riblets, stitched resin-infused composites, adaptive compliant TE.	
T+W301-GTF		
N3-X	Hybrid-wing-body with two highly efficient turbo-electric generators (BPR 29, OPR 84) and distributed propulsion using superconducting motors/generations and BLI.	Felder (2014) and Berton & Haller (2014)

Table 53: Future aircraft concept studies with drop-in fuels in the large twin aisle class showing main technologies

Name	Technology	Source(s)
H3.2	Hybrid-wing-body with four advanced ultra-high BPR fans, distributed propulsion, variable area nozzle, thrust vectoring, advanced combustor and BLI. Lifting body with leading edge camber, no LE movables, advanced materials, active load alleviation and health and usage monitoring. Adjusted cruise altitude.	MIT (2010)
HWB400	Hybrid-wing-body with three upper-fuselage 2nd gen. geared turbofans, ultra-high BPR 17.6, OPR 60. Hybrid laminar flow control (wing, VT, nacelles), riblets, stitched resin-infused composites.	Nickol & Haller (2016), Airliner World (2009)
T+W400	Tube and wing with four under wing 2nd gen. geared turbofans, ultra-high BPR 21.75, OPR 50. Hybrid laminar flow control (wing, HT, VT, nacelles), riblets, stitched resin-infused composites, adaptive compliant TE, winglets.	

Appendix D.2 Aircraft with non-drop-in fuels

Tables 54 up to and including 56 show concept studies of future aircraft using non-drop-in fuels, starting with the regional class before moving on to the single aisle, small/medium twin aisle and large twin aisle classes.

Table 54: Future aircraft concept studies with non-drop-in fuels in the regional class showing main technologies

Name	Technology	Source(s)
Airbus ZEROe Turboprop	Hydrogen hybrid turboprop engines using liquid hydrogen, stored in the rear of the fuselage.	Airbus (2020d; 2020c)
PEGASUS	Hybrid-electric (500Wh/kg) with high-wing and two turbine-electric motors at wing tips, two underwing electric motors and one aft-fuselage motor utilizing BLI, natural laminar flow, advanced composites and lightweight electrical systems and cabin furnishings	Antcliff & Capristan (2017) and Antcliff et al. (2016)
S1	Hybrid-electric with high-wing and two underwing parallel motors (conventional configuration), 1000Wh/kg (2948kg).	Voskuijl, van Bogaert & Rao (2017) and Veldhuis & Voskuijl (2016)
VoltAir	Fully electric (Li-air, 1000Wh/kg, approx. 10.000kg) with high-AR, natural laminar flow wings, winglets, low slenderness ratio fuselage, BLI and double counter-rotating aft-mounted fans.	Stückl, van Toor & Lobentanzer (2012)
Z1 – Parallel	Hybrid-electric (Li-air, 750Wh/kg) high-wing and two under-wing thermal engines and zero (Parallel), four (Parallel/Series) or ten (Series) under-wing electric motors. Savings for 500Wh/kg limited to ± 5%.	Zamboni, Vos, Emeneth & Schneegans (2019)
Z1 – Parallel / Series		
Z1 – Series		

Table 55: Future aircraft concept studies with non-drop-in fuels in the single aisle class showing main technologies

Name	Technology	Source(s)
A320neo-HEP	Parallel hybrid-electric (2025: 500Wh/kg / 2045: 1000 Wh/kg), downscaled turbofan (90%), electric taxiing, electrical architecture of non-propulsive systems, fuel cell implementation (2025: 0.5kW/kg / 2045: 1kW/kg), photovoltaic exterior (2025: 0.5kW/kg / 2045: 0.9kW/kg)	Lammen & Vankan (2019)
Airbus ZEROe Turbofan	Hydrogen hybrid turbofan engines using liquid hydrogen, stored in the rear of the fuselage (Turbofan) or underneath the wings (Blended-Wing Body). Blended-Wing Body also utilises distributed propulsion.	Airbus (2020d; 2020c)
Airbus ZEROe Blended-Wing Body		
Bauhaus FBH	1500 Wh/kg (8.765kg) interchangeable batteries	Pornet, Kaiser, Isikveren & Hornung (2014)
Bauhaus HER	Hybrid-electric (940Wh/kg) tube-and-wing with two conventional underwing engines and an electric tail-motor. 20% improvement at 1300nm with 1300Wh/kg.	Bauhaus Luftfahrt (2017)
Bauhaus HET	Hybrid-electric (1000-1500Wh/kg, 11.740kg) tube-and-wing with two underwing advanced geared turbofans and two underwing electrical fans	Pornet & Isikveren (2015)
Ce-Liner	Fully electric (2000Wh/kg, “aggressive assumptions”) open box-wing (‘C-wing’) with two aft-fuselage mounted ducted fans powered by high-temperature superconducting motors, self-trimming wing with active poly-morphing capability, continuous GFRP window-belt (rather than individual cut-outs), electric systems architecture. Batteries in LD3-containers to enable quick turn-around.	Hornung, Isikveren, Cole & Sizmann (2013)
MIPH	Mechanically integrated parallel hybrid-electric (1000Wh/kg, 5.300kg) turbofan	Seitz, Nickl, Stroh & Vratny (2018)
S2	Parallel hybrid-electric propulsion system (600Wh/kg) as ‘retrofit’ on A320, scaling down turboshaft engines to 90% / 80%	Ang, Gangoli Rao, Kanakis & Lammen (2019) / Veldhuis & Voskuijl (2016)
SUGAR Electric Eel	Hybrid-electric Super Refined SUGAR (Table 51)	Bradley & Droney (2011; 2015) and Wall & Meyer (2017)
SUGAR Volt	Hybrid-electric (9405kg battery) high-wing high-AR (23.1) truss-braced wing with two under-wing thermal electric engines, BPR 18 improved w.r.t. Refined SUGAR. Natural and active laminar flow wing and VT, fuselage and wing riblets, multi-functional structures, gapless movables, c.g. control, RSS, advanced composites, advanced supercritical airfoil, adaptive camber, spanload control, low drag nacelle and strut. *Hybrid-electric SUGAR High*	
SUGAR Sting Ray	*Hybrid-electric SUGAR Ray*	
ULTIMATE	Advanced high-AR tube-and-wing with two rear-fuselage mounted open-rotor engines and T-tail, using active flow control, fuselage riblets, natural laminar flow nacelle, hybrid laminar flow wing and tail, manoeuvre and gust load alleviation, foldable wingtip, variable camber, CFRP structures, fly-by-light, low-weight cabin, all electric (fuel cell powered) subsystems, advanced propulsion component and material efficiencies	Heinemann, et al. (2017)

Table 56: Future aircraft concept studies with non-drop-in fuels in the small/medium twin-aisle class showing main technologies

Name	Technology	Source(s)
AHEAD (LNG)	Multi-fuel blended wing body with contra-rotating fans using BLI, dual combustion chambers using cryogenic fuel, flameless combustion.	Gangoli Rao, Yin & van Buijtenen (2014), Grewe et al. (2016) and Yin, Gangoli Rao, Bhat & Chen (2018)
AHEAD (LH_2)		
ULTIMATE	Advanced tube-and-wing with two underwing engines, using active flow control, fuselage riblets, natural laminar flow nacelle, hybrid laminar flow wing and tail, manoeuvre and gust load alleviation, variable camber, CFRP structures, fly-by-light, low-weight cabin, all electric (fuel cell powered) subsystems, advanced propulsion component and material efficiencies	Heinemann, et al. (2017)

Appendix E Comparison to Waypoint 2050

Stressing the relevance of the challenge treated in this study, numerous other reports have investigated decarbonisation of aviation as well. This section briefly compares the results presented in this work to Waypoint 2050-report published by ATAG (2020b), to clarify any potential differences and highlight similarities.

Approach

Published in September 2020, Waypoint 2050 (ATAG, 2020, p. 4) presents a view of "how the industry can accelerate working together to contribute to the world's climate action mission". Much like Destination 2050, it looks at improvements in aircraft and engine technology[174], operations and ATM[175], the use of sustainable aviation fuel and economic measures[176]. Both reports focus on CO_2 emissions from flight operations. Waypoint 2050 takes global aircraft emissions as its scope, whereas this study was limited to flights within and departing from the EU+ region (further specified in Section 1.4).

Waypoint 2050 is focused on ways to meeting the current industry goal of reducing 2050 CO_2 emissions by 50% compared to levels in 2005. The Waypoint 2050 analysis suggests global aviation industry could be in a position to reach net zero emissions by 2060/2065, without the significant use of economic measures. It notes that some regions and individual companies could meet net zero earlier, but some parts of the world may need a little longer to reach that point. Due to the leading role of the European Union in tackling climate change as presented in the Green Deal, it is most likely that Europe reaches net zero before other regions. Destination 2050 is focused on assessing the feasibility of net zero carbon emissions from European aviation in 2050. The higher ambition level presented in this roadmap is aligned with the ATAG objective to encourage "all parts of the industry to focus on how they can play a role in accelerating a decarbonisation pathway".

Comparison between pathways

The anticipated contributions of the different pillars are similar to Waypoint 2050's consolidated scenario 3, with the exception of an explicit demand effect forecast by Destination 2050. Focussed on flights departing from the EU+ region, there is most agreement with Scenario 2 – although with a larger (but limited) reliance on economic measures (or: "out-of-sector carbon reduction measures").

Reference scenario and traffic forecast

Also published after the outbreak of the COVID-19 pandemic, the Waypoint 2050 forecast shows a 1.9% compound annual growth rate up to 2050 for the European region in terms of revenue passenger kilometres; comparable to the 2.0% growth rate (in terms of passengers) modelled in Destination 2050.

Improvements in aircraft and engine technology

Waypoint 2050 has modelled multiple technology evolution scenarios, ranging from a baseline (that only includes aircraft types indicated in this study as 'upcoming', described in Section 3.2 of this report) to an aspirational technology scenario. This study balances these different visions, including both currently in production or recently announced upcoming aircraft, as well as future tube and wing aircraft ("evolutionary technology"), such as the strut-braced wing or blended wing body; and open-rotor technology ("new configurations"), battery systems in lower seat classes and hybridisation ("towards electrification") and focused used of hydrogen-powered aircraft ("aspirational technology"). Anticipated entry into service (indicated in Waypoint 2050 on page 48) is consistent within margins of

[174] Grouped as "Innovating with aircraft technology".
[175] "Improvements in operations and infrastructure".
[176] "Investing in out-of-sector carbon reduction measures (offsetting)".

plus or minus 5 years, but there may be differences in fleet integration (roll out of new models into the fleet) due to aircraft size and ambition level following from aforementioned regional context.

Improvements in operations and ATM

Improvements in operations and ATM were modelled in more detail in Destination 2050, as more detailed information was available for the region studied, compared with a global analysis. The 5 to 6% improvement potential noted here fits between the 'mid' and 'high' improvement scenarios, leading to total CO_2 emissions reductions of 3 to 6% for 2050. Also in terms of measures modelled, there is much overlap between Waypoint 2050 and Destination 2050 and ATAG, too, notes operational and ATM-related improvement can make a notable benefit in the shorter term. The Waypoint 2050 analysis also considered the incremental airline efficiency improvements from load factor as a sustainability measure, whereas Destination 2050 includes it in both the reference and sustainability scenarios.

Sustainable aviation fuels

Waypoint 2050 has modelled four SAF scenarios, one baseline and three backcasting scenarios. The backcasting scenarios show similar percentage ranging between 77-86% which is in line with the 83% share of SAF modelled in Destination 2050.

Economic measures

Waypoint 2050 identified how much economic measures are needed to reach the 50% CO_2 emissions reduction goal after aircraft technology, operational measures and the use of sustainable aviation fuels have been implemented. It notes that depending on the cost differential between SAF and the cost of offsetting, the use of SAF can be partly replaced by out-of-sector carbon reduction. This might initially take the form of offsetting, but towards 2050 will be based on carbon removal, using natural carbon sinks or dedicated technologies. The report does not specify which part of emission reductions can be achieved by offsetting and carbon removal over the longer term: modelling such economic forecasts at a global level and then individually for nearly 200 countries brings with it significant challenges which were outside of the scope of Waypoint 2050. Destination 2050 makes an estimation of SAF supply until 2050. The remainder of CO2 emissions are covered by economic measures to reach net zero in 2050.

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Postal address
PO Box 90592
1006 BM Amsterdam, The Netherlands
e) info@nlr.nl **i)** www.nlr.org

NLR Amsterdam
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113

NLR Marknesse
Voorsterweg 31
8316 PR Marknesse, The Netherlands
p) +31 88 511 4444