THE PRICE OF NET ZERO

AVIATION INVESTMENTS TOWARDS DESTINATION 2050

RESEARCH REPORT

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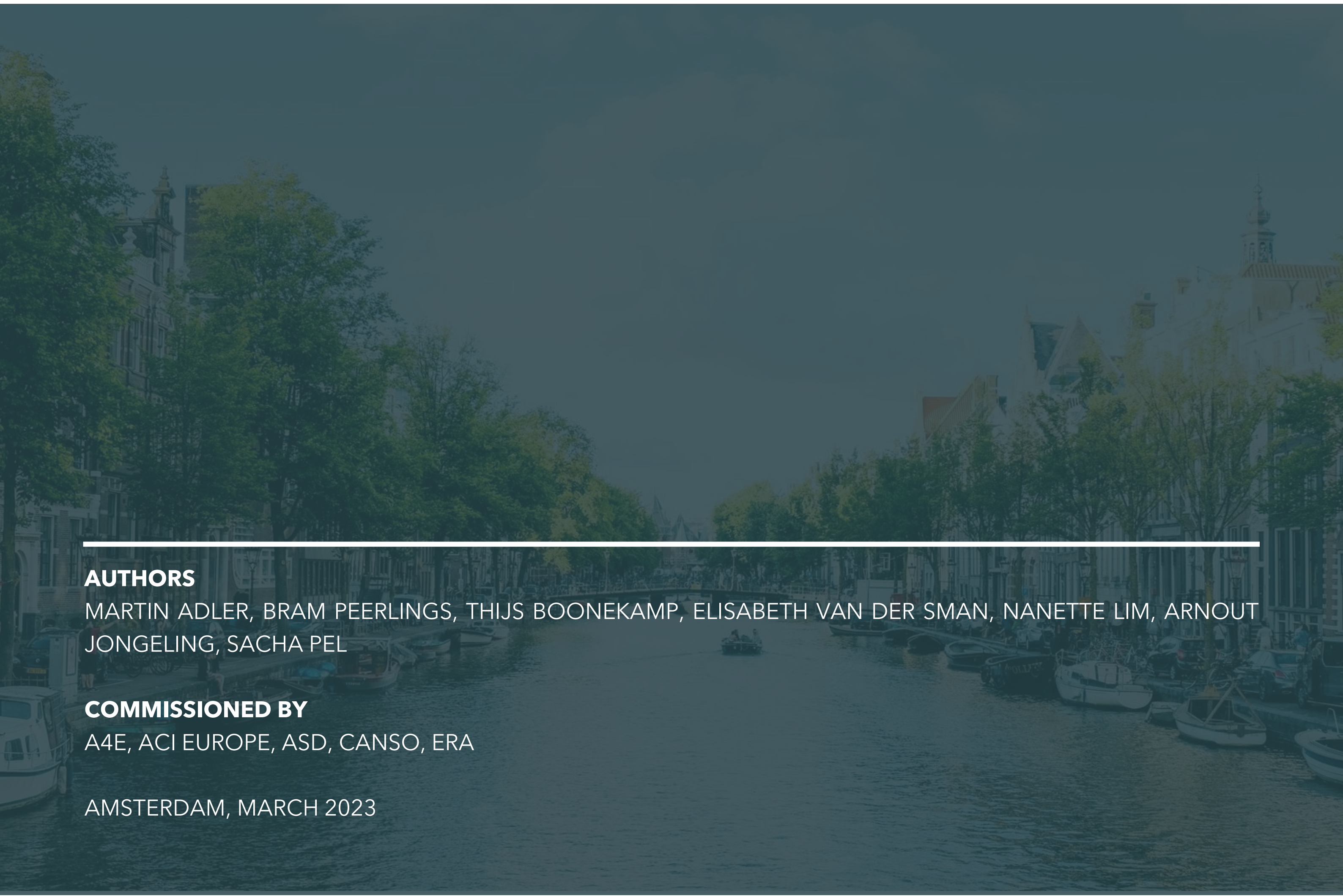

AUTHORS

MARTIN ADLER, BRAM PEERLINGS, THIJS BOONEKAMP, ELISABETH VAN DER SMAN, NANETTE LIM, ARNOUT JONGELING, SACHA PEL

COMMISSIONED BY

A4E, ACI EUROPE, ASD, CANSO, ERA

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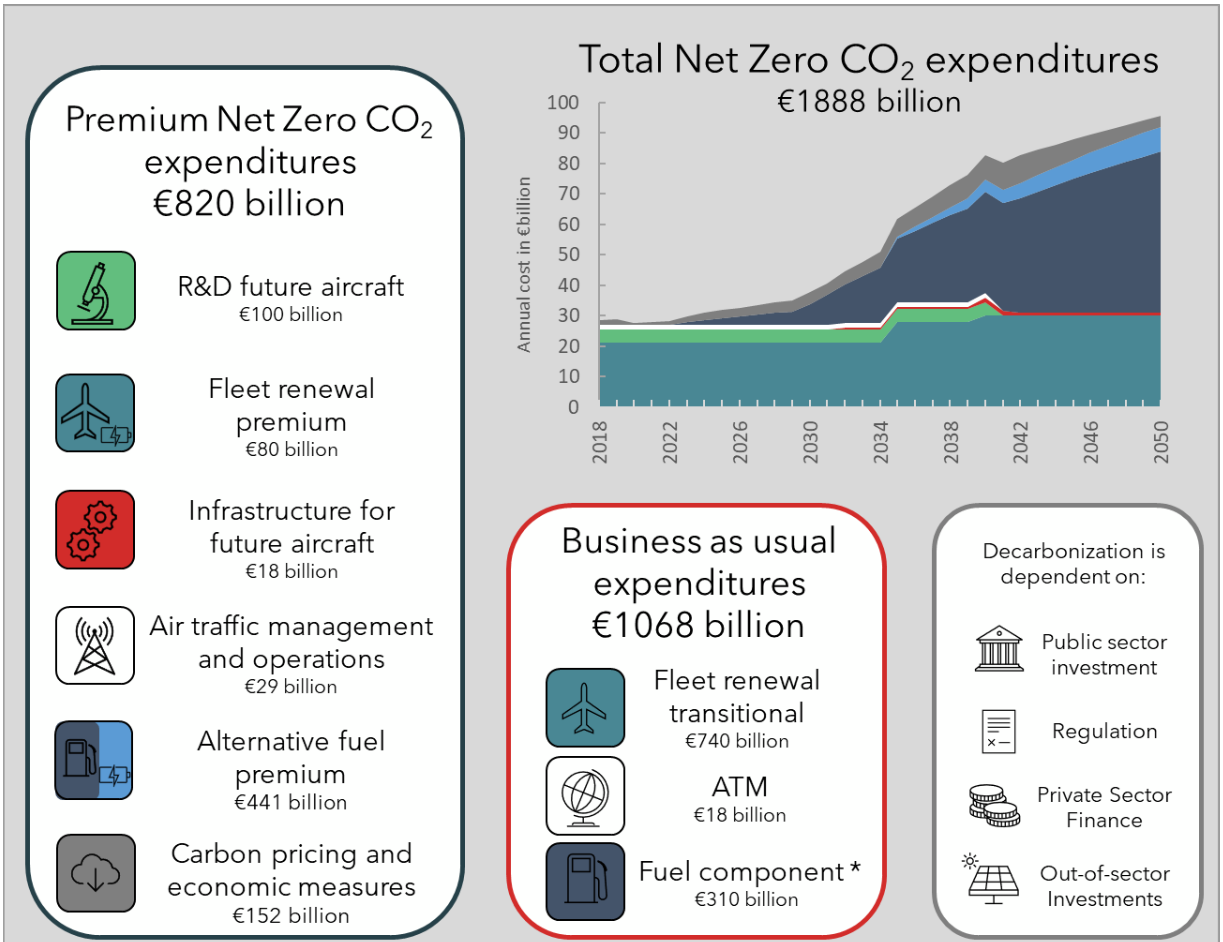
Executive Summary: The Price of Net Zero

Expenditures needed to reach net zero aircraft emissions for European aviation by 2050 require considerable additional efforts compared to business as usual. The premiums paid towards new aircraft technologies, air traffic management, sustainable aviation fuels and negative emissions amount to €820 billion over the 32-year period. A successful, on-time decarbonization therefore requires sufficient access to finance and public investments, which in turn depend on supportive legislation.

In this study, SEO Amsterdam Economics (SEO) and Royal Netherlands Aerospace Centre (NLR) calculate the expenditures necessary to achieve net zero aircraft CO_2 emissions along the Destination 2050 pathway. The investment needs and associated cost are identified for the four main mechanisms of emissions reduction: technology, air traffic management (ATM) and operations, sustainable aviation fuels (SAF) and economic measures.

Figure S.1 Destination 2050 expenditures

European Aviation Net Zero CO_2 Expenditures (2018 – 2050)



*The fuel component in the business as usual expenditures measure the share of kerosene fuel expenditures replaced by alternative fuels. The total alternative fuel expenditure is then €441billion + €310 billion = €751 billion. The kerosene fuel expenditures that are not replaced in the 32-year period are not part of the net zero expenditures and cost an additional €730 billion.

The total price premium towards achieving net zero, i.e. the sum of expenditures entirely towards sustainability is €820 billion, see Figure S.1. This sum is composed of:

- €441 billion towards drop-in sustainable aviation fuels (54%),
- €152 billion for carbon pricing and economic measures (19%),
- €100 billion future aircraft research and development (12%),
- €80 billion towards fleet renewal with advanced, ultra-efficient future aircraft (10%),
- €29 billion for realising efficiency improvements in air traffic management (ATM) and ground operations at airports (3%),
- €18 billion for realising the necessary infrastructure to support alternatively fuelled future aircraft (2%).

As this study is limited to expenditures with a direct relation to aircraft carbon emissions, expenditures related to (e.g.) maintenance, repair and overhaul, personnel costs, and other fees and charges are considered out of scope and are as such not included in the presented estimates.

Total expenditures and business as usual

The total expenditures towards Destination 2050, the sum of business as usual (BAU) expenditures and premium expenditures are €1.9 trillion over the 32-year period. The BAU expenditures, which do include the cost of kerosene replaced by SAF (€310 billion) but do not include the cost for the continued use of fossil kerosene (an additional €730 billion) are required for the hypothetical continued operation without sustainability measures. The BAU expenditures amount to €1.1 trillion. The majority (70%) of this is due to ongoing fleet renewal towards newer airplanes. Clearly, part of these fleet renewal expenditures not only bring environmental benefits, but enable operational cost savings. BAU expenditures are relatively constant over time with approximately €33.3 billion per year. This can be compared to an average annual premium expenditure of €25.6 billion. The latter notably increase over time, in particular due to increased use of SAF. Further variation in expenditures over time is mainly caused by increasing fleet renewal cost from 2040 due to more expensive future aircraft, and the fact that investments in future aircraft R&D, airspace and ATM improvements end by that same year. The combined average annual expenditures towards net zero of €59 billion can be contrasted to European airline revenues, estimated at €145 billion in 2018.[1]

Comparison to out-of-sector decarbonization

Financing in-sector sustainability measures yields substantially lower costs than realizing the same emission savings through out-of-sector carbon reduction. The out-of-sector scenario has been aligned with the reference (emissions) scenario presented in Destination 2050 (labelled a 'hypothetical no-action growth scenario') in terms of traffic development and baseline emissions. The difference between the baseline emissions and the net emissions is the emission reduction that in the out-of-sector scenario is solely realised through carbon pricing (i.e., carbon compensation and/or negative emissions projects). Realizing the same emission savings out-of-sector amounts to €3012 billion. It is therefore essential to reach a successful on-time transition to sustainable measures within the aviation sector. This transition is dependent on access to finance from the private sector and public investments, both influenced by legislation.

Source of finance

There are four primary sources of capital for the aviation sector: the private sector, the public sector, ticket prices and profit margins. Since the latter are historically low due to high levels of competition and compounded by recent crises, the absorption capacity by the sector, in particular that of European airlines and hubs is expected to be low. A lack of access to finance might compound the competitive distortion, lack of level playing field and carbon leakage

[1] EU GDP share (20.7%) of global airline revenues €700 billion. See https://www.iata.org/en/pressroom/pr/2017-12-05-01/

found in a recent study on the consequences of Fit for 55 on aviation (Adler et al., 2022). The explorative assessment of public sector investment aid contained within this study finds a wide variety of suitable state and supranational programs but the planning horizons are shorter than that of Destination 2050. Access to finance for the CO_2 net zero transition will be vital when capital reserves are insufficient to make large upfront payments for new aircraft, infrastructure and other deployment of decarbonisation technologies such as sustainable aviation fuels. Having access to 'green' finance following the Taxonomy Regulation is therefore of key importance, particularly for the measures crucial to achieving the Destination 2050 objectives.

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1 Introduction

Joint, coordinated and decisive action is required for the European aviation sector to achieve net zero CO_2 emissions by 2050. This study presents the expenditures needs to implement Destination 2050, which outlines a pathway to net zero from all flights within and departing from the EU. We analyse the expenditures in terms of timepoint, source, place in the EU Taxonomy and carbon abatement efficiency.

In 2021, European representatives of the aviation sector launched a sustainability initiative, called "Destination 2050". The goal of this initiative is net zero CO_2 emissions from all flights within and departing from the EU+ in 2050.[2] The related Destination 2050 report provides a decarbonization pathway to achieve this goal (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The pathway combines four types of measures or pillars: technological improvements, improved operations, drop-in sustainable aviation fuels and economic measures. Box 1.1 reiterates the key outcomes; Appendix A discusses in greater detail the contributions of the different pillars.

Box 1.1 Key outcomes of Destination 2050

Based on an extensive literature review, expert workshops and dedicated modelling, the Destination 2050 study concluded that net zero CO_2 emissions from all flights within and departing from the EU+ region can be achieved by 2050 through joint, coordinated and decisive industry and government efforts. It was found that no 'silver bullet' exists: improvements in aircraft and engine technology, in air traffic management and operations, the use of sustainable aviation fuels and economic measures were all found to be necessary to meet the target, to which the European aviation industry has committed. Similarly, the report stressed the pathway it described is *a* pathway, rather than *the* pathway. Indeed, as technologies and contexts evolve, adjustments might be necessary or beneficial.

Implementing the proposed measures were anticipated to make 2019 the peak year in absolute CO_2 emissions from European aviation, surpassing the industry target of carbon neutral growth from 2020 onwards. In the year 2030, net CO_2 emissions were estimated to be reduced by 45% compared to the hypothetical reference scenario. For intra-EU+ flights specifically, it was found that 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.

The Destination 2050 report concluded that the measures leading to net zero CO_2 emissions from European aviation can be realised through collective policies and actions by governments and industry. Both should work towards a global commitment to a net zero carbon future for aviation, to avoid differentiated policies, carbon leakage and transfer of activity. Moreover, Europe should maintain and evolve its leading position in sustainable aviation. The industry should do so by, among others, developing and bringing into operation more fuel-efficient and/or alternatively propelled aircraft, implementing the latest ATM and flight planning innovations, scaling up drop-in SAF production and uptake and compensating remaining emissions through carbon removal projects. Governments should then support those investments, ensure sufficient availability of renewable energy at affordable cost and contribute to optimising ATM, in particularly by implementing the Single European Sky.

The European aviation sector enables about 700 million passenger movements annually, surpassing 1 billion by 2050 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). This comes at a cost of up about 171 million

[2] EU+ represents the European Union (EU), the United Kingdom (UK) and the European Free Trade Association (EFTA).

tonnes of CO_2 emissions, or about 5.6% of European greenhouse gas emissions (UNFCC, n.d.; EASA, EEA, & EUROCONTROL, 2019). Aviation is crucial to people's lives and for the European economy. Hence, decarbonization needs to be a high priority, since the societal cost of inaction are unfathomable (IPCC, 2022).

To successfully realize the objective set out in Destination 2050, the aforementioned study identifies key actions that industry and governments need to take. Many of these actions require investment, such as in the development of new technology and commercialization of sustainable aviation fuels. This study complements the Destination 2050 study by estimating the necessary levels of expenditure. Moreover, this present study identifies to what extent these expenditures are public or private, when they occur and how they classify according to the EU Taxonomy (based on Steer, 2021). Furthermore, financial mechanisms that might be used to realize these expenditures are identified.

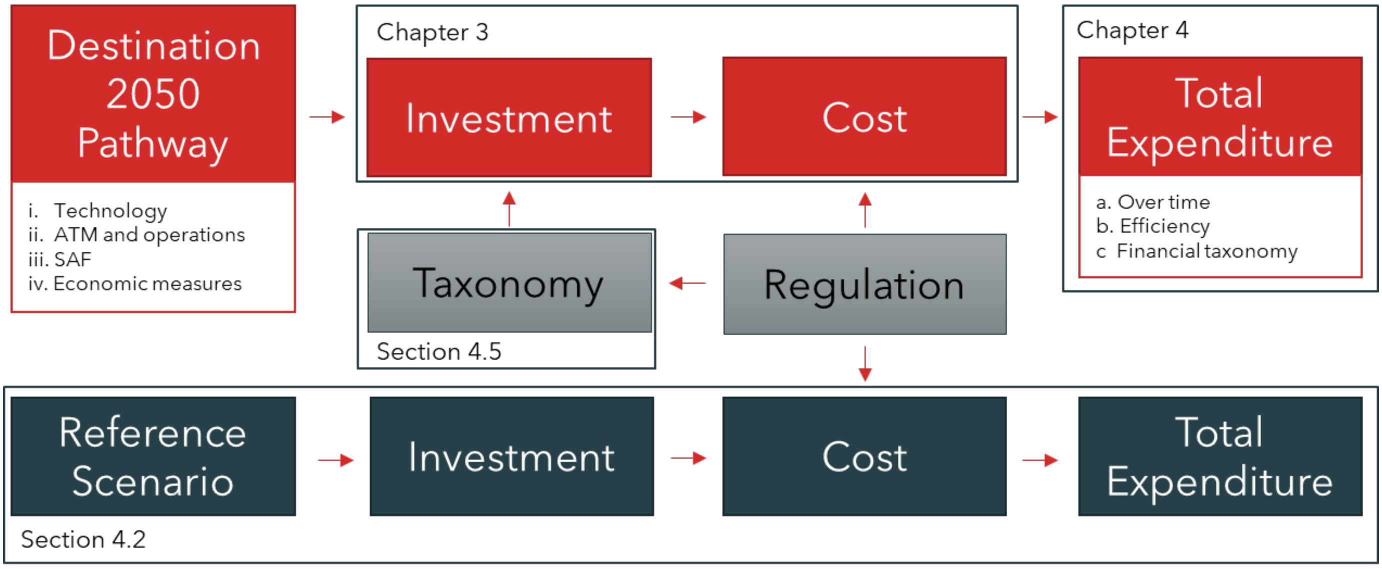
The remainder of this report is structured as follows. Chapter 2 presents the methodology for the work. Chapter 3 identifies the expenditures associated with the decarbonisation pathway outlined in Destination 2050. Chapter 4 aggregates these expenditures, computes their CO_2 abatement efficiency and classifies these according to the EU taxonomy. Chapter 5 discusses possible public support mechanisms. Finally, Chapter 6 presents conclusions. Additional information is provided in various appendices. For example, these appendices briefly summarise Destination 2050, present updated outcomes, and provide supplementary information.

2 Approach

The total expenditure requirements for implementing Destination 2050 are determined bottom-up. The individual investments and costs for all necessary measures are identified and subsequently aggregated. A distinction is made between total and premium expenditures, and expenditures are compared to a reference scenario relying only on out of sector measures. Finally, expenditures are presented along various dimensions such as time and efficiency before highlighting taxonomy considerations and available public support measures.

The starting point for this investment and cost analysis are the measures proposed in the Destination 2050 pathway to achieve net zero CO_2 aircraft emission for flights within and departing from the EU+ region[3] by 2050. Consistent with that report, the present study is limited to emissions resulting from the combustion of kerosene. Measures to reduce (net) emissions can be subdivided along four main trajectories: i) improvements in aircraft and engine technology, ii) improvements in air traffic management (ATM) and operations, iii) use of sustainable aviation fuels, and iv) economic measures. Figure 2.1 provides an overview.

Figure 2.1 Schematic representation of the study approach



According to the measures defined in the pathway, investments and costs are determined bottom up though literature research, expert interviews and desk research in Chapter 3. Depending on the time horizon and nature of the expenditure, we distinguish investment and costs, as well as their interdependencies. It is well established that proposed government regulation on aviation, such as included in the Fit for 55 package of measures.[4] also has a cost impact (Adler, Bonnekamp, & Konijn, 2022). More explicitly, the mandate on sustainable aviation fuel uptake

[3] The EU+ region is defined as the European Union (EU), the United Kingdom (UK), and the European Free Trade Association (EFTA).

[4] https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541

(ReFuelEU Aviation), the Alternative Fuels Infrastructure Regulation (AFIR) and the measures leading to increased EU ETS prices for the remaining carbon emissions increase costs for the sector. For consistency with the previous Destination 2050 report (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), simplicity and inherent uncertainty of the future, the assumptions and modelling choices made in that report, which are closely resembled in the aforementioned three Fit for 55 proposals, have been maintained. [5]

The necessary individual investments and costs are aggregated in Chapter 4 to the total expected expenditures of the aviation sector towards Destination 2050. Subsequently, these are aggregated and then subdivided along the following dimensions of interest:

a) Timepoint of investments and costs
b) Investment and cost efficiency (i.e. tonne of CO_2 saved per € invested)
c) Financial taxonomy (i.e. enabling activities, transitional and low carbon activities)

Furthermore, Chapter 4 makes two comparison in order to better understand the expenditures identified:

1. Comparison with additional or 'premium' expenditures, outlining what investments and costs are additional to a traditional development path.
2. Comparison to an out-of-sector carbon reduction scenario, highlighting the (cumulative) cost difference of in-sector decarbonisation versus reliance on carbon pricing and (out-of-sector) carbon compensation and removal.

2.1 Scope

We take the financial perspective of the aviation sector in achieving net zero CO_2. Hence, expenditures that are necessary to achieve net zero, both in terms of cost and investments, are in scope. Due to their interdependencies and the pass-through of expenditures between different stakeholders, costs and investments cannot always easily be distinguished. For example, investments into new aircraft technology for manufacturers can constitute either an investment or a cost for airlines, depending on such a plane being purchased or leased. We attempt to make a clear distinction for the purpose of this study. Costs are here defined as short-term, operational expenditures. Investments have a long-term operational focus usually towards fixed assets.

Investments are only considered in scope if they occur within the aviation sector. Key examples are aircraft R&D and fleet renewal and adjustments to ATM or airport infrastructure. Out-of-sector investments, such as those required for developing production facilities for SAF, are considered out of scope. Rather than determining the investment cost, it is assumed that those investments costs are passed on in the selling price of – in this case – SAF. Another question regarding cost accounting is the geographical context of the study discussed in Box 2.1 below.

When considering total expenditures, this study is limited to expenditures with a direct relation to aviation carbon emissions. That logically includes all investments related to measures identified in Destination 2050, and furthermore spans costs for fuel (in various forms, including fossil kerosene) and carbon costs. Expenditures related to (e.g.) maintenance, repair and overhaul, personnel costs, and other fees and charges are considered out of scope.

[5] It is acknowledged that in some cases (e.g. fuel and carbon prices), these assumptions might not reflect latest forecasts or policy developments. As an update of such assumptions would alter the Destination 2050 decarbonisation pathway (as, for example, carbon pricing has an impact on demand), and there is substantial uncertainty surrounding any choice set, it was opted for consistency in the assumptions across the two studies.

Box 2.1 Geographical accounting of costs

This study identifies the total investment needed to achieve the decarbonisation pathway outlined in the Destination 2050 report, published in 2021 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The scope of Destination 2050 is limited to CO_2 emissions from flights within and departing the EU+ region, defined as the EU, UK and EFTA.

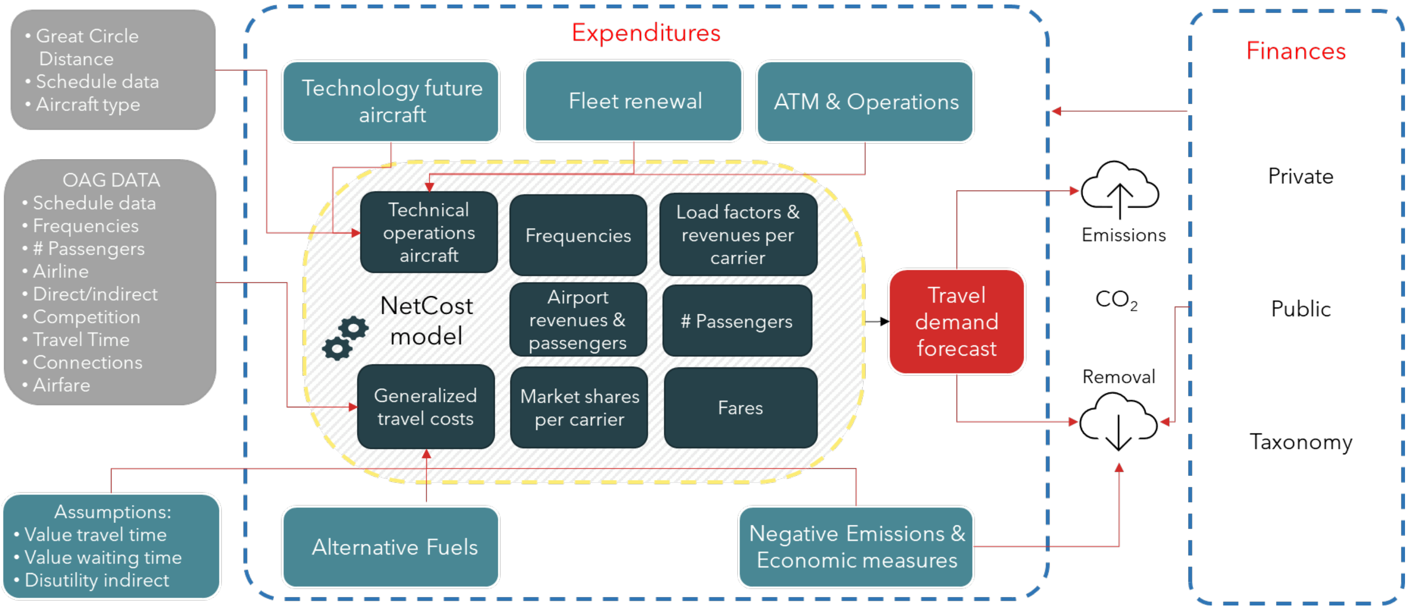
Part of the to-be-mitigated emissions are the consequence of actions by non-EU+ actors and as such, the decarbonisation measures modelled in Destination 2050, not exclusively target EU+ stakeholders. Examples are fleet renewal by non-EU+ airlines (for those parts of their fleets used to operate flights departing from EU+ airports), ATM modernisation efforts by non-EU+ ANSPs (which help reduce the fuel burn and CO_2 emissions from intercontinental flights departing from EU+ airports) or measures to reduce aircraft emissions from ground emissions at airports.

The aforementioned means that the total investment need identified here includes investments or costs to be borne by non-EU+ actors. Consequently, the costs identified are not exclusively for the EU+ region (or European Union). While not studied in detail, the investment need for EU+ (or EU) actors is likely smaller than the total need reported in this study.

2.2 Interplay between emissions reductions and costs

The research of the technical considerations towards CO_2 emissions savings and the financial aspects are closely interlinked. Each technology and measure of Destination 2050 contributes towards the goal of net zero but also to the expenditures by the aviation sector. In the Destination 2050 report, ticket price increases and the respective demand impacts of the use of SAF and economic measures were taken into account. Other cost increases and the potential demand impacts from these (other) cost increases were not considered. The underlying connection between (NetCost) model calculations, exogenous external inputs from third parties, necessary assumptions on utility as well as component of sectoral expenditures are presented in Figure 2.2. The relation between flight movements determined within the model, the associated expenditures and resulting changes in travel demand are apparent. Similarly, the effect these have on CO_2 emissions and savings is depicted next to the potential other financial sources towards this goal.

Figure 2.2 Methodology schematics



Due to the difficulty of assessing investment needs for airline operational actions (in the pillar of airspace and ATM), the possible investments required for implementing these measures are assumed to be funded through cost savings, realised by the implementation of these measures. In support of this assumption, (cumulative) cost savings realised by reductions in fuel consumption and associated CO_2 emissions are determined. If these are likely to cover the investment, the cost neutrality assumption is maintained.

All cost and investments throughout the remainder of this study are expressed in 2018 Euros and therefore exclude inflation. The effect of COVID-19 which had a major impact on the aviation sector is taken into account in terms of rebounding of the global travel demand to pre-pandemic levels by somewhere between 2024 and 2026. A few expenditure forecasts we report later predate the COVID pandemic, and we assume those continue to be fully applicable according to the rebound in air traffic.

3 Expenditure identification

The total expenditure to realise the decarbonisation pathway outlined in Destination 2050 spans investment in technology development, fleet renewal, airspace and ATM, ground operations at airports, costs for alternative fuels and economic measures. Fleet renewal investment and alternative fuel costs make up the largest share of the total expenditure.

This chapter identifies the costs associated to each of those measures, or to parts from which these measures are composed. Similar to the Destination 2050 report, it reports on improvements in technology, improvements in ATM and operations, alternative fuels and negative emissions.

For the most substantial investments and costs, estimates are derived from literature and purpose-built modelling output. This is further referenced or elaborated in the text. For a wider set of less precisely defined measures, the cost neutrality assumption made in the previous Destination 2050 report was maintained as starting point, and validated using modelled costs savings – following from reductions in fuel consumption and emissions.

Following this hybrid approach, each section either finds a total monetary sum for an investment or cost, or concludes that measures can be implemented in a cost-neutral fashion. Those inputs are subsequently used in Chapter 4 to, among others, compute grand total aggregates and evaluate investment efficiencies. Through a comparison with a reference scenario in which the sustainability investments are not made, Chapter 4 (Section 0 specifically) also estimates the cost savings (in aircraft fuel and CO_2 cost[6]) that sustainability investments (e.g. in fleet renewal and operational improvements) help realise.

3.1 Improvements in technology

Improvements in technology modelled in the Destination 2050 roadmap will help reduce fleet CO_2 emissions by 7 percent in 2030 and by 37 percent in 2050 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The Destination 2050 study discerns between two 'generations' of aircraft: upcoming aircraft and future aircraft. Upcoming aircraft are aircraft types which are currently already available in the market, or will be introduced shortly. Key examples are the Airbus A220, A320neo-series and A350, Boeing 737MAX, 787 and 777X and the Embraer E2. Future aircraft are then a next generation, which enter into service from 2035 onwards.[7] Specific models have not been announced yet, but for which efficiency improvements of 30 percent were modelled. The group of future aircraft also includes a hybrid-electric regional aircraft and a hydrogen-powered single aisle aircraft, which was modelled in

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[6] The sustainability measures detailed in the Destination 2050 report might also have other cost impacts, e.g. on maintenance, personnel costs, fees and charges. These impacts have not been studied in this work. In the cost comparison of reference and sustainability scenarios (in Section 0), such costs are assumed to remain unchanged.

[7] Destination 2050 also modelled the introduction of a future aircraft in the 'Small' segment (up to 19 seats) from 2030. Due to its very limited share of ASK (0.01%) and CO_2 emissions (0.02%), uncertainty about technology options and probably very limited applicability of public funding, the current study assumes that – in this segment – costs for research and development as well as fleet renewal are (at least) balanced by savings during their operational life. Investment need is therefore not studied.

the previous Destination 2050 report as serving intra-European routes up to 2000 kilometres (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021).

Three categories of investments are considered:

- Research and development of aircraft
- Fleet renewal: acquisition of new aircraft to replace older ones or accommodate activity growth
- Supporting infrastructure: recharging and refuelling infrastructure for hybrid-electric and hydrogen-powered aircraft

Costs related to the use of alternative energy (electricity for use in hybrid-electric aircraft and liquid hydrogen for hydrogen-powered types) are treated in Section 3.3. Investments related to retrofitting existing aircraft with technology to enable improvements in ATM are not covered in this section, but discussed in Section 3.2.

3.1.1 Future aircraft research and development

Realising reductions in CO_2 emissions by aircraft starts with research and development. As upcoming aircraft are already available on the market (or will be shortly), research and development costs will already have been incurred. For future aircraft, that is not the case: in order to introduce a next generation of aircraft from 2035 onwards, technology readiness is required by 2027 to 2030.

The Clean Aviation Strategic Research and Innovation Agenda (SRIA), discussed as funding mechanism in more detail in Section 5.1, projects a **12B€** effort for Research & Innovation up to 2028 (Clean Aviation Partnership, 2020).[8] This R&I effort concerns research at lower technology readiness levels (up to TRL 6), which can find applications across multiple future products. The approach proposed in the SRIA will require a research effort of roughly 4B€ as a key component of the overall 12B€ effort. The public funding budget involves an EU contribution from the Horizon Europe programme of 1.7B€. Private members support the programme financially with in-kind contributions, contributing a total of at least 2.4B€. The remaining effort can be covered by national research programmes and other activities which contribute to achieving the goals of Clean Aviation. The Clean Aviation SRIA itself spans three thrusts (Clean Aviation Partnership, 2020, p. 17):

- Hybrid electric and full electric architectures;
- Ultra-efficient aircraft architectures, including highly integrated, ultra-efficient thermal propulsion systems;
- Disruptive technologies to enable hydrogen-powered aircraft.

Jointly, these three thrusts span the technologies also foreseen for the future aircraft as modelled in Destination 2050: a regional hybrid-electric turboprop, ultra-efficient aircraft in the SA, SMTA and LTA classes and – additionally – a hydrogen-powered single aisle model.

Once technologies have been matured for commercial application, product development starts (TRL 7). Note 1 in Figure 3.1, copied from the aforementioned Clean Aviation SRIA notes an investment of 15B€ for aircraft development, per type (Clean Aviation Partnership, 2020), in line with historical figures and trends (Bowen, 2010, p. 68; Rodrigue, 2020). Taking this as an average, the product development investments as shown in Table 3.1 are

[8] This study only considers Research & Innovation action and associated investment need up to approximately 2030, as by that year, the technologies to be introduced on the future generation of aircraft modelled in the original Destination 2050 study have to be ready (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Of course, research and innovation efforts will have to continue beyond 2030 for subsequent generations of aircraft, introduced from 2045 or 2050 onwards. Due to the fact that this generation of aircraft is not considered in the Destination 2050 pathway, associated investments are not considered in this study.

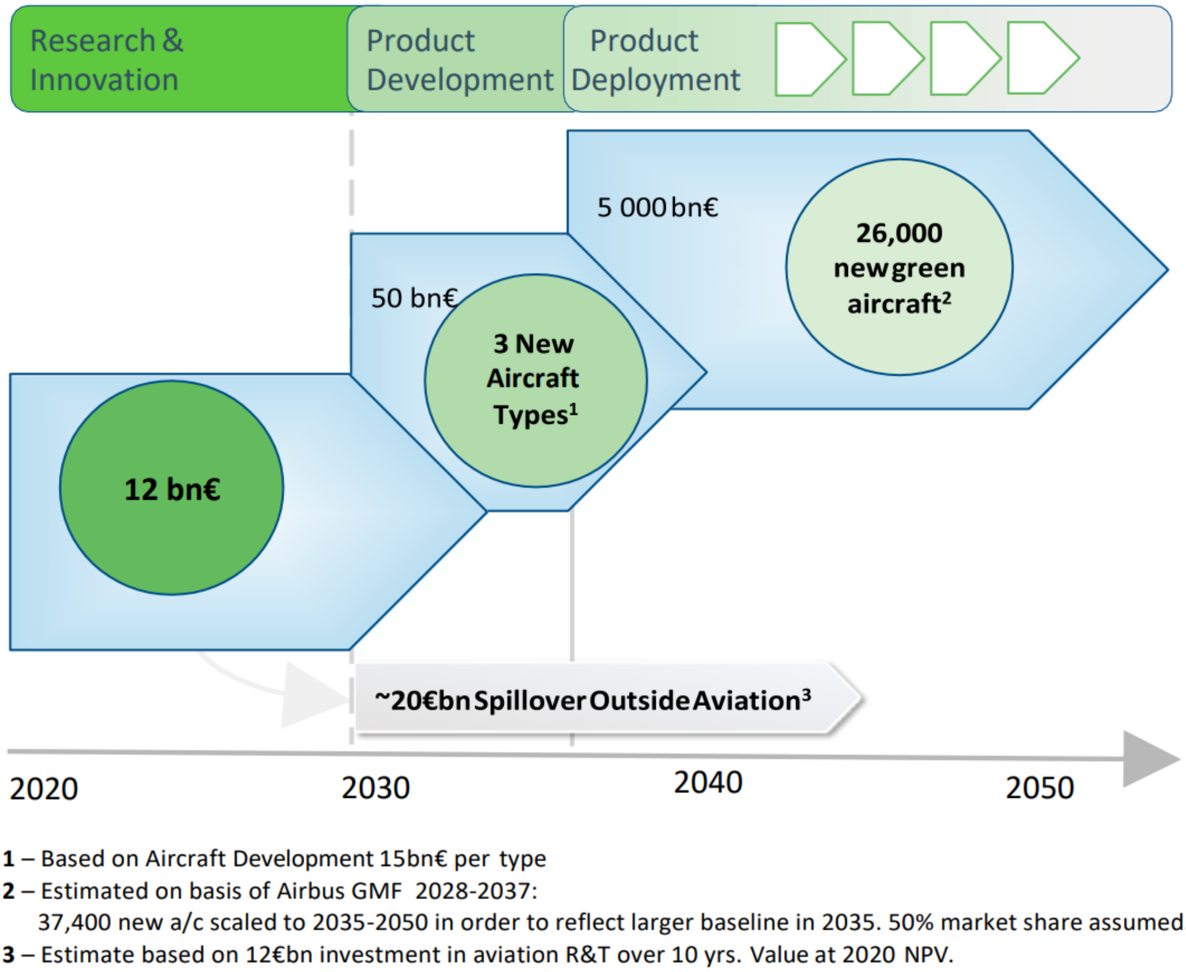
estimated per class, taking into account that larger aircraft programmes have in the past seen higher cost (ICAO, 2022, Figure 21, p. M1-34). For all classes combined, this totals **88B€**.

Combined, the investment requirements for lower-TRL research and innovation and higher-TRL product development add up to **100B€**.

Table 3.1 Product development investments for future aircraft

Class	Product development investment [B€]	Remarks
Regional (R)	12.5	Estimated.
Single-aisle (SA)	15.0	Baseline value.
Hydrogen-powered single-aisle (H_2-SA)	17.5	Value for single-aisle, increased by 2.5B€ to take into account the more advanced technology
Small/medium twin-aisle (SMTA)	20.0	Estimated.
Large twin-aisle (LTA)	22.5	Estimated.
Total	**87.5**	

Figure 3.1 Effort required according to the Clean Aviation Partnership (Clean Aviation Partnership, 2020, p. 23)



The aforementioned investment estimate only takes into account the cost of developing one aircraft model per class. In reality, multiple aircraft types are likely to be introduced, as different aircraft manufacturers will develop a (competing) product. For the size classes considered in this research, the market is assumed to consist of only two aircraft manufacturers. This implies that the estimated investment will have to be made twice. It is counted only once in this work, however, assuming a 50/50 market share of European and non-European built aircraft. This is consistent with the market share assumption in the Clean Aviation SRIA (Note 2 in Figure 3.1).

3.1.2 Fleet renewal

Improvements in technology typically enter the fleet through fleet renewal: the replacement of older aircraft by newer types. In addition to realising decarbonisation through improvements in technology by fleet replacement, retrofitting existing aircraft can reduce CO_2 emissions. This research takes these retrofits into account mainly in relation to improvements in ATM and operations, described in Section 3.2. In line with the main Destination 2050 study, additional and currently unknown retrofits or product enhancements which may be introduced are not taken into account. Nevertheless, for illustrative purposes, Box 3.2 at the end of this chapter (p. 13) presents cost estimates for retrofitting kerosene-powered aircraft currently in operation with propulsion systems based on hydrogen fuel cells. This is pursued in the regional aircraft segment by various businesses.

Cost of upcoming aircraft

Fleet renewal investment cost is modelled identical to the method used for modelling CO_2 reduction potential in Destination 2050: for upcoming aircraft that directly succeed a current or previous generation model (such as the Airbus A320neo or Boeing 737MAX), one-to-one fleet replacement of older aircraft is assumed. In case a direct successor does not exist, average improvement figures for an aircraft class are used. Required investments are modelled based on average aircraft (or class-averaged) sales prices, determined from list prices and typical discount rates per class (Schonland, 2016). Class-based averages are shown in Table 3.2; figures per aircraft type are included in Appendix B. This is combined with the fleet renewal rates as modelled in Destination 2050, using a 22.5 years airframe lifetime.

Table 3.2 Class-based list prices, discount rates and sales prices for upcoming aircraft

Class	Example aircraft	List price [M€] Average / min / max			Discount	Sales price [M€] Average / min / max		
Regional (R)	ATR72-600, Embraer E175-E2	39	21	49	35%	**25**	14	32
Single-aisle (SA)	Airbus A220, Airbus A320neo, Boeing 737MAX	94	56	126	45%	**52**	37	69
Small/medium twin-aisle (SMTA)	Airbus A330neo, Boeing 787	238	202	276	45%	**131**	111	152
Large twin-aisle (LTA)	Airbus A350, Boeing 777X	319	269	361	50%	**159**	134	180

Box 3.1 Accelerated fleet renewal

Destination 2050 (p. 54) acknowledged calls by industry to use the COVID-19 crisis as an opportunity for accelerated fleet renewal, replacing aircraft after 15 years of service, rather than the industry-average 22.5 years. Such a measure was not included in the modelling, as the study only assessed emissions in horizon years 2030 and 2050 – whereas accelerated fleet renewal would only affect CO_2 emissions in intermediate years.

In order to ensure consistency with the main Destination 2050 study, this current research also does not include accelerated fleet renewal in the main modelling effort. As such, 0 addresses accelerated fleet renewal in a separate assessment. If possible to realise in a very short term, the accelerated replacement of existing aircraft by upcoming models can help reduce cumulative CO_2 emissions, mainly in the period up to 2030. The accelerated replacement of upcoming aircraft by future aircraft in the 2040s, however, might make a bigger decarbonisation impact. This is especially the case if aircraft are targeted for which alternatively propelled successors exist (hybrid-electric turboprop and hydrogen-powered single-aisle), as such replacements would yield the largest reduction in CO_2 emissions per flight.

Cost of future aircraft

Following their development (described in Section 3.1.1), future aircraft can be introduced into the market. This too requires investment. Clean Aviation estimates a 5,000B€ investment for 26,000 new aircraft – averaging 192M€ per aircraft. Compared to the average (list) price of 154M€ (computed from Table 3.2), this is a 25 percent increase.[9] As such, and given the fact that there is no indication of current discount policies changing towards the future, average sale prices for future aircraft are modelled as those for upcoming aircraft, increased by 25 percent. Because no concrete future products have been defined, this investment is completely based on class-averaged figures shown Table 3.2. The results are presented in Table 3.3.

Table 3.3 Class-based sales prices for future aircraft

Class	Sales price [M€]	Remarks
Regional (R)	**31**	
Single-aisle (SA)	**65**	
Hydrogen-powered single-aisle (H_2-SA)	**77**	Destination 2050, based on McKinsey & Company (2020), notes a 31% increase in aircraft CAPEX. This is applied to the estimated sales prices of a future kerosene-powered aircraft of similar size (165 seats, Airbus A319neo segment).
Small/medium twin-aisle (SMTA)	**163**	
Large twin-aisle (LTA)	**199**	
Average	**192**	

[9] Destination 2050 (p. 139) concluded these prices to be roughly in line with current (list) prices of upcoming aircraft. This is refined in the current modelling. The Clean Aviation SRIA does not provide a rationale for these higher prices. The ICAO LTAG report (2022), however, notes that "aircraft technology improvements are not expected to 'come for free'" (p. M1-56).

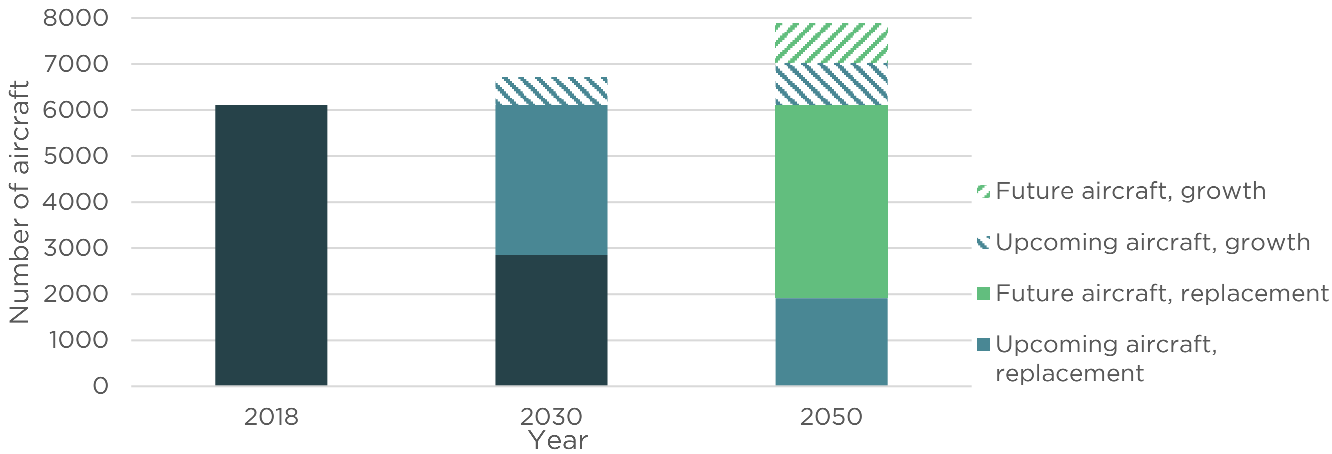
Number of aircraft

The total investment figure for fleet renewal and expansion follows from the multiplication of the aircraft sales price[10] and the number of aircraft to be replaced.

For the latter derivation, the number of EU registered aircraft in 2018 (some 5200 airframes) forms the starting point. Per aircraft size class, the number of airframes has been scaled up by the ratio of ASKs produced by EU+ carriers (operating EU+ registered aircraft) versus non-EU+ carriers. Based on the total number of aircraft in 2018 used to operate the flights in scope of Destination 2050 (about 6120) and the 0.8 percent annual increase in number of flights, the 2050 fleet is estimated to span approximately 7880 aircraft. Supporting per class figures are included in Appendix B.

For most classes (R, SA, H_2-SA and SMTA), 2/3rds of the aircraft in the 2050 fleet will be future models.[11] The remaining 1/3rd will be of the upcoming generation. Based on an average aircraft lifetime of 22.5 years, these will be upcoming aircraft that will have been produced from 2028 onwards. Moreover, by 2028, about 45 percent of the 2018 fleet will consist of upcoming aircraft.[12] Figure 3.2 shows the fleet composition per generation for the baseline year (2018) and the two horizon years (2030 and 2050).

Figure 3.2 Fleet composition per aircraft generation for 2018, 2030 and 2050.



Total investment need

The previous analysis shows three situations can apply to existing aircraft:

1. Existing > upcoming > future: existing aircraft being replaced by upcoming aircraft between 2018 and 2028, in turn replaced by future aircraft between 2040 and 2050.
2. Existing > upcoming: existing aircraft being replaced by upcoming aircraft between 2028 and the year a future aircraft is introduced (2035 or 2040, depending on the class). These aircraft will remain in the fleet until 2050.
3. Existing > future: existing aircraft being directly replaced by a future aircraft.

[10] This builds upon the aircraft sales prices identified previously. Actual sales prices might deviate.
[11] These future aircraft are introduced in 2035. Based on an average aircraft lifetime of 22.5 years, by 2050, 15 / 22.5 = 2 / 3 of aircraft will have been replaced. For the LTA-class, the share of future aircraft will be 44.4%, based on an entry into service in 2040.
[12] Computed from (2028 – 2018) / 22.5 = 44.4%

From the perspective of an airframe, these situations are mutually exclusive: an airframe in operation today can only follow one of these replacement paths. However, the situations can and are likely to occur in parallel, depending on differences in current fleet composition and on fleet development strategies.

Furthermore, as Figure 3.2 previously indicated, activity growth will require aircraft acquisition. Depending on the time period in which fleet expansion is realised (between 2018 and 2028, between 2028 and 2035/40 or after 2035/40), either of the aforementioned situations applies.

For both fleet replacement and growth, the associated investment need for the groups of aircraft to which each of these situations apply is **200B€** for case 1 (existing > upcoming > future), **210B€** for case 2 (existing > upcoming) and **410B€** for case 3 (existing > future). This sums to **820B€**.

Box 3.2 Retrofit implementation of hydrogen-powered aviation

Since Destination 2050 was published in early 2021, more disruptive forms of retrofitting have gained traction. Various businesses are developing retrofits that replace the kerosene-based propulsion system of regional turboprop aircraft (most notably, the ATR42 and ATR72 platforms) by hydrogen fuel cell systems, which would enable zero-carbon flight.

- ZeroAvia anticipates EIS of a 40 to 80 seat TP with 1,800 km range by 2026.
- Universal Hydrogen aims to have EIS one year earlier (2025) on regional aircraft such as the ATR72 and DeHavilland Canada Dash-8.

As such retrofits were not included in the decarbonization modelling of Destination 2050, associated investments also are not included in the primary modelling effort of this study. Nevertheless, such retrofits would likely be a highly cost-efficient way to decarbonize. This requires such hydrogen-powered aircraft to be indeed fuelled using green hydrogen, such that CO_2 emissions of the base aircraft (before retrofitting) would be completely nullified. Furthermore, the total amount of emissions that could be mitigated this way is limited, due to the limited market and emissions share of regional turboprops (estimated below 1%).

3.1.3 Ground infrastructure for future aircraft

With the introduction of future aircraft that are not (solely) powered using kerosene – in fossil, sustainable or blended form – comes the need to realise changes to ground infrastructure for aircraft. This section presents estimates for investments in airport ground infrastructure required for recharging hybrid-electric aircraft and refuelling hydrogen-powered aircraft.

Recharging infrastructure for hybrid-electric aircraft

Destination 2050 modelled the introduction of a hybrid-electric regional aircraft from 2035 onwards, realising a 50 percent reduction in CO_2 emissions per flight. The work did not specify the amount of hybridisation, but only noted thermal engines to be sized optimally for cruise condition and batteries to supply additional power to cover the peak power loads. Literature suggests this is consistent with a 10 percent hybridisation factor (Jux, Foitzik, & Doppelbauer, 2018). This means an amount of electric energy equivalent to 10 percent of the energy content of kerosene consumed is required.

Intermediate results of Destination 2050 modelling show that the total amount of kerosene consumed by hybrid-electric regional aircraft in 2050 is 1.1 Mt. 10 percent of that would be 0.11 Mt or 1,300 GWh, equivalent to an average of 3,600 MWh per day. Actual electricity demand for charging hybrid-electric aircraft will vary from airport to airport:

- Average electricity demand for about 400 (smaller) airports is 9 MWh/day, per airport.
- For about 30 larger airports, per-airport electricity demand will be over 30 MWh/day (up to 250 MWh/day).

Assuming 10 hours per day effectively available for charging, hourly energy demand would be 0.9 MWh on average.

The investments are then modelled based on the following infrastructure characteristics:

- Charger output of 400kW (based on Driessen & Hak, 2021). For an average flight requiring 120 kWh of electricity, charging would take under 20 minutes.
- Currently existing ultra-rapid charging points for road transport deliver up to 350kW (EC, 2021c, p. 129).
- Cost of charging infrastructure at 2M€/MW, based on Driessen & Hak (1.7 to 2.5M€/MW, 2021) and Van Oosterom (2M€/MW, 2021). Costs are notably higher than for road infrastructure, indicated at 0.4 to 0.5M€/MW by the European Commission (EC, 2021c, p. 129), but given the complexities of developing airport ground infrastructure, the 2M€/MW figure is considered a realistic estimate.
- For redundancy reasons, 10 percent additional charging capacity is modelled, and the minimum amount of chargers per airport is set at 3.

Based on the above characteristics, investments total **1.5B€** across more than 400 airports. Actual investment will vary from airport to airport. For approximately 335 airports, the minimum amount of three charging stations will suffice, at a cost of 2.4M€ per airport. Fifty airports will require between 4 and 10 chargers, at an average cost of 5M€ per airport. More than 10 chargers are required for 24 airports, with per-airport costs ranging from 8.8M€ (11 chargers) to 55M€ (69 chargers), averaging 17M€.

Refuelling infrastructure for hydrogen-powered aircraft

Destination 2050 modelled the introduction of a hydrogen-powered single-aisle aircraft seating 165 passengers from 2035 onwards on intra-EU+ routes below 2,000 kilometres, based on work by McKinsey & Company (2020).

The overall demand for liquid hydrogen in 2050 was previously found to be 3.7 million tonnes (Destination 2050, p. 40). Intermediate results were used to determine the demand for liquid hydrogen by each of the 335 airports served by a hydrogen-powered aircraft in 2050:

- By 2050, average hydrogen demand for about 300 (smaller) airports is below 100 tonnes/day, or below 36.5 kilotonnes/year. Together, the hydrogen demand totals 1.5 million tonnes in 2050.
- For about 30 larger airports, demand figures for 2050 vary between 100 tonnes/day to approximately 325 tonnes/day. In total, these airport require a supply of 2.1 million tonnes of hydrogen in 2050.

Following McKinsey & Company (2020), it is assumed that the first group of smaller airports receives its supply of liquid hydrogen by truck, delivered from a nearby hydrogen plant or liquefaction facility[13]. A daily demand of 100 tonnes translates into 25 4-tonne truckloads, which is "feasible" (McKinsey & Company, 2020, p. 40)[14]. For the group of airports with a larger demand for liquid hydrogen, this option is no longer suitable due to for example road congestion and increasing safety risks. In this case, a gaseous supply pipeline and liquefaction facility at the airport premises are suitable[15]. Regardless of the option, a local storage facility acts as buffer volume. Refuelling of

[13] Liquefaction is the process of transforming gaseous hydrogen into liquid form.

[14] Referring to the same study, ACI & ATI (2021, p. 6) assume 5-tonne trucks and note 15 trucks per day "could be easily managed".

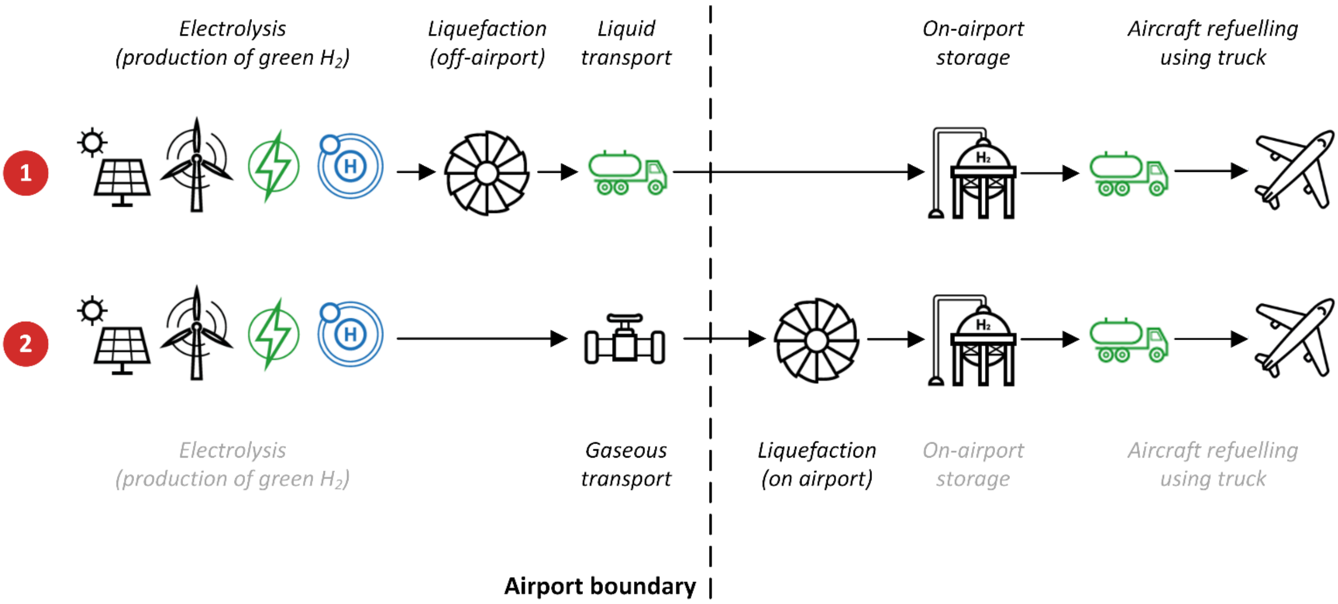
[15] As a pipeline would to be pressurised or kept at a very low temperature (well below minus 200°C) in order to transport *liquid* hydrogen, gaseous hydrogen is used instead. This is then liquefied at the airport.

individual aircraft with liquid hydrogen sourced from the local storage facility is done by trucks. The two pathways are illustrated in Figure 3.3[16].

Box 3.3 Hydrant systems for hydrogen-powered aircraft

Alternatively to using trucks for refuelling individual aircraft, hydrant systems might be considered. According to McKinsey & Company (2020, p. 51), these, "for the foreseeable future" seem to be "technically and economically infeasible". A recent FlyZero report is more positive, noting that by 2050, hydrant systems might be introduced at "medium" to "large" airports (Postma-Kurlanc, Leadbetter, & Pickard, 2022). For these airports, daily hydrogen demand would be 6.5 (medium) to 22 (large) million litres – equivalent to 450 to 1560 tonnes at a density of approximately 70 kg/m^3. Even the 450 tonne figure is much higher than the maximum value found in this study. For small airports (daily demand of 700 thousand litres or about 50 tonnes), FlyZero sees truck-based systems (so-called bowsers) are economically most attractive.

Figure 3.3 Hydrogen supply pathways from production to airport and aircraft considered (adapted from ACI World & ATI, 2021)



The investment need for each of the three different phases – on-airport liquefaction (if applicable), on-airport storage and aircraft refuelling – are determined from base values per unit in combination with the hydrogen supply for a particular airport. Unit costs are determined as follows:

- The investment for a **liquefaction** plant is determined using

$$C = A \cdot P^{2/3}$$

with C the investment need, A a scaling factor equal to 9.83[17] and P the plant capacity in tonnes per day (Stolzenberg & Mubbala, 2013). Due to the two-thirds power, the unit costs realised by larger facilities are lower than the unit costs for smaller facilities, consistent with Cardella, Decker & Klein (2017). The costs determined this way for a liquefier with a capacity of 120 tonnes per day – 239M€ – are found in line with

[16] Alternatively to those options, completely local production of hydrogen could take place at airports – meaning that the renewable energy generation and electrolysis also happens on site (ACI World & ATI, 2021; Postma-Kurlanc, Leadbetter, & Pickard, 2022). This option has not been studied, as it is an unlikely scenario (Postma-Kurlanc, Leadbetter, & Pickard, 2022).

[17] Stolzenberg & Mubbala (2013) use $A = 7.37$, but a payback period of 20 years. Adjusting this to a period of 15 years (the period between 2035 and 2050), A is updated to 7.37 × 20/15 = 9.83.

projections from the IEA (2019)[18] and estimates based on McKinsey (2020)[19]. For smaller liquefaction plants, costs projected this way are higher than in literature, whereas for larger liquefaction facilities, costs are notably smaller. Connelly et al. (2019) estimate (in "current markets") a 200 tonnes per day liquefaction facility to have a total cost of 800M$ (680M€), whereas the aforementioned equation projects an investment need of 336M€.

- Combining various sources (Derking, van der Togt, & Keezer, 2019, p. 7; Vos, Douma, & van den Noort, 2020, p. 25; McKinsey & Company, 2020, p. 47) and expert estimates, the capital expenditure for **on-airport storage** is estimated at 75€/kg. On-site storage facilities are sized for a 7-day supply (based on IATA, 2008) or 8 tonnes (two truckloads), whichever is highest.
- The costs of 40000-litre (or 2.8-tonne) bowsers used for **refuelling aircraft** are estimated at 400k€. The number of bowsers required is found by assuming the daily demand for hydrogen is to be uplifted to aircraft in 10 hours (consistent with the time available for charging hybrid-electric aircraft) and that one loaded bowser can provide liquid hydrogen to two aircraft[20] in one hour (based on Postma-Kurlanc, Leadbetter, & Pickard, 2022). Bowsers are modelled to remain in service for 7.5 years and all bowsers required to meet the demand at the end of either phase (2042 or 2050) are modelled to enter service at the start of that phase.

The investments to supply hydrogen to the airport – whether truck-based or using a pipeline – are not included in the cost estimates, as these activities happen outside the airport perimeter.

The modelling discerns between two phases of 7.5 years each: from 2035 up to and including the first half of 2042, and from the second half of 2042 up to and including 2050. For both phases, capacities are sized for the requirements at the end of the phase – 2042 and 2050, respectively. This is a consequence of the fact that facilities cannot be scaled up gradually – or only in a way hurting overall efficiency. By 2042, the hydrogen demand of 10 airports is already such that on-site liquefaction is most feasible; approximately 20 others change from truck-based supply to gaseous supply and on-site liquefaction between 2042 and 2050.

Modelling based on the aforementioned parameters yields a total investment need of **16.4B€** across all 335 airports serviced by hydrogen-powered aircraft. Investment need for airports for which an on-site liquefaction facility is required is substantially higher than for airports who can be supplied by trucks. Over the period from 2035 to 2050:

- 10 airports equipped with a liquefaction facility from 2035 onwards, investment need averages 670M€ and ranges from 575M€ to 760M€.
- 22 airports for which supply using trucks can meet demand up to 2042 but afterwards have to switch to gaseous supply and on-airport liquefaction, need to invest between 270M€ and 440M€, or 330M€ on average.
- 303 airports that are supplied using trucks for both phases, on average need to invest 8M€, with investment requirements per airport ranging from 1.4M€ (1M€ storage facility plus one bowser) to 54M€.

Due to the non-linear relationship between liquefier cost and production output, immediately installing in 2035 facilities sized for 2050 would reduce the total investment need (by approximately 1B€). On the other hand, this

[18] In its "Assumption annex", IEA (2019) describes a liquefaction capacity of 260 kt/year at a capital expenditure of 1400M$ (1190M€), equivalent to approximately 4600€/kt. With an annual production of 365 × 120 = 43800 tonnes or 43.8 kilotonnes per day, the investment is 201M€.

[19] McKinsey (2020) projects on-site liquefaction costs for 2040 of 0.89$/kg (0.75€/kg), of which 50% is assumed to be capital expenditure (Cardella, Decker, & Klein, 2017; Aziz, 2021). With a 15 year plant lifetime and an annual production of 365 × 120 = 43800 tonnes per day, the investment totals 246M€,

[20] Based on the 48 MWh – or 1.44 tonnes – energy requirement of a hydrogen-powered aircraft (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 40).

increases risk, and would require not only the availability of higher-capacity liquefaction plants (the two-phases scenario models two smaller plants as opposed to one large one), but also their availability by 2035[21].

Box 3.4 Infrastructure costs beyond 2050

The infrastructure investments outlined in this section are figures for 2035 to 2050. That means they are based on the traffic scenario up to 2050 and also on the amount of alternatively fuelled aircraft that have entered the market by that date. As both the hybrid-electric regional and the hydrogen-powered single-aisle aircraft enter into service in 2035 and overall phase-in takes 22.5 years, they have only attained 2/3rds of their potential market share. In order to facilitate a growing number of movements operated by those aircraft (and realise the associated reductions in CO_2 emissions), recharging and refuelling infrastructure will have to be expanded as well. This will require additional investment, beyond what has been modelled in this report.

3.2 Improvements in ATM and operations

CO_2 emissions can be reduced by 8 percent by 2030 and 9 percent by 2050 by a wide array of improvements in air traffic management (ATM) and operations, as documented in 0. Matching the main Destination 2050 study, this study considers three categories of investment, further detailed in the upcoming sections:

1. Airline operations, related to e.g. flight planning, on-board weight reduction and airframe condition and maintenance;

As indicated in Chapter 2, (airline) expenditures related to (e.g.) maintenance, repair and overhaul, personnel costs and other fees and charges are considered out of scope of this study.

2. Airspace and air traffic management, encompassing the Single European Sky and other ATM improvements, and including the necessary retrofitting of aircraft with new or updated communication, navigation and surveillance technology; and
3. Ground operations at airports, related to measures reducing or eliminating emissions from taxiing or stationary aircraft.[22]

3.2.1 Airline operations

The decarbonisation opportunities in airline operations identified in Destination 2050 consists of a multitude of measures, in turn composed of numerous individual actions. Most of these bring incremental CO_2 reduction and require smaller investment. They are further described in the main Destination 2050 report (pp. 54 – 57).

Rather than mapping these investments bottom-up, this research computes the (monetary) benefits from CO_2 reduction per measure and subsequently assesses whether those benefits are likely to be enough to fund their realisation.

- Cost savings are modelled based on fuel burn and associated CO_2 reduction per flight, taking into account average fuel prices (including a portion of SAF) and the applicable carbon pricing mechanism (if any).

[21] For the 10 airports with on-site liquefaction from 2035 onwards, liquefier capacity ranges from approximately 110 to 160 tonnes per day (tpd). Conventional plants output 5 tpd (Cardella, Decker, & Klein, 2017), with plants in the United States ranging from 6 to 70 tpd (Connelly, Penev, Elgowainy, & Hunter, 2019). Connelly et al. (2019) provide costs projections for facilities up to 200 tpd, such that the 160 tpd facility modelled here seems feasible.

[22] Destination 2050 was limited to emissions from aircraft operations, and so is this work. This means emissions from e.g. terminal buildings and ground support equipment (GSE) are not considered.

- Carbon costs are modelled as 30€/tCO_2 for EU ETS and 0€/tCO_2 for CORSIA in 2018, increasing to 60€/tCO_2 for both EU ETS and CORSIA in 2030, and subsequently to €160 (CORSIA) and 315€/tCO_2 (EU ETS) by 2050. Average fuel prices (including SAF) are 510€/tonne in 2020, 700€/tonne in 2030 and approximately 1500€/tonne by 2050.

The results – in terms of the cumulative cost saving over the period the measure is implemented – are shown in Table 3.4, from which it is estimated that cost savings are likely to cover the (investment) costs of realising these reductions. The costs savings are derived from fuel and CO_2 savings as computed in the Destination 2050 modelling in 2030 and 2050 and linearly interpolated.

Table 3.4 Airline operational measures and associated cumulative cost saving due to reduction in fuel burn and associated CO_2

Measure	Fuel and CO_2 saving	Timeline	Cumulative cost saving over timeline [M€]	Likely to cover investment?
Improved flight planning	2%, 75% of flights	2020 – 2025	3300	Yes
Flight management system updates	1%	2025 – 2030	1400	Yes, 200k€ / airframe
Weight reduction	10 kg / seat, 75% of flights	2020 – 2030	7200	Yes, > 1M€ / airframe
Airframe condition and maintenance	0.2%	2020 – 2050	3500	Yes

As indicated in Chapter 2, (airline) expenditures related to (e.g.) maintenance, repair and overhaul, personnel costs and other fees and charges are considered out of scope of this study.

3.2.2 Airspace and air traffic management

Destination 2050 modelled a number of measures reducing fuel burn and CO_2 that relate to airspace and air traffic management. Four groups were defined: the Single European Sky and its associated SESAR research programme, ATM efficiency improvements outside Europe that benefit intercontinental flights departing from EU+ airports, improved flight efficiency over the North-Atlantic, and wake energy retrieval.

Single European Sky and SESAR

The EU ATM Master Plan provides a Business View on SES investment (SESAR JU, 2019a). Based on median estimates in the associated Companion Document (SESAR JU, 2019b), Table 3.5 details the anticipated investment need, totalling 29.5B€. Investments have been split over the period 2018 to 2030 and 2030 to 2035, reflective of the fact that the total SES(AR) contribution to CO_2 emissions reduction was modelled in Destination 2050 to occur between 2018 and 2035[23]. Moreover, it has been taken into account that 4B€ investments had already been made by 2018. This yields a total investment need for 2018 to 2035 of **25.5B€**.

[23] This means that 12/17 or 70% of the total investment occurs between 2018 and 2030 and 5/17 or 30% occurs between 2030 and 2035.

Table 3.5 Investment need for Single European Sky and SESAR (based on SESAR JU, 2019a; SESAR JU, 2019b)

Stakeholder	Investment need [B€] 2012-35 / 2018-30 / 2030-35			Remarks
ANSPs	13.1	8.0	3.4	
Airspace Users	7.5	4.6	1.9	Includes total 3B€ retrofit cost for mainline and regional airlines and business aviation, at 1M€ per aircraft. Excludes total 1.5B€ forward fit cost for aircraft, as that is included in fleet renewal.
Military	6.1	3.7	1.6	Cost breakdown uncertain. Likely to include investments out of the scope of this research.
Airports	1.2	0.7	0.3	20M€ per (very) large airport; 7M€ per medium airport; 3M€ per small airport.
Network Manager	0.9	0.6	0.2	
MET	0.2	0.1	0.1	
Total	**29.5**	**18.1**	**7.5**	**Totals 25.5B for period 2018 - 2035**

Additionally, Destination 2050 modelled a further 2 percent CO_2 emissions reduction potential through fuel and CO_2 optimised routing, to be realised between 2025 and 2040. This grows intra-EU+ SES(AR)-related CO_2 reductions from 5.1 percent to 7.1 percent - an increase of 40 percent. If one were to assume a linear relationship between CO_2 savings and investment cost, this additional emissions reduction would mean a 40 percent additional investment, equal to 10.3B€[24] over the period 2025 to 2040. This would however disregard the fact that the additional CO_2 emissions reduction can likely be realised with technology improvements delivered by SESAR (which are included in the associated 25.5B€ investment need identified previously), As some additional investment might be still required, this study conservatively assumes a possible **2B€** additional investment need.

Non-European ATM efficiency improvements

Besides a potential for CO_2 reduction in European airspace, realised by the implementation of SES(AR), efficiency improvements in non-European airspace are possible. Only applicable to intercontinental departures, these improvements could reduce fuel burn and emissions by 2.1 percent. Destination 2050 assessed that these improvements could be implemented by 2040.

As global estimates on the associated investment need are unavailable, it is approximated here based on the investment need for the Single European Sky and SESAR. For that, the previous section identified a 25.5B€ investment to realise a CO_2 reduction of 5.1 percent (based on figures for intra-EU+ flights) – equivalent to 5B€ for each percent. With a potential of 2.1 percent for non-European ATM efficiency improvement, the associated investment for those improvements is estimated to be **10.5B€**. This concerns an investment to be made outside Europe.

Improved North-Atlantic flight efficiency

Improvements in the flight efficiency over the North-Atlantic, specifically through the increased use of ADS-B and decommissioning the current North-Atlantic Organised Track System, could save almost 150kt of fuel and 0.5MtCO_2 per year. For the implementation period (2020 to 2027), this means a cumulative cost saving of 700M€. Annually, cost savings increase from 131M€ in 2030 to 302M€ in 2050 due to increased fuel and CO_2 costs. Also considering substantial progress (Young, 2021; Young, 2022), it is estimated that these costs savings cover the associated investment.

24 Computed as 40% of the sum of the investment needs for 2018 to 2030 (18.1B€) and for 2030 to 2050 (7.5B€).

Wake energy retrieval

Wake energy retrieval would reduce fuel burn and carbon emissions by 240kt and 0.75Mt by 2030 (at a value of 215M€). For 2050, these figures would rise to 1.1Mt kerosene and 3.5MtCO2, thereby realising a cost saving of 2.4B€. Over the 2025 to 2040 period during which wake energy retrieval was modelled to be implemented, cumulative cost savings associated to reduced fuel burn and CO_2 emissions are estimated at approximately 9B€. The infrastructure investments required to realise these savings, estimated at 3M$ per ANSP (ICAO, 2022), are therefore covered. As the savings are made by aircraft operators, whereas investments are also required from ANSPs, it is conceivable that airline savings can be partially used to fund these investments.

3.2.3 Ground operations at airports

The emissions from ground operations at airports studied in the Destination 2050 scope are limited to emissions from aircraft engines – either during taxi, or when parked at the gate. As such, reducing these emissions comes down to reducing taxi emissions and reducing APU usage. Costs identified thus exclude costs related to the decarbonisation of e.g. terminal buildings[25]. Given this study's focus on investment needs, operational costs by (additional) ground support equipment are also not included.

Reducing taxi emissions

Destination 2050 identified two groups of measures to reduce taxi emissions: reduced engine taxi (also referred to as single engine taxi) and electric taxi or operational towing. For the former, no investments are deemed necessary. For the latter, introduced between 2025 and 2035 for 80 percent of flights, investments are estimated from the implementation of TaxiBot (Smart Airport Systems, 2022). These hybrid tractors have recently been trialled at Amsterdam Airport Schiphol (Schiphol, 2020) and are able to tow aircraft from the gate to the runway, thereby reducing aircraft fuel burn. Even though other electric taxi solutions exists (see e.g. Lukic, Giangrande, Hebala, Nuzzo, & Galea, 2019; also van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), this analysis is focused on TaxiBot as it currently seems the most promising and market-ready option.

The price of a single TaxiBot unit is thrice as much as the price of a similar towing tractor (Jakub, 2014), meaning a price of 1.4M€ (Lukic, Giangrande, Hebala, Nuzzo, & Galea, 2019). Estimate costs for a twin-aisle compatible TaxiBot are double that amount – 2.8M€ (GreenAir Communications, 2012)[26]. The total number of TaxiBot units is derived from the number of flights per airport, typical airport-specific taxi-times (EUROCONTROL, 2019b; EUROCONTROL, 2019a) and a number of additional modelling assumptions:

- 3 minutes required to couple the TaxiBot to the aircraft;
- 2 minutes required to decouple the TaxiBot from the aircraft;
- TaxiBot utilisation of 6 hours per day.

[25] ACI (2021), supported by Oxford Economics, studied these in more detail.

[26] ICAO (2022) estimates electrical tugs (used to convey the aircraft to the runway) are only 30 to 35% more expensive than conventional tugs. This makes the estimate presented here conservative. On the other hand, ICAO separately accounts for charging stations, valued at 140k€. These costs are here assumed to be included in the purchase investment.

This brings the total number of TaxiBot units required (based on 2030 traffic) at EU+ airports to almost 3100[27], at a total cost of **4.7B€**. The number of units per airport varies substantially across airports: 409 of 515 EU+ airports in scope require at most 5 TaxiBots. For the approximately 100 remaining airports, the average amount of units is 21, with the major European hub airports (London Heathrow, Frankfurt, Amsterdam, Paris Charles de Gaulle and Madrid) needing more than 80. This variation in numbers also reflects variation in investment, averaging 9M€ and in case of 5 airports, growing beyond 100M€. When traffic increases by 2050, total investment for EU+ airport increases to **5.9B€** (+1.2B€) for a total of approximately 3900 units[28].

To handle intercontinental flights departing EU+ airports upon arrival, some 500 units are required at non-EU+ airports, at a cost of **1.1B€**. In most cases, just one or two TaxiBots suffice. In case of five non-EU+ airports, more frequently visited by flights departing from EU+ airports, more than 5 units and up to 19 TaxiBots are required per airport. In 2050, the number of units stationed at non-EU+ airports will have grown to about 570, increasing the total investment to **1.3B€** (+0.2B€).

Reducing APU usage by providing ground power and pre-conditioned air

In order to cut back CO_2 emissions from the use of aircraft APUs, electricity and pre-conditioned air (PCA) were modelled to be supplied to aircraft while they are parked at a contact gate or remote stand (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 79).[29]

The number of contact gates and remote stands is determined from average gate and stand numbers for different size groups of airports, based on an ACI EUROPE sample of 217 airports in 2019. The sum of the product of the number of gates or stands per airport and the number of airports in each size group, yields the total number of contact gates and remote stands, as indicated in Table 3.6.

Table 3.6 Estimated number of contact gates and remote stands for airports in scope, based on 2018 traffic

Group	Traffic Band (mppa)	Number of airports	Number of contact gates Average / min / max / total				Number of remote stands Average / min / max / total				Total
1	> 25	21	41	9	99	861	59	10	149	1239	2100
2	< 25 & > 15	11	23	9	29	253	49	17	110	539	792
3	< 15 & > 5	55	7	0	17	385	37	12	111	2035	2420
4	< 5 & > 1	99	3	0	9	297	15	0	32	1485	1782
5	< 1	334	0	0	6	0	4	0	18	1336	1336
All		**520**				**1796**				**6634**	**8430**

Due to a 0.8% annual growth in traffic movements, of which 50% is assumed to be accommodated by using existing infrastructure more efficiently, the number of contact gates and remote stands is likely to grow. This results in the totals per year presented in Table 3.7.

[27] ICAO (2022) estimates a need for 13000 tugs worldwide. Noting that approximately 30% of all international RPKs in 2018 was European (Graver, Rutherford, & Zheng, 2020), these numbers align rather well.
[28] This assumes all aircraft will make use of a TaxiBot (or similar) solution. For hybrid-electric and hydrogen-powered aircraft, however, self-taxi might be zero CO_2, such that towing solutions might not be required to mitigate these CO_2 emissions.
[29] The effectiveness of PCA might depend on local circumstances such as temperatures, seasonality and traffic. A total coverage of all parking stands with PCA might lead to under-used equipment at small/regional airports with highly seasonal traffic.

Table 3.7 Estimated number of contact gates and remote stands for airports in scope for 2018, 2030 and 2050

Year		Number of contact gates Total	Number of remote stands Total	Total
2018		1796	6634	8430
	Δ	+88	+326	+414
2030		1884	6960	8844
	Δ	+157	+578	+735
2050		2041	7538	9579

For 2018, a total of 1800 contact gates and 8430 remote stands is then found, increasing slightly towards 2030 (to 1890 and 8850) and 2050 (to 2040 and 9580) due to increases in traffic volume.[30]

Ground power

Cost of providing electricity depend on the way it is supplied. Two possibilities exist:

- Fixed installation (fixed electrical ground power or FEGP), at an approximated cost between 100 and 200k€ per installation, for only the unit itself, or the unit itself plus electricity provision (EC, 2021c, p. 64; Oxera, 2022, p. 13). An average of 150k€ is used for modelling.
- Mobile installation (electrical ground power unit or e-GPU), at an average cost of 170k€ per unit, based on input from ACI EUROPE member airports.

For small to medium twin-aisle aircraft (e.g. Airbus A330 and Boeing 787), costs are modelled to be double and for large twin-aisle aircraft (e.g. Airbus A350 and Boeing 777), costs are modelled to be quadruple (based on ACI World, 2021). The number of gates for twin-aisle aircraft is conservatively estimated at 10 percent of the total (8 percent for SMTA; 2 percent for LTA) and similarly, the number of twin-aisle remote stands (only SMTA, per ACI World, 2021) was modelled as 10 percent.

Table 3.8 Current fixed electrical ground power (FEGP) infrastructure

Range	Share of airports with range of gates and stands is equipped with FEGP	Average of range	Cumulative share of gates and stands equipped with FEGP, based on average of range
0	17.7%	0%	0.0%
1 – 10%	2.0%	5.5%	0.1%
11 – 20%	8.0%	15.5%	1.2%
21 – 40%	6.0%	30.5%	1.8%
41 – 60%	14.1%	50.5%	7.1%
61 – 80%	14.1%	70.5%	9.9%
81 – 100%	38.2%	90.5%	34.5%
All			**54.7%**

Based on a survey by ACI EUROPE (also referred to in EASA, EEA, & EUROCONTROL, 2019; EC, 2021c), it is estimated that about 55 percent of gates and stands are already equipped with ground power facilities, leaving 45 percent of existing gates (about 810 in 2018, growing to 1060 in 2050) and stands (3000 in 2018, growing to 3910 in 2050). Table 3.8 provides details of that.

30 The number of contact gates and remote stands was assumed to scale with 50% the growth in flight movements, determined to be 0.8% per year in Destination 2050 (sustainability scenario). The growth in flight movements was scaled by 50% following the assumption that part of the growth can be accommodated by increasing utilization of existing infrastructure.

Gates are modelled to be equipped with fixed installations. For remote stands, it is assumed that 1/3rd of stands will be equipped with a fixed installation and that the remaining 2/3rds of stands share one mobile unit per two stands. This yields a total investment figure of **490M€** for existing infrastructure (to be realised by 2025, per the implementation timeline provided in Destination 2050). By 2030, infrastructure expansion will add **55M€** and in the period between 2030 and 2050, further expansion will require an additional **95M€**. Total investments up to 2050 then total **640M€**. Table 3.9 provides further details, indicating total costs for FEGP for gates, FEGP for stands, and e-GPU for stands.

Table 3.9 Investment costs for ground power infrastructure

Year		Number to equip		Investment costs [M€]			
		Gates	/ stands	FEGP for gates	/ FEGP for stands	/ e-GPU for stands	/ Total
2018		813	3003	139.0	163.5	188.1	490.6
	Δ	88	326	15.1	17.7	20.4	53.2
2030		901	3328	154.1	181.2	208.5	543.8
	Δ	157	578	26.8	31.5	36.2	94.5
2050		1058	3907	180.9	212.7	244.7	638.3

Pre-conditioned air

Also for PCA, two main supply pathways exists:

- Fixed installation, in either centralised or decentralised form. Although it is acknowledged that costs can differ substantially per case, an average cost estimate of 240k€ (based on e.g. ACI World, 2021; FAA, 2021) is used for modelling. Depending on the implementation efforts necessary, total project costs could be higher.
- Mobile installation. Based on the cost for a fixed PCA installation and the cost difference between fixed and mobile ground power installations (150k€ versus 170k€), the cost for mobile PCA units is modelled as 270k€.

Costs for small to medium twin-aisle aircraft are identical to those for single aisle aircraft, whereas costs for LTA types (only served at contact gates) is twice as high (ACI World, 2021).

Alike Table 3.8, the left side of Table 3.10 shows the results of an 2018 ACI EUROPE survey on existing infrastructure for pre-conditioned air, used to derive an overall estimate of the share of contact gates and remote stands equipped is found. In 2018, PCA was available at some 27 percent of contact gates and remote stands, leaving 73 percent of existing gates (about 1300 in 2018, growing to 1550 in 2050) and stands (some 4810 in 2018, growing to 5720 in 2050) to be equipped.

Table 3.10 Current pre-conditioned air (PCA) infrastructure

Range	Share of airports with range of gates and stands is equipped with FEGP	Average of range	Cumulative share of gates and stands equipped with FEGP, based on average of range
0	43.1%	0%	0.0%
1 – 10%	13.7%	5.5%	0.8%
11 – 20%	3.9%	15.5%	0.6%
21 – 40%	3.9%	30.5%	1.2%
41 – 60%	13.7%	50.5%	6.9%
61 – 80%	7.8%	70.5%	5.5%
81 – 100%	13.7%	90.5%	12.4%
All			**27.4%**

Similar to modelling for electricity supply, it has been assumed that all contact gates and 1/3rd of the remote stands are equipped with a fixed PCA, with the remaining 2/3rds of remote stands sharing one mobile PCA-unit per two stands. The total investment to 2025 is then determined as **1.1B€** for existing infrastructure. For gates and stands built to accommodate increases in traffic, a further investment of **75M€** is required by 2030, followed by an (additional) investment of **140M€** between 2030 and 2050. By 2050, total investment will have summed to **1.3B€**. Again, Table 3.11 provides further details.

Table 3.11 Investment costs for pre-conditioned air infrastructure

Year		Number to equip		Investment costs [M€]			
		Gates /	stands	Fixed PCA for gates /	Fixed PCA for stands /	Mobile PCA for stands /	Total
2018		1303	4814	314.6	375.9	426.1	1116.6
	Δ	88	326	21.3	25.4	28.8	75.5
2030		1391	5139	335.9	401.4	454.9	1192.1
	Δ	157	578	37.8	45.2	51.2	134.2
2050		1548	5718	373.7	446.5	506.1	1326.3

3.3 Alternative fuels

A large part of the decarbonisation of aviation is the use of alternative fuels. Alternative fuels that contribute in 2050 are drop-in sustainable aviation fuels, hydrogen and renewable electricity. Drop-in sustainable aviation fuels are already being used in existing aircraft. Hydrogen and renewable electricity are for recharging hybrid-electric aircraft and refuelling hydrogen-powered aircraft in the future.

This sub chapter describes the minimum selling prices of the different types of alternative fuels in 2030 and 2050, based on literature review. No deviation was found compared to the prices mentioned in Destination 2050. The prices below therefore correspond to the prices mentioned in Destination 2050. These prices are based on the assumption that the construction of production facilities and infrastructure is included in the minimum selling price and will therefore also exceed the price of fossil kerosene. For comparison, the price of fossil kerosene is estimated at 600 euros per tonne in 2030 and 690 euros per tonne (excluding carbon pricing) in 2050.

3.3.1 Drop-in sustainable aviation fuel

Destination 2050 determined the potential of SAF based on the development of industrial production capacity and long-term policy framework (including the blending obligations). The supply of SAF is set to 3Mt (6 percent of total kerosene volume) in 2030 and 32 Mt (83 percent of total kerosene volume) in 2050. This means that SAF has a major contribution to net zero carbon emissions in 2050.

The expected production cost of SAF for the most promising pathways in 2030 and 2050 are sourced from the original Destination 2050 study, in which an extensive amount of literature was reviewed to arrive at expected minimum selling prices. These prices are minimum viable selling prices, which may differ from the final sales prices that fuel suppliers ask on the market. In case ranges of costs were found in literature, averages were used. Estimates for 2030 are based predominantly on announced production facilities and take into account a cost premium associated to many first-of-a-kind facilities. Estimates for 2050 are based on multiple scenarios and, due to the longer time horizon, inherently more uncertain.

The total annual costs for SAF depend on the pathway type and selling price per quantity of fuel. For 2030, these are shown in Table 3.12, leading to a total cost of 6.8B€. Compared to the price of fossil kerosene, estimated to be 600€/tonne in 2030 in the original Destination 2050 study (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), the total premium is 4.9B€.

Table 3.12 Overview of model assumptions in 2030

Pathways	SAF amount (Mt)	Price range (€/tonne)	Minimum selling price (€/tonne)	Total cost (B€)	Price premium w.r.t. fossil at 600€/t (M€)	Total premium (B€)
HEFA	1.4	938 - 1300	1170	1.6	570	0.8
Other biofuel pathways[31]	0.6	1296 - 4822	2765	1.7	2165	1.3
Power-to-liquid	1.2	1144 - 3125	2900	3.5	2300	2.8
Total	**3.2**			**6.8**		**4.9**

The same parameters are included to calculate the cost for 2050. However, multiple factors make the estimations of the SAF amount more uncertain for 2050 compared to 2030. Factors that influence the SAF amount are for example the economic capacity of the fuel industry to invest in new production facilities, political focus and the energy transition pathways for other sectors and competition with other sectors for the use of sustainable feedstocks. Based on the analysis in Destination 2050, the total costs are calculated to **53B€**.

[31] The cost estimate for SAF from other biofuel pathways are assumed 40% higher than average due to the use of first-of-a-kind facilities with require technological learning and upscaling (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 97).

Table 3.13 Overview of model assumptions in 2050

Pathways	SAF amount (Mt)	Price range (€/tonne)	Minimum selling price (€/tonne)	Total cost (B€)	Price premium w.r.t. fossil at 690€/t (M€)	Total premium (B€)
Biofuel	13	926 - 3444	1790	23	1100	14
Power-to-liquid	19	935 - 1675[32]	1557	30	867	16
Total	**32**			**53**		**30**

For the period between 2018 and 2050, total cumulative costs are interpolated. In that effort, SAF usage is assumed to linearly increase from 2022 to 2030, and again from 2030 to 2050. Prices between 2022 and 2030 are modelled as constant[33]. This yields an aggregate total of **689B€**. The price premium, compared to fossil fuel, over the period from 2018 to 2050 is found to be **440B€**.

3.3.2 Hydrogen for use by hydrogen-powered aircraft

In 2050, the original Destination 2050 report modelled 2/3rds of intra-EU+ single-aisle flights below 2000 kilometre to be operated by a hydrogen-powered single-aisle aircraft and hence use liquid hydrogen as fuel. The total amount of hydrogen consumed by these aircraft is estimated at 3.7 Mt in 2050. At an estimated cost of 2200€/tonne, derived in Destination 2050 (with price estimates ranging from 1800€/tonne to 2700€/tonne, van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 42), this yields a total cost of 8.1B€ in the year 2050.

To find the total aggregate cost over time (between 2035 and 2050), costs were modelled to linearly decrease from 3075€/tonne in 2035 (based on Trinomics, 2020; McKinsey & Company, 2020; van Wijk & Chatzimarkakis, 2020; FlyZero, 2022) to aforementioned 2200€/tonne in 2050, while the amount of liquid hydrogen consumed increases linearly from its introduction in 2035 to its final value in 2050. This yields a total cost of 78B€. As this costs also covers the investments explicated in Section 3.1.3 (totalling 16.4B€), an aggregate value of **62B€** is used in the remainder of this work. The price premium is less than 1B€.

3.3.3 Electricity for use by hybrid-electric regional aircraft

Renewable energy is energy from renewable non-fossil sources, such as solar, onshore and offshore wind energy. Based on research done by (Kalavasta and Berenschot, 2020), (IRENA, 2019a), (IRENA, 2019b) (Searle & Christensen, 2018), the expected price of renewable energy is set to be 56€/MWh in 2050. Since it is noticeable that the range varies widely, also confirmed by (Beiter, et al., 2021), this price is an average of levelized costs of energy (LCOE's) from the sources mentioned above. LCOE's are based on an average revenue per unit of electricity generated to cover the cost for building and operating the electricity plant, during an assumed financial life and life cycle of the plant. Taxes and grid fees are included as well. In Section 3.1.3 it, it has already been mentioned that an expected 1,300 GWh of renewable energy will be needed for hybrid-electric aircraft by 2050. The makes the total cost **72M€** for the year 2050**.**

Similar to the approach used for hydrogen cost, the cumulative cost between 2035 and 2050 was computed by linearly interpolating. Costs are modelled to decrease from 78€/MWh in 2035 to the previously mentioned 2050

32 Price range combines EU and non-EU power-to-liquid costs. EU prices range from 1530 to 1675€/tonne; non-EU prices vary between 935 to 1658€/tonne.

33 Even though unit SAF costs are likely to decrease over time, 2030 sees a more diverse mix of feedstocks, which yields an average price similar to current prices of SAF (produced using less heterogeneous feedstocks).

value, and usage linearly increases from 2035 to 2050 (Kalavasta and Berenschot, 2020; IRENA, 2019a; IRENA, 2019b; Searle & Christensen, 2018). The total obtained this way is **690M€**. The price premium is less than 1B€.

3.4 Economic measures and negative emissions

Destination 2050 modelled the use of economic measures to compensate for (part or all of) emissions remaining, after application of the aforementioned three pillars of in-sector decarbonisation measures. Both the EU Emissions Trading System (EU ETS) and ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) were considered, the former only applicable to intra-EU+ flights and the latter only to extra-EU+ flights. Table 3.14 summarises the modelling assumptions made in that work, slightly updated to reflect the updated results of Destination 2050 presented in 0[34].

As indicated in Table 3.14, any residual emissions remaining in 2050 are compensated for using carbon removal projects – relying on so-called negative emissions technology. Negative emissions can be defined as the removal of carbon dioxide from the atmosphere by human effort, after the CO_2 has already been emitted. Negative emission technologies (NETs) are the different ways and methods in which this removal of CO_2 can take place. Furthering the work presented in the previous Destination 2050 report, the remainder of this section assesses the available technologies, and provides cost estimates up to 2050 based on a thorough literature review.

Table 3.14 Overview of model assumptions in the Destination 2050 study concerning economic measures (updated and adapted from van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 143)

Year	Type of economic measure	Amount ($MtCO_2$)	Price (€/tonne)	Total cost (B€)	Remarks
2030	EU-ETS	65	60	3.9	Part auctioned allowances (50% CO_2 reduction) and part allowances bought from other sectors. 65 Mt of allowances yields 52 Mt CO_2 reduction.
	CORSIA	0	60	0	
2050	EU-ETS	1	315	0.3	All allowances issued due to carbon removal projects (Direct Air Carbon Capture and Storage in the EU+ region)
	CORSIA	21	160	3.4	Carbon removal projects (various types, global)

[34] Due to a slightly higher CO_2 emissions reduction realised by improvements in ATM and operations, the amount of economic measures to achieve an identical level of net CO_2 emissions was reduced.

3.4.1 Negative emission technologies

A multitude of negative emission technologies is currently studied or in development. This study (non-exhaustively) considers seven technologies:

1. AR – Afforestation and Reforestation
2. SCS – Soil Carbon Sequestration
3. BC – Biochar
4. EW – Enhanced Weathering
5. BECCS – Bioenergy with Carbon Capture and Storage
6. DACCS – Direct Air Carbon Capture and Storage
7. OF – Ocean Fertilization

All NETs have advantages and disadvantages. Therefore, in 2030, no technology can a priori be identified as optimal and thereby preferred. CO_2 removal strategies can involve a mix of technologies. This section gives a short description of all seven NETs considered, including their most important pros and cons (Nemet, et al., 2018). Table 3.15 provides an overview of these for all the NETs.

Afforestation and Reforestation (AR) both refer to the planting of trees, which will capture CO_2 as they grow (Fuss et al, 2018). Afforestation refers to the situation where trees are being planted on land that has not been afforested in recent history (i.e. less than 50 years). Reforestation is the planting of trees on land which has been deforested more recently. A large disadvantage of AR is the albedo effect. The albedo effect is the degree of reflection of solar radiation from an object, in which a higher albedo indicates higher reflection. Snow and ice have a very high albedo effect, around 90 percent. They barely retain any solar radiation and thus have a cooling effect on the earth. When planting large areas of forest on land which otherwise would be covered by ice or snow, this could retain more heat than it otherwise would have. Due to the albedo effect, the CO_2removal efficiency is highest in the tropics. Another disadvantage is that AR requires large amounts of land and is relatively easily reversible by future land use management decisions. An advantage of AR is that the costs are relatively low, compared to other NETs. Also, this technology does not need additional innovation or research in order to implement it at this moment. Its technological readiness makes it a viable option, especially in the short run (Fuss, et al., 2018).

Soil Carbon Sequestration (SCS) is the process of managing land so that soils absorb and hold more carbon. This can be done in various ways, including: (i) changing planting schedules or rotations, (ii) reducing soil disturbance by switching to low-till or no-till practices[35], (iii) manage grazing of livestock or (iv) applying compost or crop residues to fields. Tilling is beneficial in the short term, but causes harm in the long term. Costs of SCS are low and most side effects are likely to be less of an issue than for many other NETs, though sink saturation and reversibility (non-permanence) are significant drawbacks. SCS could be immediately implemented since the agricultural and land management practices required are generally well known by farmers and land managers.

Biochar (BC) refers to the process of burning biomass in a low-oxygen environment in order to produce a certain type of charcoal. This charcoal is then buried or added to soils, where it can remain for multiple decades or even centuries. If the emissions from production and transport do not negate the captured CO_2, and if other greenhouse gas emissions are not increased by the application of biochar, the overall greenhouse effect will decrease when biochar is applied (Roberts, Gloy, Joseph, Scott, & Lehmann, 2010). Biochar produces a product which can be used

[35] Low-till or no-till practices refer to the activity of 'tilling', which involves turning over the first 15 – 20 cm of soil before planting new crops. See Powlson et al. (2014) and Luo, Wang & Sun (2010).

to produce energy in industries where net zero CO_2 emissions are difficult to reach. However, in this case, this would not classify as NET, as the captured CO_2 will be released back into the atmosphere when used.

Enhanced weathering (EW) is the process of grounding selected rock material into ground rock powder and spreading this onto land or sea. Besides being a CO_2 removal strategy, EW can ameliorate soil deficiencies and act as a long-term nutrients source. Areas in which biomass is under nutrient limitation conditions are the most attractive targets for implementing EW (de Oliveira Garcia, Amann, & Hartmann, 2018). A drawback of this NET is the environmental and health concerns that are associated with mining of the materials. Another concern is the contamination of soil and water, due to the leakage of heavy metals from powdered rock. Overall, this technology has large research gaps. Publications so far are mainly based on model studies or theoretical discussions. The first major field trials are currently underway in Canada (Power, Dipple, Bradshaw, & Harrison, 2020).

Table 3.15 Advantages and disadvantages of negative emission technologies

NETs	Advantages	Disadvantages
AR - Afforestation and reforestation	• Price effectiveness • Innovation process	• Restricted; land • Albedo effect • Reversible; Dependent on future management
SCS - Soil carbon sequestration	• Land/water/energy footprint is zero • Improved health • Improved crop yield • Improved soil quality • Low costs	• Saturation (20 years) • Reversible • Measurement is difficult
BC – Biochar	• Improved soil quality • Energy production	• Reversible • Monitoring & verification
EW - Enhanced weathering	• Improved soil quality • Large potential	• Environmental and health concerns • Water contamination
BECCS - Bioenergy with carbon capture and storage	• Long-term; storage • Not vulnerable once stored	• High (initial) costs • Restricted; biomass • Restricted; land & storage • Innovation process • Storage
DACCS - Direct air carbon capture and storage	• Long-term; storage • Unlimited potential	• High (initial) costs • High energy use • Restricted; land & storage • Innovation process
OF - Ocean fertilization	• Ocean acidification	• Wide impact on ecosystems • Energy use • Trace metals • Short-term storage

Source: SEO Amsterdam Economics based on Minx et al. (2018) and Fuss et al. (2018).

Bioenergy with Carbon Capture and Storage (BECCS) is a NET that consists of two steps. The first step is the conversion of biomass into electricity, heat or liquid of gaseous fuels. The next step is the capturing of the carbon emissions that come from this bioenergy conversion and storing it or converting it into products. However, in order for BECCS to be carbon negative, the CO_2 needs to be removed completely from the CO_2 circle and stored, for example, in underground depleted oil and gas reservoirs. As with many NETs, one of the limiting factors is the amount of biomass available. This is dependent on many uncertain factors, among which the growth of the future population, diets and technological development. Another limiting factors are storage and land space (Smith, et al., 2015). Then there are the risks and uncertainties of very large-scale BECCS, like food insecurity, displacement of communities, biodiversity losses, increased fertilizer use, water resources and concerns about geological storage. In terms of technology readiness, the technology as a whole is relatively new and needs to be researched further in order to be scaled up in a significant matter.

The primary goal of **Direct Air Capture and Carbon Storage (DACCS)** systems is to remove CO_2 from the atmosphere and subsequently store the extracted CO_2 in a (geological) storage medium. It covers several different technologies, including chemical processes to capture and separate CO_2 from the atmosphere, and either put it in storage or use it in production. Only the first option, storage, would create negative emissions. The latter, use in production, for example, towards sustainable aviation fuels, would not be carbon negative (but 'only' carbon neutral) as the captured carbon would be released back into the atmosphere after used for combustion. A disadvantage of DACCS is the large amount of energy needed (Sanz-Pérez, Murdock, Didas, & Jones, 2016). Sufficient renewable energy sources are essential in order for DACCS to be considered a viable option. Another disadvantage is the limited storage and land combination necessary for large implementation, as also discussed with BECCS.

Ocean Fertilization (OF) considers the process of adding nutrients to the upper level of the ocean to increase marine food production and remove carbon dioxide from the atmosphere. This technology is not a viable negative emission strategy, especially compared to the other NETs, as the negative aspects of the technology (e.g. negative impact on ecosystems, energy use) outweigh the positives.

3.4.2 Costs and potential

Based on a selection of state-of-the-art meta-analyses, we derived the total CO_2 removal potential and cost of the negative emission technologies described above (see Table 3.16). Noteworthy is that this provides global outlook of the cost forecast, since regional cost of technologies might vary.[36]

Technologies with lower negative external costs (such as DACCS) tend to have higher initial cost and lower technological readiness, making these accessible only later at comparative prices.

Costs per ton of CO_2 removed vary significantly over the studies taken into account. This is due to variations in study methodology, scope and assumptions of the researchers. Therefore, Fuss et al (2018) takes a subset of authors from different articles in the literature review and have them assess the NETs of their expertise in terms of their costs and established a range of the costs per NET. An average of these ranges is taken in this review, so that the different technologies are more easily comparable. However, it is important to keep an eye on the ranges and take this into account when making decisions.

The same has been done for the data on potential. The same subset of authors, with all their own expertise in one or multiple NETs, have created the mentioned ranges of the potential of removed CO_2 by the year 2050 per NET. These ranges have been averaged out to simplify the comparison between NETs.

The last column shows the technological readiness of the NETs, also based on Fuss et al (2018). The technology readiness differs widely for all NETs. Afforestation and reforestation, Soil Carbon Sequestration and Biochar are

[36] In Destination 2050, different CO_2 price forecasts were used for intra-EEA emissions and emissions on flights outside the EEA, assuming that removing CO_2 inside the EEA is likely to be more expensive than CO_2 removal at a global level.

currently ready to be implemented on the large scale. Some other technologies, like BECCS, DACCS and Enhanced Weathering, appear to be more in the developing phase and are not yet ready for large-scale implementation.

Table 3.16 Negative emission cost and CO_2 removal capacity

NETs	$/t CO_2 by 2030	$/t CO_2 by 2050	Range	Average potential $GtCO_2$ removal per year by 2030	Average potential $GtCO_2$ removal per year by 2050	Technological readiness
AR - Afforestation and reforestation	$50	$27,50	$5 - $50 $18 - $30 $20 - $100	2.05	2.05	Already used for large scale implementation
SCS - Soil carbon sequestration	$100	$50	$0 - $100	3.5	3.5	Ready, but substantial upscaling necessary
BC - Biochar	$120	$75	$30 - $120 $8 - $300	1	1.25	Ready, but limited by cost and availability of facilities
EW - Enhanced weathering	$200	$125	$50 - $200 $33 - $578	2	3	Not ready. Major trial fields are under way
BECCS - Bioenergy with carbon capture and storage	$200	$150	$100 - $200 $70 - $250 $45 - $250	0.0003	2.75	Ready on small scale, but limited by economic reasons
DACCS - Direct air carbon capture and storage	$600	$315	$ 40 - $600 $100 - $300	1	2.75	First full operational plant by 2025

Source: Based on Minx et al. (2018) and Fuss et al. (2018). For the purpose of this study, the expected $/t CO2 in 2030 is assumed to be the maximum of the range and by 2050 the average.

Overall, it becomes clear that the different NETs can, and will have to, alternate. Some technologies that are ready for large-scale implementation now will saturate over a relatively short amount of time and/or are limited by factors such as available land, which is the case for most land management options (SCS, AR and BC). Another reason why these land management options are not the best choice after 2050, is that the marginal costs of abatement of these technologies are likely to increase with deployment, due to opportunity cost of land and the exhaustion of 'low-hanging' management options and deployment locations. Other technologies, especially DACCS, have great potential, but need time to develop. DACCS is unlikely to make a significant contribution to the goals of 2030, but is necessary to be developed for the long-term. This development is currently mainly restricted by the economic and energetic feasibility to scale-up.

3.4.3 Total cost implication

As the previous sections indicate, the costs of carbon removal differs – both with the type of NET used and with time. Given the 160€/tonne paid in CORSIA in 2050 and the costs per NET as shown in Table 3.16, reliance on a variety of technologies is likely. Due to its higher cost, DACCS is unlikely to play a major role in removing residual carbon emitted by intercontinental flights.

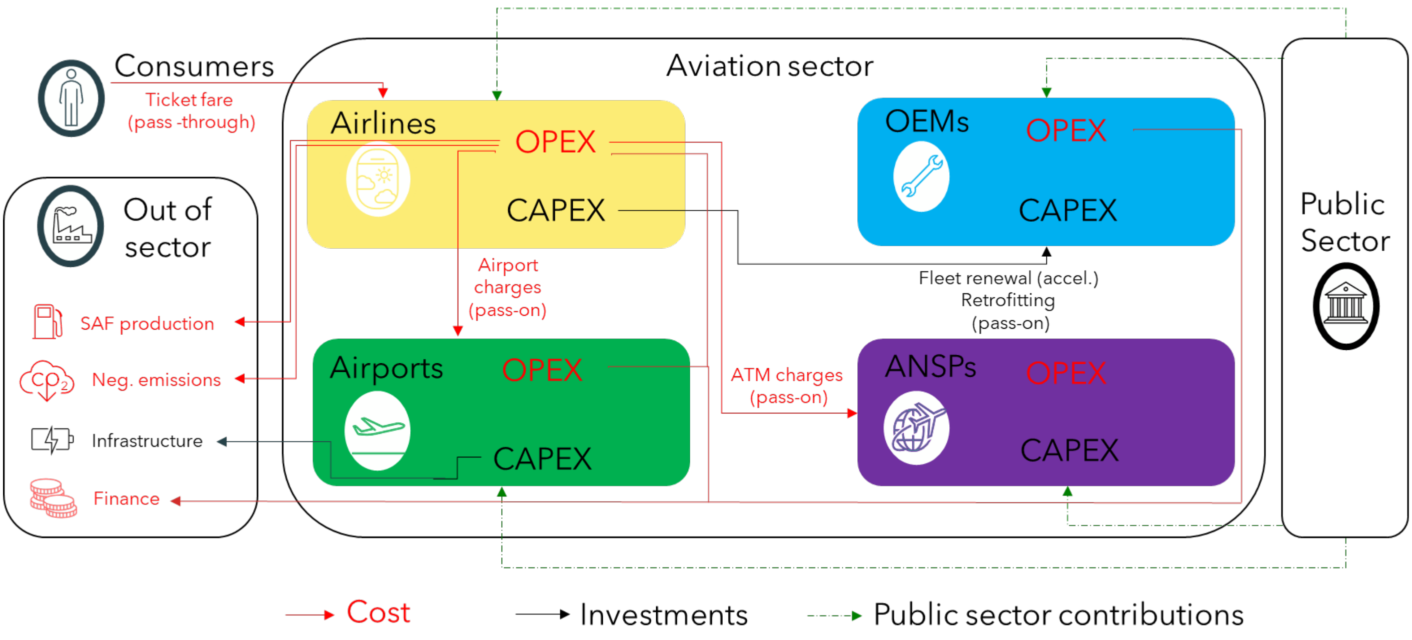
In order to maintain consistency with the Destination 2050 report as published in 2021, total costs are computed based on the carbon prices assumed in that work (summarised in Table 3.14). Cumulative costs for this pillar are determined using interpolation (of both carbon prices and amount of CO_2 to be paid for) between 2018 and 2030, and 2030 and 2050. For 2018 carbon prices, a value of 30€/tonne was modelled for both EU ETS and CORSIA. This yields a total of **152B€**.

4 The price of net zero

The aviation industry's additional expenditures required to achieve net zero emissions between 2018 and 2050 amount to €819 billion. These expenditures consist of costs and investments shared by stakeholders within aviation. Financing in-sector sustainability measures yields substantially lower costs than realizing the same emission savings through out-of-sector carbon reduction.

Most of the costs and investments required to achieve net zero emissions occur within the aviation sector itself. At the same time, these efforts are intricately linked to out-of-sector cash flows, the public sector as well as consumers. The monetary flows, namely all expenditures connected to achieving net zero, are schematically illustrated in Figure 4.1.[37] Costs and investments are not always easy to distinguish, especially due to the fact that long-term investment can be amortized through regular loan repayment cost over time. We attempt to make a clear distinction for the purpose of this study. Costs are here defined as expenditures with a short-term horizon between purchase and use. Costs are then part of the operational expenditure (OPEX). Investments have a long-term operational focus usually towards fixed assets and are therefore part of capital expenditures (CAPEX). The investment into operation of fixed assets can have direct implications towards operational expenditure, i.e. cost. For example, investment into newer airplanes might change the amount of SAF purchases and EU-ETS allowances in the future. The sum of cost and investments are defined as expenditures, essentially the price of achieving net zero emissions in aviation.[38]

Figure 4.1 Modelled cost and investment flows towards net zero emissions



[37] The figure includes some simplifications. For example, some of the costs and investments attributed to OEMs will (also) affect their suppliers, and some of the costs and investments linked to airports are actually borne by ground handling companies.
[38] Expenditures = Price of net zero = Industry efforts= cost +investment (cost)

The monetary flows within the aviation sector are a complex set of investments and costs taking place between the four main actors considered: airlines, aircraft manufacturers (OEMs), airports and ANSPs. Investments are marked in black, contributions from the public sector with a green dashed line and costs in red. The direction of the arrows in Figure 4.1 indicates the flow of expenses between the actors. Within sector expenditures such as R&D cost for OEMs are indicated by OPEX and CAPEX. For example, the organizational adjustment necessary for ANSPs are part of their OPEX. As previously stated, investments in CAPEX can affect the cost in OPEX. The direction of this interaction, increasing, decreasing, or a combination is a priori unknown. For example, investment in new aircraft by airlines (CAPEX) might introduce new cost for alternative fuels (electricity or hydrogen), but also decreases expenditures on EU-ETS due to emission reductions (both OPEX). Out of sector cost, such as for SAF infrastructure and transport are captured in the price of fuels, so that infrastructure and SAF cost are partially or fully matched.

Box 4.1 Pass-through/Pass-on

Airlines as provider of travel to consumers are the logical spot for most expenditures to originate. In the Destination 2050 study (p. 132), costs from economic measures EU-ETS and CORSIA were modelled to be passed on at 100 percent to consumers reducing travel demand with respect to the refence scenario without such measures. There is an intensive debate about pass-through rates in the aviation sector (see, for example, ICF Consulting; Air Transportation Analytics; NewClimate Institute; Cambridge Econometrics; HFW; Sven Starckx, 2020; Adler, Bonnekamp, & Konijn, 2022). For consistency and simplicity, we assume that all expenditures are passed-on between aviation actors at 100 percent. Public sector subsidies and investments can reduce the need to pass-on expenditures, for example, investment support towards R&D cost by OEMs. Such support is warranted when there is a societal interest in the outcome and the risks associated with necessary investment too large for private stakeholders as in the case with climate change and net zero technologies.

There are some caveats in the cost accounting of this study. For example, fleet renewal by airlines will cover the part of R&D of OEMs that is covered by public support contributions. Also, R&D by OEMs apply to products that are available on the world market. Hence, purchases of airlines outside the EU, cross-finance European net zero to a certain extent. This is partially taken into account in section 3 by cost accounting of similar investments by non-EU OEMs that do not enter R&D cost of this study. This implicitly assumes proportionality of net zero investments and global revenues of the OEMs.

4.1 Total and premium expenditures

The aviation sector's total expenditures towards net zero between 2018 and 2050 are about €1.9 trillion over the entire period, based on the cost accounting in Chapter 3. The largest share of these expenditures are towards fleet renewal at €820 billion and alternative fuels (drop-in sustainable aviation fuels, hydrogen and renewable electricity) at €751 billion as indicated in Table 4.1. The cost of the economic measures towards negative emissions constitute an additional €152 billion. A lower amount of investment is necessary for aircraft R&D by OEMs (€100 billion). The remainder are ATM, airline operations and ground operations at airports at €38 billion. Another €18 billion is foreseen as airport investment, in order to realise infrastructure for alternatively powered aircraft.

Besides presenting total expenditures, Table 4.1 lists the additional or 'premium' expenditures that Destination 2050 necessitates[39]. For most cost components, it is already clear that these are indeed a premium, compared to a

[39] The distinction between total expenditures and price premium with respect to business as usual are not clear cut. Hence we focus on total expenditures and give premiums when possible. Both perspective are interesting. Expenditures are relevant from a finance viewpoint of the industry whereas premiums are more a consumer and policy maker perspective.

scenario in which Destination 2050 would not be implemented. Examples are future aircraft R&D and the investments associated with airport ground infrastructure for new aircraft. In two cases, further clarification is appropriate:

- Fleet renewal: even if not for sustainability or fuel efficiency reasons, aircraft fleets need to be renewed to remain operational. Limiting fleet renewal to currently available aircraft (so-called upcoming types) would cost 740B€[40]. Compared to fleet renewal including (more expensive, as indicated in Table 3.3 in Section 3.1.2) future aircraft, this means a premium of 80B€.
- Airspace and air traffic management: as some of the costs related to airspace and air traffic management yield benefits beyond sustainability alone (e.g. capacity increase and delay prevention), it is assumed that half of the investments for Single European Sky and SESAR (25.5B€) and for Non-European ATM efficiency improvements (10.5B€) would have to occur anyway, such that the other 50% is counted as a premium. The 2B€ additional investment, linked to realising the 2 percent further CO_2 emissions reduction potential, is fully accounted for as premium. This yields a total premium of 20B€.

Table 4.1 Total and premium expenditures of realising Destination 2050

Pillar	Cost component	Report section	Total expenditures Destination 2050	Premium expenditures Destination 2050
Improvements in technology	Future aircraft research and development	3.1.1	100	100
	Fleet renewal	3.1.2	820	80
	Infrastructure for future aircraft	3.1.3	18	18
Improvements in ATM and operations	Airline operations	3.2.1	(cost neutral)	(cost neutral)
	Airspace and air traffic management	3.2.2	38	20
	Ground operations at airports	3.2.3	9	9
Alternative fuels	Drop-in sustainable aviation fuels	3.3.1	689	
	Price premium w.r.t. fossil kerosene			440
	Hydrogen	3.3.2	62	
	Price premium w.r.t. fossil kerosene			< 1[41]
	Renewable electricity	3.3.3	< 1	
	Price premium w.r.t. fossil kerosene			< 1
Carbon pricing / negative emissions		3.4	152	152
Total			**1888**	**820**

For alternative fuels, the price premiums with respect to fossil kerosene were used. The pillar for carbon pricing (/ negative emissions) is counted fully as premium expenditure. The share of premium expenditures towards net zero would be smaller if costs and investments were perfectly divisible (for example, if components towards aircraft sustainability could be bought separately and installed at no cost).

[40] This figure has been derived from omitting the 25% anticipated increase in list price of future aircraft, discussed in Section 3.1.2, especially Table 3.3.

[41] The investment related to hydrogen refuelling infrastructure is already accounted for under the 'Infrastructure for future aircraft' heading. The remaining price premium of hydrogen compared to fossil kerosene is relatively negligible in the context of overall Destination 2050 expenditures.

4.2 Comparison with out-of-sector carbon reduction

In addition to the identification of premium expenditure in Section 4.1, this section compares costs of the sustainability measures modelled in Destination 2050 to a scenario in which the same emissions reduction is to be achieved, but no in-sector decarbonisation action is taken. This assumption is supported by the increasing level of policy and regulations working towards net zero CO_2 emissions by 2050 (e.g. EC, 2019; EC, 2021b), or advocacy work towards creating such targets and measures to achieve this (French Presidency of the Council of the European Union, 2022)[42].

In order to make an as-fair-as-possible comparison, this section includes for both the Destination 2050 and out-of-sector scenario all fuel and CO_2 emissions costs. The out-of-sector scenario has been aligned with the reference (emissions) scenario presented in Destination 2050 (labelled a 'hypothetical no-action growth scenario') in terms of traffic development and baseline emissions. The difference between the baseline emissions and the net emissions is the emission reduction that in the out-of-sector scenario is realised through carbon pricing (i.e., carbon compensation and/or negative emissions projects)[43].

Consistent with the way in which premium expenditures were determined in Section 4.1, the out-of-sector scenario still includes a limited number of investments, in two categories:

- Fleet renewal: as indicated before, fleet renewal will need to occur in order for fleets to remain operational. In the out-of-sector scenario, two situations are considered:
  - FR1. Fleet renewal without improvements in fuel burn. This aligns most closely to the reference emissions scenario in Destination 2050. It assumes that aircraft are renewed at their typical rate (22.5 years) and are replaced by aircraft of the upcoming generation, as these are the only ones currently available for order. Even though these aircraft realise fuel burn improvements, these improvements are not taken into account. As fleet replacement is also necessary by 2050, it is assumed that these aircraft will remain in production indefinitely. Over that period, the sales price of an individual airframe is assumed to remain constant to the cost identified in Section 3.1.2 (Table 3.2, specifically).
  - FR2. Fleet renewal with improvements in fuel burn. In this case, fleet renewal happens according to the same logic as in the previous situation (replacement by upcoming aircraft, availability up to 2050 and constant sales price), but fuel burn improvements and associated emissions savings are taken into account. This results in lower (fossil) fuel and emissions costs in this variant of the reference scenario. It has better internal consistency, but deviates more from the Destination 2050 reference scenario for emissions.

  In both situations, fleet renewal costs are lower than in the Destination 2050 scenario. This is due to the fact that the future aircraft, which are not included in the out-of-sector scenarios but are part of the Destination 2050 scenario, were in Section 3.1.2 anticipated to be more expensive (Table 3.3).
- Airspace and air traffic management: as indicated before, it is assumed that half of the costs for Single European Sky and SESAR (25.5B€; i.e., excluding the 2B€ additional investment assumed to realise the 2 percent further CO_2 emissions reduction potential) and for Non-European ATM efficiency improvements (10.5B€) will occur.

Table 4.2 shows that the out-of-sector scenario is more expensive in both fleet renewal situations (FR1 and FR2). The cost difference is largest when comparing the Destination 2050 scenario to out-of-sector scenario FR1, as that

42 Nevertheless, the out-of-sector scenario is more stringent than policies and regulations currently in effect, especially with respect to intercontinental flights (CORSIA).

43 Whereas it is likely that such carbon pricing will affect demand (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), this is not modelled in the reference scenario.

scenario does not include fuel burn improvements. Scenario FR2 does include these to some extent and accordingly, has a smaller cost difference compared to the Destination 2050 scenario.

Table 4.2 The total expenditures of achieving Destination 2050 compared to two out-of-sector scenarios. FR1 does not take fuel efficiency improvements realised by fleet renewal into account; FR2 does.

Pillar	Cost component	Total expenditures Destination 2050 (B€)	Expenditures out-of-sector (B€) FR1	FR2
Improvements in technology	Future aircraft research and development	100		
	Fleet renewal	820	740	740
	Infrastructure for future aircraft	18		
Improvements in ATM and operations	Airline operations	(cost neutral)		
	Airspace and air traffic management	38	18	18
	Ground operations at airports	9		
Alternative fuels	Drop-in sustainable aviation fuels	689		
	Hydrogen	62		
	Renewable electricity	< 1		
Fossil fuel		730	1489	1302
Carbon pricing / negative emissions		152	765	689
Total		**2618**	**3012**	**2749**
Difference with Destination 2050 scenario			**+ 393 (+ 15%)**	**+ 130 (+ 5%)**

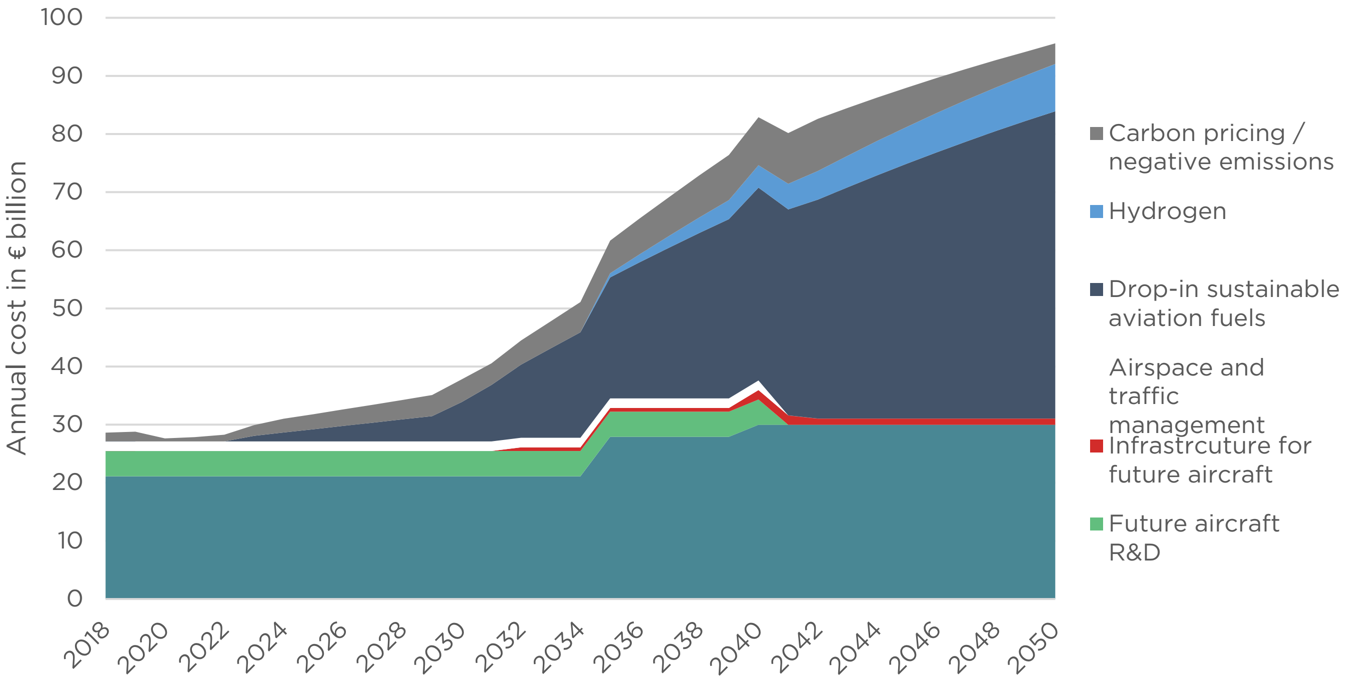
As stated previously, these cost comparisons do not take into account all operational expenditures, such as MRO, personnel costs, and fees and charges. (The sum of these costs components was assumed to remain unchanged, regardless of the scenario.) This means that relative cost comparisons between these scenarios cannot be made based on the figures reported here.

4.3 Expenditures over time

The expenditures of the aviation sector towards net zero are based on our findings in Chapter 3 and Section 4.1, depicted over time in Figure 4.2.[44] Expenditures start at €31 billion in 2018 and increase over time to € 98 billion in the year 2050. Annual average expenditures total €59 billion.

[44] Due to increased uncertainty from 2030 and especially 2035 onwards, the introduction and delivery date of measures has often been estimated at a resolution of five years (i.e., rounded to five years). For some of those years, this results in step changes. In reality, these are likely smoothened out.

Figure 4.2 Cumulative Net zero expenditures Destination 2050 by aviation sector over time



Variations in the annual cost over time are caused by modelling choices with respect to the introduction and scale-up of particular measures, consistent with the timelines assumed in the previous Destination 2050 study (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Working across the wedges shown in the graph from bottom to top, the following changes can be identified over time:

- Fleet renewal cost increase in 2035 and 2040, due to the introduction of higher-cost future aircraft (Section 3.1.2);
- The expenses for future aircraft R&D considered in this report end in 2040, when the latest of the future aircraft types enters into service (Section 3.1.1);
- Costs associated to infrastructure to support the operation of future aircraft are modelled from 2032 onwards; three years prior to the introduction of the regional hybrid-electric and hydrogen-powered single-aisle aircraft (Section 3.1.3).
- The investments in airspace and ATM end in 2040, when all measures are implemented.
- Costs for sustainable aviation fuels rise substantially over time, following the increased uptake of SAF.
- Hydrogen costs start in 2035 with the introduction of the hydrogen-powered single-aisle and rise over time, in line with fleet penetration timelines.
- Economic measures vary over time in order to comply with regulation, including an update to CORSIA in 2035, raising its ambition level to work towards net zero CO_2 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Besides the changes in the amount of carbon emissions covered by economic measures, the cost per tonne varies with time, resulting in changes in total annual cost.

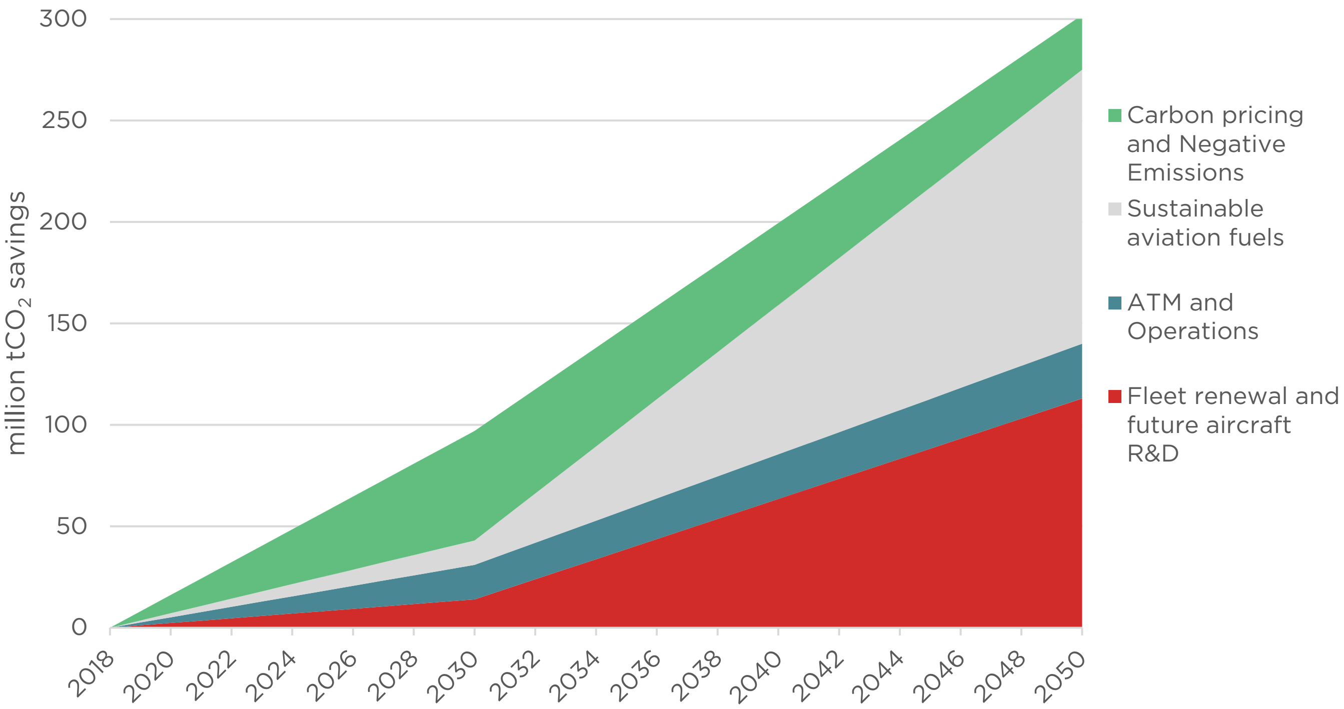
Further investments supporting the transition to net zero will be necessary beyond 2050, in terms of further fleet renewal, the realisation of necessary infrastructure, and to accommodate activity growth. We do not count these expenditures outside the horizon of Destination 2050. The historical full expenditures between 2018 and the end of 2021 amount to 122B€.

The are several well documented economic principles connected to cost accounting over time, namely, depreciation, replacement rate and economies of scale, that are of relevance here. The cost detailed in Chapter 3 account for economies of scale, as far as these are foreseeable currently. The replacement rate for fixed assets such as airplanes is taken into account but renewed replacement of upgraded airport infrastructure that might be necessary due to utilization is not predictable currently. Depreciation of these fixed assets beyond fleet renewal is not taken into account.

4.4 CO_2 savings and efficiency

The Destination 2050 measures are linked to associated CO_2 savings. We show these expected CO_2 savings stacked over time in Figure 4.3. We infer the annual CO_2 saving contribution as linear approximation between the reference years 2030 and 2050, see also Table A.1 and A.2 in the Appendix respectively.[45]

Figure 4.3 Sustainable aviation fuels, fleet renewal and R&D bring about the highest CO_2 savings



CO_2 savings from fleet renewal and R&D savings are jointly reported, similar to ATM and operational improvements. SAF and economic measures include demand reductions from higher consumer prices. In-sector reductions should be preferred instead of out-sector reductions (e.g., EU-ETS) since the latter have high exposure risk to out of sector reduction aims.

From the CO_2 savings above and expenditures in Section 4.1 we can infer CO_2 efficiency. Lower expenditures per tCO_2 removed indicates a higher efficiency. The efficiency of economic measures depends on the availability and the price of EU-ETS allowances as well as global policies such as CORSIA. Fleet renewal is inefficient by comparison to remove CO_2 but a necessity for use of SAF and alternative fuels, as shown in Table 4.3. Improvements in ATM and

[45] Historical savings prior to 2018 are omitted here, e.g., from fleet renewal. Linear developments up to and beyond transition point in 2030 are a crude approximation of reality.

operations are highly efficient, with €85 per ton CO_2 reduced. Similarly, negative emissions technologies and economic measures have a suitable efficiency but contain technological and economic risks. As (part of) the decarbonisation potential of various pillars are interlinked (e.g. technology improvements and alternative fuels), the table cannot be used to unilaterally prioritise investments.

Table 4.3 Total expenditures per pillar, associated CO_2 savings, and average efficiency

Pillar	Cost components	Total expenditures (B€)	CO_2 reduction (Mt)	Average efficiency (€/tCO_2)
Improvements in technology	• Future aircraft R&D • Fleet renewal • Infrastructure for future aircraft	938	1410	665
Improvements in ATM and operations	• Airline operations • Airspace and ATM • Ground operations at airports	47	555	85
Alternative fuels	• Drop-in SAF • Hydrogen • Renewable electricity	751	1609	467
Carbon pricing / negative emissions		152	1148	132
Total		**1888**	**4820**	**392**

4.5 Taxonomy

The EU Taxonomy Regulation for sustainable finance endeavours to classify investments and establish a list of environmentally sustainable economic activities (EC, 2020). As such, the Taxonomy Regulation would provide companies, investors and policymakers with appropriate definitions for environmentally sustainable economic activities (EC, 2021a). The aviation sector faces challenges demonstrating the sustainability of their activities, limiting the sector's potential to access green or sustainable financing (Norton Rose Fulbright, 2021). Limited access to sustainable finance could increase the cost of capital for the aviation sector.

In a study commissioned by the European Commission, Steer (2021) developed a methodology to assess the green impacts of investments in the aviation sector and projects. The report considers four sub-sections within aviation, being:

- Aircraft related: manufacturing, maintenance and technology development;
- Fuel production, storage and distribution;
- Air traffic management;
- Airport related: airport operations, ground handling and airport infrastructure.

These economic activities mainly contribute to the Taxonomy Regulation objectives 'climate change mitigation' and 'pollution prevention and control'. In order to qualify as contributing substantially to climate change mitigation, it must qualify as a "low-carbon activity", a "transition activity" or an "enabling activity". In addition, eligible activities must "do no significant harm" to any of the other objectives in the Regulation (i.e. Do No Significant Harm or DNSH criteria).

Low-carbon activities should increase clean or climate-neutral mobility, for example by operating aircraft powered by clean fuels (hydrogen, electric or advanced biofuels).

Table 4.4 Examples of low carbon, transition and enabling activities in the air transport sector

	Low carbon	Transition	Enabling
Aircraft related	Sale, lease or operation of any aircraft powered by clean fuels (electric, hydrogen), or advanced biofuels	Sale, lease or operation of aircraft above a threshold level in terms of CO_2 reduction. The threshold increases over time and varies by aircraft size class.	Manufacturing of aircraft powered by 'clean' fuels
Fuel production			Production of advanced biofuels (already in Taxonomy Framework Production of electrofuels with GHG emissions savings of 70% compared to fossil fuels.
ATM & operations	Investments in zero-emissions ground service equipment; investments in taxi-bots.		ATM R&D and deployment categorised by SESAR as being in line with the scenarios and solutions delivering environmental benefits. Activities/investments in line with implementation of (cross-border) Free Route Airspace (FRA)
Airport related		Infrastructure for storage and delivery of SAF.	Infrastructure to support supply of renewable electrical power. Infrastructure for storage and delivery of zero carbon fuels.

Transition activities are more difficult to determine. The Taxonomy Regulation states that economic activities may qualify as transitional if low-carbon alternatives are not technologically or economically feasible. In this case, the activity should have greenhouse gas emissions that correspond to the best performance in the sector. Moreover, such activities should not hamper development or deployment of low-carbon alternatives, nor should they lead to a lock-in of carbon-intensive assets.

Activities qualified as enabling are activities that are needed to make one of the environmental objectives technologically or economically feasible, for example the manufacturing of aircraft powered by 'clean' fuels. Steer (2021) provides a number of examples of investments in aviation and how they could be classified (see Table 4.4).
The Platform on Sustainable Finance provides recommendations on technical screening criteria for the environmental objectives of the Taxonomy regulation for (i) manufacturing of aircraft, (ii) leasing of aircraft, (iii) Passenger and freight air transport and (iv) Air transportation ground handling operations (Platform on Sustainable Finance, 2022b).

4.5.1 Manufacturing of aircraft

Climate change mitigation criteria

- **Low carbon activity:** Zero-emission aircraft (e.g. electric or green hydrogen)
- **Transitional activity:**
    - Until 2027, commercial aircraft (excl. business aircraft) meeting "best in class" criteria, and for which delivery does not increase the global fleet.
    - From 2028 to 2032, aircraft meeting the "best in class" criteria and have 100 percent SAF compatibility.
    - From 2033, aircraft meeting future criteria to be defined later.

DNSH criteria

- Climate change mitigation conditions do not compromise safety or airworthiness of aircraft
- For transition to a circular economy, aircraft manufacturing should adopt techniques that support reuse and recycling of raw materials and components. Waste management plans need to ensure maximal reuse or recycling at the end of life)
- With regards to noise and engine emissions, manufacturers should at least comply with the latest regulations set out by ICAO (Chicago Convention) or the relevant EU regulations.

For leasing of aircraft, similar conditions apply.

4.5.2 Passenger and freight transport

Climate change mitigation criteria

- **Low carbon activity:** Operations performed using zero emission aircraft (e.g. electric or green hydrogen).
- **Transitional activity:**
  - Operations performed using aircraft as mentioned under transitional activity for aircraft manufacturing, and do not increase the global fleet. This is ensured by either (i) multiplying the economic activity by the global ratio [aircraft decommissioned/aircraft delivered], or (ii) for which the new aircraft replaces another aircraft in the fleet (either decommissioned or sold).
  - From 2030 onwards, aircraft operators should use at least 10 percent of SAF, increased by 2 percentage points annually thereafter, for aircraft meeting the transitional criteria for manufacturing. For less fuel-efficient aircraft, the share of SAF should be 5 percent in 2022, increased by 2 percentage points annually thereafter.

DNSH criteria

- Climate change mitigation conditions do not compromise safety or airworthiness of aircraft
- Measures should be put in place to prevent generation of waste during the use phase of aircraft, and recycle waste after aircraft life.
- With regards to noise and engine emissions, manufacturers should at least comply with the latest regulations set out by ICAO (Chicago Convention) or the relevant EU regulations.

4.5.3 Ground handling operation

Climate change mitigation criteria

- All ground handling vehicles, devices and equipment should have zero emissions.

DNSH criteria

- For de-icing activities, measures should be in place to ensure the necessary discharge controls to reduce the environmental impact on watercourses and ecosystems.
- Measures should be in place to manage waste, including the reuse and recycling of batteries and electronics.

4.5.4 Overview

The aviation sectors expenditures towards achieving net zero detailed in the previous section are substantial. There are various potential sources for these cost and investments, as shown in Table 4.5. For cost components in terms of fuels and negative emissions, investments takes place outside the aviation sector. The other components are investments and therefore associated with a taxonomy. Throughout the study and also for the precursor study, we assume that capital is available by the time it needs spending. Hence, if finances are not available, then investments occur later and net zero by 2050 cannot be guaranteed.

Table 4.5 Source, type and taxonomy overview

Components	Public vs. private	Investment vs. cost	Finance taxonomy
a. Future aircraft R&D	Private and public Private: new aircraft Public: high risk R&D	Investment	Transitional and green Transitional: efficient kerosene aircraft Green: zero-carbon aircraft
b. Fleet renewal	Mostly private	Investment	Transitional and green Transitional: efficient kerosene aircraft Green: zero-carbon aircraft
c. Airport infrastructure	Private and public Private: Revenue generating projects Public: Subsidies replacement	Investment	Transitional and green Transitional: more efficient ground ops. Green: SAF infrastructure
d. ATM & operations	Private and public	Investment	Transitional and green Transitional: more efficient ATM Green: electric taxing
e. Alternative fuels	Private and public Public funding possible to reduce price gap (examples) to prevent negative connectivity effect	Cost	Out of sector investment
f. Economic measures and negative emissions	Private	Cost	Out of sector investment

5 Public support mechanisms

Several public support mechanisms are available to help financing the necessary investments for net zero aviation. Public support mechanisms exist on both the EU and the national level. The EU-level mechanisms that are fully dedicated to sustainable aviation are the Clean Aviation Partnership and SESAR III.

5.1 Available public support mechanisms

The necessary investments to achieve net zero European aviation in 2050 can partly be financed through public support mechanisms. These mechanisms are available on both the EU and the national level. In this chapter we discuss the following EU-level public support mechanisms:

i. Aviation-specific mechanisms;
ii. Mechanisms for economy-wide sustainability;
iii. Regional development funds;
iv. Financial instruments (e.g. bank guarantees and loans);
v. Subsidies for semi-public research institutes.

Subsequently, we examine the following two national level mechanisms:

i. Aviation-specific mechanisms;
ii. Mechanisms partly dedicated to aviation.

5.1.1 Public support mechanisms on the EU-level

The EU provides two public support mechanisms that are fully dedicated to sustainable aviation. These are the Clean Aviation Partnership and SESAR III. The former funds research and development of novel aircraft, e.g. hybrid and electric aircraft. The latter supports research efforts to make airspace management more efficient and sustainable. Both mechanisms are part of Horizon Europe. The European Commission grants €3.4 billion through these mechanisms in the period 2021 – 2027 (see Table 5.1). Next to the EC, other (private and/or public) parties also contribute to these projects.

There exists also EU-level public support mechanisms for sustainability, which are not sector specific. Part of their funds can be used for financing net zero aviation. The Innovation Fund is the largest EU-mechanism for economy-wide sustainability. It provides €25 billion of funding from 2021 to 2030 (see Table 5.1). Through this mechanism the EU supports the development of low-carbon technology. This fund may, for example, be used to develop hydrogen-powered aircraft. Other EU-level public support mechanisms focused on sustainability include Horizon Europe (program climate, energy and mobility), InvestEU (sustainable infrastructure program) and LIFE (clean energy transition program). These mechanisms provide respectively €11.7, €9.9 and €1 billion of funding over the period 2021-2027 (see Table 5.1).

The regional development funds of the EU are also important public support mechanisms for financing net zero aviation. These funds represent approximately a third of all available funding on EU level. Through these funds the European Union The aim of these funds is to support the development of less prosperous EU regions. The largest regional development fund is the European Regional Development Fund. It provides € 215 billion of funding over the period 2021-2027 (see Table 5.1). The aim of the European Regional Development Fund is to reduce inequalities between European regions. Part of the funding is used for making less prosperous regions more sustainable. For that reason, the European Regional Development Fund provides opportunities for funding of sustainable aviation initiatives. Other regional development funds are the Modernisation Fund and the Just Transition Fund. These funds provide respectively €14 and €19 billion of funding in the period 2021-2027 (see Table 5.1).

Investments in sustainable aviation are also supported by the EU through the provision of financial instruments (like loans and bank guarantees). The European Investment Bank (EIB) is the most important provider of financial instruments. The EIB also supports investments in sustainable aviation. For example, the EIB lent €250 million to ENAV, the Italian air navigation service provider, to make investments in ATC infrastructure possible (EIB, 2017).

The clean hydrogen partnership of the EU can be used for financing investments in hydrogen aircraft. The European Union contributes € 1 billion to this partnership. This project is part of the climate, energy and mobility program of the EC Horizon Project. The research agenda of the partnership shows that among others research into on-board storage of hydrogen and safety of hydrogen aircraft is funded. The partnership is not fully dedicated to aviation: also research into the application of hydrogen in other transport modes and the production and storage of hydrogen is funded (Clean Hydrogen JU, 2021).

Research and development towards net zero aviation is also indirectly supported by the EU through subsidies to semi-public research institutes. This is an important support mechanism, since a substantial part of research and development towards net zero aviation is done by these research institutes. In Europe there are fourteen semi-public research institutes that conduct research into aviation. They cooperate via the Association of European Research Establishments in Aeronautics (AEREA). An example of this cooperation is the Future Sky research initiative.[46] Within this initiative the research institutes collaboratively research new propulsions systems (like hydrogen or electric engines), innovative aircraft architectures and energy on board systems.

It is important to note that the EU is usually not involved in the allocation of regional funds available on the EU-level. This task is delegated to the member states. Since all member states can allocate regional funds according to their own criteria, the efficiency of these public support mechanisms on the EU-level is of interest. An improvement of sustainability efficiency might be possible with further coordination of member states. For example, by taking into account benefits of synergy that could arise between research projects funded by different member states.

Some EU-level public support mechanisms are only loosely related to sustainable aviation. For example, the Digital Europe Programme (DIGITAL) funds projects that widen the use of digital technologies. A small part of these funds might go to the aviation sector, since digital technologies are also used in newly developed aircraft.[47] We did not include this type of mechanisms in Table 5.1.

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46 https://futuresky.eu/themes/energy/
47 https://digital-strategy.ec.europa.eu/en/activities/digital-programme

Table 5.1 From 2021 to 2027 the European Commission grants € 3.4 billion through aviation-focused mechanisms

Fund	Industry	Period	EU Contribution (in € billion)	Relevant goals for aviation industry
		Aviation-specific support mechanisms		
Horizon Europe (Clean Aviation partnership)	Aviation	2021-2027	1.7	Reducing aircraft emissions
Horizon Europe (SESAR III)	Aviation	2021-2027	1.7	An efficient and sustainable airspace
		Support mechanisms focused on sustainability		
Innovation fund	General	2021-2030	25	Low-carbon technologies. Fund provided by EU ETS revenues.
Horizon Europe (program climate, energy and mobility)	Energy and mobility	2021-2027	10.7	Renewable energy and sustainable mobility
InvestEU (program sustainable infrastructure)	Infrastructure	2021-2027	9.9*	Sustainable infrastructure through bank guarantees
LIFE (program Clean energy transition)	General	2021-2027	1	Energy-efficient, renewable energy-based, and climate-neutral and –resilient technology
Horizon Europe (Clean hydrogen partnership)	Energy and mobility	2021-2027	1	Clean hydrogen technologies
		Regional development funds		
European Regional Development Fund	General	2021-2027	215	Reduce inequalities between European regions
Just Transition Fund	General	2021-2027	19	Sustainable economy in lower-income EU regions
Modernisation fund	General	2021-2030	14	Climate-neutrality lower-income EU regions Fund provided by EU ETS revenues.

Source: SEO Amsterdam Economics based on government websites
Notes: i) Amounts marked with * are contributions in the form of bank guarantees

ii) The Clean Aviation partnership, the integrated ATM partnership and the Clean Hydrogen partnership are part of 'Horizon Europe – program climate, energy and mobility'. As these partnerships (partly) focus on the aviation industry they are listed separately in the table. To avoid double counting the EU contribution for 'Horizon Europe – program climate, energy and mobility' in the table excludes these three partnerships.

5.1.2 Public support mechanisms on the national level

In addition to EU-level support mechanisms, investments in net zero aviation can also be financed through national public support mechanisms. According to Air Transport Net (2016) thirteen EU member states provide national mechanisms for aviation R&D.[48] Seven member states have aviation-specific public support mechanisms. The other six member states provide mechanisms that are partially dedicated to aviation. These mechanisms can be used to finance the necessary R&D efforts to realize net zero aviation.

Most national public support mechanisms do not solely provide funding for R&D. For example, eight mechanisms also organize network events for aviation researchers. Thanks to these events new research projects can arise. There are also five mechanisms that - next to providing funding - facilitate staff exchanges between institutions for aviation R&D.

The national public support mechanisms differ in the phase(s) of the R&D cycle they target. Five national mechanisms support the innovation phase of aviation R&D. In the innovation phase researchers develop concepts of future technologies. An example is designing an aircraft that uses solar panels as energy source.[49] Nine of the thirteen national public support mechanisms provide funding for the development phase of aviation R&D. In this phase prototypes of technology are developed and subsequently tested. For example, testing new aircraft technology in a wind tunnel belongs to this phase. The public support mechanisms of Austria, Belgium, Greece, Malta and Switzerland provide funding for the market introduction phase. In summary, the largest amount of public support on the national level goes towards the development phase of R&D (Air Transport Net, 2016).

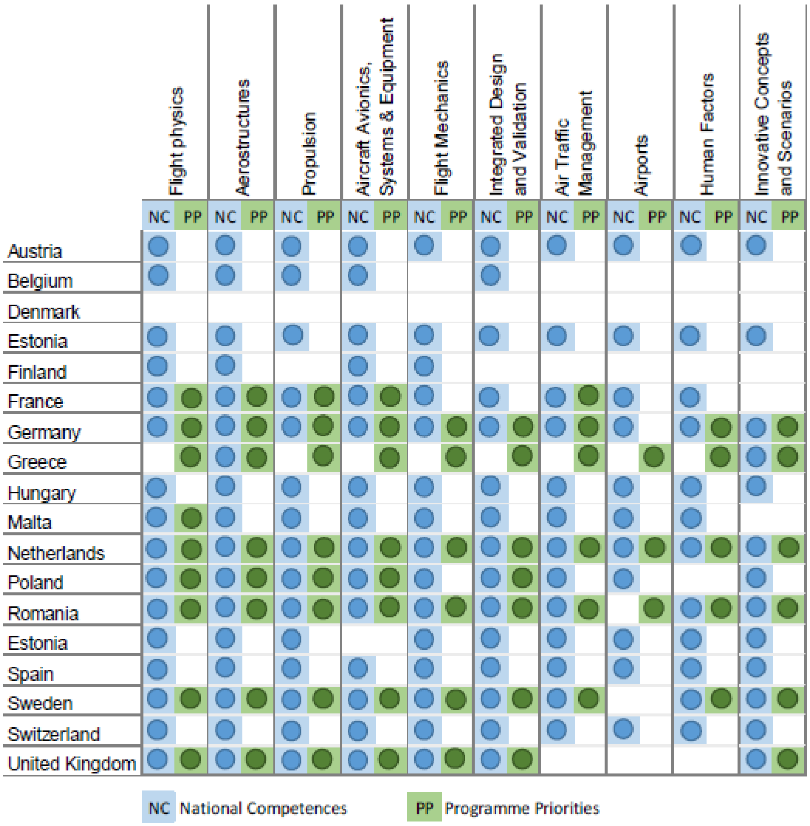
Figure 5.1 shows that the majority of national public support mechanisms target all possible fields of aviation R&D. Only the mechanisms of France, Malta, Poland and the United Kingdom prioritize certain fields of aviation R&D. Like is the case with EU-level funding, the absence of specialization creates room for improving the effectiveness and efficiency of public support. When every member states focuses its public support on one field of aviation R&D economics of scale can be created.

The German public support mechanism provides the largest amount of funding for aviation R&D, namely € 300 million over the 2016 – 2020 period. The Swedish public support mechanism comes in second place with € 46 million of funding over the 2017 – 2021 period. The third largest amount of funding is provided by the Polish mechanism, namely € 30 million from 2017 till 2020 (Air Transport Net, 2016). National and regional funding is highly complex and legally challenging, with an assessment of available budget and opportunities for further efficiency gains a worthy goal for a separate, more detailed study.

48 Air Transport Net (2016) does not provide information about the following ten member states: Bulgaria, Cyprus, Czech Republic, Ireland, Italy, Latvia, Lithuania, Portugal, Slovakia and Slovenia.

49 Jiajan et al. (2019) provide a tentative design for an aircraft powered by sun panels.

Figure 5.1 Most national public support mechanisms target all fields of aviation research



Source: Air Transport Net (2016)

5.2 Outlook

Various public support mechanisms are available to help financing the necessary investments for net zero aviation. Despite the presence of these public support mechanisms, private parties within the aviation industry also need to provide funding. One of the reasons being that the EU and the national governments require that public funds provided through a support mechanism are matched with private funds. For example, the European Commission contributes €1.7 billion to the Clean Aviation Partnership, whereas private partners to this program contribute approximately €2.4 billion.[50]

Estimations carried out by the Clean Aviation Partnership provide an illustration of the subdivision of funding between the aviation industry and public support mechanisms Clean Aviation Partnership, 2020). According to these estimations, research activities to develop an ultra-efficient short-medium range aircraft and a hybrid electric regional aircraft require €12 billion of funding. Around half of the funding (€5-6 billion euro) is expected to be covered by public support mechanisms on both the European and the national level. The remainder is covered by the aviation industry. Note that these estimations are of rough order of magnitude and only pertain to the period 2021 – 2030. Moreover, only research activities are taken into account (e.g. product development is not included).

[50] https://www.clean-aviation.eu/clean-aviation/participation

It is important to investigate whether sufficient public support mechanisms are available in every phase of the R&D cycle to realize the necessary investments for net zero aviation. The reason being that the necessary amount of investments differ over the R&D cycle. For example, product development requires substantial more investments than research and development. Lack in funding within a certain phase of the R&D cycle might be a reason for the EU and/or individual member states to set up new public support mechanisms.

6 Conclusions

The European aviation industry will require to spend a premium of €820 billion to decarbonize in line with its ambitions. The expenditures involve both investments in assets such as new aircraft and infrastructure as well as cost towards alternative aviation fuels and negative emissions. Achievement of net zero CO_2 emissions by 2050 is dependent on available finance from the private and public sector.

This study assess the necessary expenditures of the aviation sector towards achieving net zero aircraft CO_2 emissions from all flights within and departing from the EU+ by 2050. It adds a cost and investment identification to the pre-cursor study Destination 2050 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Expenditures over the 32 year time horizon can be split into costs and investments, and into premium and business as usual expenditures.

The **costs** premiums are:
- €441 billion towards sustainable aviation fuels (54%),
- €152 billion for economic measures, i.e. emission trading and negative emission technologies (19%),

The **investments** premiums are:
- €100 billion for future aircraft research and development (12%),
- €80 billion towards the zero emission fleet renewal (10%),
- €29 billion for airspace and air traffic management, and ground operations at airports (3%),
- €18 billion for airport infrastructure in support of alternatively fuelled future aircraft (2%).

Expenditures increase over time due to sharp cost increases after 2035 – mainly caused by increased use of SAF. Investments were found to be rather constant, with the exception of limited increases due to the higher cost associated with future aircraft, entering service from 2035 onwards.

Total expenditures and business as usual

Expenditures needed to reach net-zero emissions in 2050 require additional efforts compared to a business as usual development of the aviation sector. The premiums paid towards new aircraft technologies, ATM, SAF and negative emissions amount to €819 billion, whereas BAU-only costs would be €1.1 trillion, yielding a total expenditure of €1.9 trillion. Fleet renewal is then the largest expenditure with €820 billion (43% of the overall total).

Out-of-sector decarbonization

Alternatively to realising net zero CO_2 largely through in-sector action, it is theoretically possible to achieve the same goal by out-of-sector carbon reduction alone. As fuel efficiency in this case is left unimproved compared to today, fuel cost savings will not be realised. Moreover, the costs for economic measures and negative emissions technology will decrease substantially. Total expenditures, including cost of fossil fuel, will then potentially rise from €2.6 trillion (in the in-sector decarbonisation scenario) to €3 trillion. In addition to increasing cost, such a scenario dramatically increases risk for the sector due to price uncertainties of negative emissions technologies. Moreover, it introduces risk in the form of a dependency on out-of-sector measures to achieve the net zero emission goal.

Taxonomy and sources of finance

A successful, on-time transition is dependent on the access to finance from the private sector and public investments, both conditional on legislation. Financing in-sector sustainability measures yields substantially lower costs than realizing the same emission savings through out-of-sector carbon reduction. It is therefore essential to reach a successful on-time transition to sustainable measures within the aviation sector.

Access to finance to make the net zero transition appears to be vital when capital reserves are insufficient to make large upfront payments for new aircraft and infrastructure. Ensuring access to finance for aviation is crucial towards achieving the net zero goal. Having access to 'green' finance following the Taxonomy Regulation is therefore of key importance, particularly for the measures that are crucial to achieve the D2050 goals. Public support mechanisms make high risk investments into new technologies feasible for the aviation sector, reduce cost pass through to consumers and thereby reduce the risk of competitive distortion and carbon leakage.

Caveats and out of scope

The pillars of Destination 2050 are technically complex and economically uncertain. The costs of future technologies and inputs are by necessity based on forecasts and therefore always an approximation and subject to change. The recent past has highlighted high volatility in carbon abatement cost in the form of EU ETS. SAF availability and prices will be crucial in the upcoming years.

Consistent with the Destination 2050 pathway, the present study is focused on and limited to CO_2 emissions resulting from the combustion of kerosene. Emissions that are generated through other means, such as energy generation for airport electivity and airplane manufacturing and operation of airport vehicles are not included. This topics deserve further attention. Similarly, 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). Furthermore, this study is limited to expenditures with a direct relation to aviation carbon emissions, meaning that expenditures related to (e.g.) maintenance, repair and overhaul, personnel costs, and other fees and charges are not included in the estimates shown.

This report is based on expected prices and regulation that are consistent with Destination 2050. Current political developments that affect the aviation market, such as the conflict between Russia and Ukraine cannot be accounted for in the current methodology due to the high uncertainties and associated complexities. Furthermore, the discussion around aviation's non-CO_2 climate effects and the associated necessary expenditures to reduce these are a suitable area for further investigation.

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Appendix A Destination 2050

Destination 2050 identified four groups of measures – called 'pillars' – that can help reduce CO_2 emissions in order to realize net zero CO_2 emissions:

1. Improvements in aircraft and engine technology;
2. Improvements in ATM and aircraft operations;
3. Use of sustainable aviation fuels;
4. Economic measures.

The emission reduction potential of the four measures was estimated on the basis of a literature review, interviews with experts from industry and model calculations. CO_2 reductions were compared against a hypothetical no-action growth scenario, in which no measures were taken. The following sections discuss the contributions of the different pillars.[51]

Improvements in aircraft and engine technology

Destination 2050 estimated that improvements in aircraft and engine technology through both upcoming and future aircraft result in a decrease of CO_2 emissions from European aviation by 79 Mton in 2050. This equals a 28 percent decrease in CO_2 emissions compared to the reference scenario. Thanks to improved technology, new aircraft are more fuel efficient than their predecessors. As a result, these aircraft emit less or no CO_2. New aircraft are introduced into the market through fleet renewal, modelled based on average aircraft lifetimes of 22.5 years.

Future aircraft, including a hydrogen-powered single-aisle aircraft modelled to enter into service from 2035 to serve intra-EU+ routes of 2000 kilometres and below, contribute the most to the reduction in CO_2 emissions.

Improvements in ATM and aircraft operations

Improvements in air traffic management (ATM) and aircraft operations were estimated to decrease CO_2 emissions by 27 Mton in 2050, representing a 9% decrease compared to the reference scenario. Destination 2050 considered a wide array of improvements within this pillar, distinguishing between improvements in airline operations, airspace and air traffic management, and ground operations at airports. The airline operations groups encompasses for example improvements in flight planning and operational weight saving. Airspace and ATM considers the Single European Sky and other ATM efficiency improvements, including wake energy retrieval. Ground operations at airports relate to emissions reductions through more sustainable taxiing and reducing APU usage.

Sustainable aviation fuels

SAF (sustainable aviation fuel) makes a major contribution to realizing net zero in 2050. According to Destination 2050, SAF decreases CO_2 emissions from European aviation by 125 Mton, or 42%. In order to be sustainable, SAF should be produced from sustainable feedstock. Examples include cooking oil, agricultural residues or forestry residues. It is also possible to convert sustainable electricity into SAF, which yields synthetic fuel. Destination 2050 focused on SAF from non-food crops and residues, and renewable electricity and modelled averaged life-cycle CO_2 emissions savings of 72% in 2030 and 98% in 2050.
The effects in 2030 are more limited, as SAF availability – and therefore use – is limited at 6%. Some 7 Mton of CO_2 can be prevented. According to Destination 2050, the share of SAF can increase to 83 percent in 2050, resulting in

[51] Tables A.1 and A.2 give an overview of the emission reduction per type of measure in 2030 and 2050. The emission reductions mentioned in the tables in Appendix A marginally deviate from those mentioned in Table 44 and 45 in the Destination 2050 report, due to a revision in assumptions.

a CO_2 emission reduction of 125 Mton. To make this possible a long-term policy framework boosting production and off-take of SAF is essential.

As SAF is more expensive than fossil kerosene, the use of SAF will result in higher costs for airlines, in turn resulting in higher ticket prices. The subsequent reduced demand and number of flights is estimated to reduce CO_2 emissions by 34 Mton in 2050.

Economic measures

Economic measures are also important for realizing net zero European aviation, especially in the short term. Destination 2050 estimates that economic measures reduce CO_2 emissions of European aviation by 52 Mton in 2030 and by 22 Mton in 2050. This equals respectively a 25% and a 7% decrease in CO_2 emissions compared to the reference scenario.

Economic measures attach a price to CO_2 emissions to make sure that airlines consider climate costs in their business operations. Destination 2050 modelled the emission reduction effect of two economic measures:

- **EU ETS:** This measure covers all intra-EU+ flights. Within EU-ETS allowances for emissions are auctioned off. Revenues of the auctioned allowances are subsequently invested in sustainability projects. These sustainability projects cause a decrease in emissions.
- **CORSIA:** this measure covers all extra-EU+ flights. Within CORSIA airlines need to offset emissions that exceed a certain threshold. The D2050 roadmap assumes that until 2035 this threshold is the emissions emitted by international aviation in 2019.

In 2030 economic measures cause the majority of the emission reductions. The reason being that improvements in aircraft and engine technology require time to develop and materialise into airlines' fleets and that SAF supply was found to be limited. As these pillars make a larger impact in 2050, the contribution of economic measures is then reduced.

As for SAF, economic measures increase costs for airlines. The resulting increase in ticket prices and reduced air travel demand reduces CO_2 emissions by 2 percent in 2050.

Updated results

Tables A.1 and A.2 show an update to the Destination 2050 results for 2030 and 2050.

Table A.1 Change in emissions in 2030 compared to the reference scenario

	Total		Intra-EU+		Non-EU+	
	Mton	%	Mton	%	Mton	%
Total CO_2 emissions in the reference scenario	208		87		121	
CO_2 emissions reduction due to demand impacts						
Improvements in aircraft and engine technology-induced demand impacts (hydrogen-powered aircraft)	0	0%	0	0%	0	0%
Sustainable aviation fuels-induced demand impacts	-5	-2%	-1	-2%	-3	-3%
Economic measures-induced demand impacts	-2	-1%	-2	-2%	0	0%
Improvements in aircraft and engine technology,						
Kerosene-powered or (hybrid)-electric aircraft	-14	-7%	-7	-8%	-7	-6%
Hydrogen-powered aircraft	0	0%	0	0%	0	0%
Improvements in ATM and aircraft operations	-17	-8%	-8	-9%	-9	-8%
Sustainable aviation fuels	-7	-3%	-3	-3%	-4	-3%
Economic measures	-52	-25%	-52	-60%	0	0%
Total CO_2 emission reduction	-97	-47%	-73	-84%	-24	-20%
Total CO_2 emissions sustainability scenario	**111**		**14**		**96**	

Table A.2 Change in emissions in 2050 compared to the reference scenario

	Total		Intra-EU+		Non-EU+	
	Mton	%	Mton	%	Mton	%
Total CO_2 emissions in the reference scenario	293		115		178	
CO_2 emissions reduction due to demand impacts						
Improvements in aircraft and engine technology-induced demand impacts (hydrogen-powered aircraft)	-2	-1%	-2	-1%	0	0%
Sustainable aviation fuels-induced demand impacts	-34	-12%	-8	-7%	-27	-15%
Economic measures-induced demand impacts	-5	-2%	0	0%	-5	-3%
Improvements in aircraft and engine technology						
Kerosene-powered or (hybrid)-electric aircraft	-51	-18%	-8	-7%	-43	-24%
Hydrogen-powered aircraft	-58	-20%	-58	-50%	0	0%
Improvements in ATM and aircraft operations	-27	-9%	-12	-10%	-14	-8%
Sustainable aviation fuels	-95	-32%	-27	-24%	-67	-38%
Economic measures	-22	-7%	-1	-1%	-21	-12%
Total CO_2 emission reduction	-293	-100%	-115	-100%	-178	-100%
Total CO_2 emissions sustainability scenario	**0**		**0**		**0**	

Appendix B Investment details related to fleet renewal

This appendix contains additional information related to Section 3.1.2.

List prices of upcoming aircraft

Table B.1 shows the list prices of upcoming aircraft. Multiplication by the class-based discount rates (shown in Table 3.2) yields the sales price (not shown). Dollars have been converted to Euros based on an exchange rate of $0.85/€.

Table B.1 List prices of upcoming aircraft

Class	Aircraft type	List price [M€]	Source(s) and remarks
R	ATR 72-600	24.7	Jane's Group UK Limited (2020)
	Embraer E175-E2	45.3	Based on cost difference between E175 and E190 (7 to 10%) and E190-E2 cost
	Embraer E190-E2	49.3	Jane's Group UK Limited (2020)
SA	Airbus A220-100	68.6	Airbus (2018)
	Airbus A220-300	77.5	Airbus (2018)
	Airbus A319neo	85.9	Airbus (2018)
	Airbus A320neo	93.6	Airbus (2018)
	Airbus A321neo	109.7	Airbus (2018)
	Airbus A321neoLR	117.7	Based on A321neo cost, plus 50% of cost difference between A320neo and A321neo
	Airbus A321neoXLR	125.7	Based on A321neoLR cost, plus 50% of cost difference between A320neo and A321neo
	Boeing 737MAX7	81.3	Boeing Commercial Airplanes (2018)
	Boeing 737MAX8	99.2	Boeing Commercial Airplanes (2018)
	Boeing 737MAX9	105.1	Boeing Commercial Airplanes (2018)
	Boeing 737MAX10	110.0	Boeing Commercial Airplanes (2018)
	Embraer E195-E2	56.4	Jane's Group UK Limited (2020). Sales price computed with discount rate for Regional class.
SMTA	Airbus A330-800	220.1	Airbus (2018)
	Airbus A330-900	251.0	Airbus (2018)
	Boeing 787-8	202.4	Boeing Commercial Airplanes (2018)
	Boeing 787-9	238.4	Boeing Commercial Airplanes (2018)
	Boeing 787-10	275.9	Boeing Commercial Airplanes (2018)
LTA	Airbus A350-900	268.8	Airbus (2018)
	Airbus A350-1000	310.3	Airbus (2018)
	Boeing 777-8	334.4	Boeing Commercial Airplanes (2018)
	Boeing 777-9	360.5	Boeing Commercial Airplanes (2018)

Number of aircraft

Table B.2 Number of aircraft in 2018 and 2050 fleet

Class	Number of EU+ registered aircraft 2018	% of ASKs by non-EU+ operators	Total number of aircraft 2018	/ 2050
R	1050	0%	1050	1350
SA	1760	32%	2320	2990
H_2-SA[52]	1550	0%	1550	2000
SMTA	350	38%	490	630
LTA	490	45%	710	910
All	**5200**		**6120**	**7880**

Table B.3 Share and number of aircraft per generation in 2050 fleet

Class	Entry-into-service year for future aircraft	Share per aircraft generation		Number of aircraft per generation		
		Future[53]	/ Upcoming	Total /	Future	/ Upcoming
R	2035	66.7%	33.3%	1350	900	450
SA	2035	66.7%	33.3%	2990	2000	990
H_2-SA[54]	2035	66.7%	33.3%	2000	1330	670
SMTA	2035	66.7%	33.3%	630	420	210
LTA	2040	40%	60%	910	410	500
All				**7880**	**5060**	**2820**

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52 The hydrogen-powered single-aisle aircraft was modelled only for intra-EU+ routes up to 2000 kilometres. The number of aircraft in the H_2-SA group is the number of aircraft used for intra-EU+ routes up to 2000 kilometres. Due to the explicit intra-EU+ scope, 0% of these ASKs are operated by non-EU+ airlines.

53 Computed from (2050 – EIS) / 22.5.

54 The hydrogen-powered single-aisle aircraft was modelled only for intra-EU+ routes up to 2000 kilometres. The number of aircraft in the H_2-SA group is the number of aircraft used for intra-EU+ routes up to 2000 kilometres. Due to the explicit intra-EU+ scope, 0% of these ASKs are operated by non-EU+ airlines.

Appendix C Impact of accelerated fleet renewal

Box 3.1 in Section 3.1.2 briefly discussed accelerated fleet renewal. As this was not included in the modelling for Destination 2050 (see van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 52), it has not been included in the main modelling effort of this report. Alternatively, this appendix approximates the investment and sustainability consequences of such a measure.

As described in Destination 2050, it would apply to airframes aged 15 years or more in the baseline year (2018), meaning they should be built in 2003 or before. Accelerated replacement would then need to occur between 2021 and 2025, as aircraft built in or prior to 2003 would have already been replaced by 2025 at regular fleet renewal rates. This also reduces the number of eligible aircraft remaining in service in 2022.

For the remainder of the analysis, accelerated fleet renewal is looked at from two perspectives:

1. Early replacement of existing by upcoming aircraft, taking the 15 years cut-off at either baseline year 2018 or baseline 2022
2. Early replacement of upcoming by future aircraft from 2035, when a more substantial step-change – possibly even to zero-carbon aircraft – can be made.

Early replacement of existing by upcoming aircraft

The following analyses look at the accelerated fleet renewal of existing aircraft by upcoming aircraft. Airframes are eligible for accelerated fleet renewal if they are 15 years or older by the baseline year.

Key examples of aircraft to be retired early are older models of the ATR72 in the regional class, the Airbus A320 and Next Generation Boeings 737 in the single-aisle class, the original Airbus A330 (-200 and -300) and the Boeing 767 in the small/medium twin-aisle class and Airbus A340s and Boeing 747s and 777 in the class of large twin-aisle aircraft.

Baseline year 2018

With the baseline year selected as 2018, aircraft built in or before 2003 are eligible for accelerated fleet renewal. Table C.1 shows the share of EU+ registered aircraft that meet that criterion and is subsequently used to compute the total number of eligible aircraft. The total cost of replacing these 2170 aircraft is 172B€.

Table C.1 Share of aircraft aged 15 years or more and number of aircraft eligible for accelerated fleet renewal

Class	Number of EU+ registered aircraft in 2018	% aircraft aged 15 years or more in 2018	Number of aircraft in 2018 Total /	Eligible for accelerated fleet renewal
R	1050	28%	1050	290
SA	3310	32%	3870	1240
SMTA	350	53%	490	260
LTA	490	53%	710	380
All	**5200**		**6120**	**2170**

With an average fleet replacement rate, these aircraft would have been replaced between 2018 and 2025. In the accelerated case, without taking into account possible limits with respect to production output, these are modelled to be replaced between 2018 and 2022. This means that between 2022 and 2025, fleet renewal only occurs because of the introduction of additional aircraft to accommodate increasing traffic activity. The accelerated transition to upcoming aircraft does not influence further fleet renewal, meaning that it does not influence the number of upcoming aircraft to be replaced by future aircraft, once these become available. It also does not affect the total investment need, but merely shifts investments forward.

Baseline year 2022

In case of a 2022 baseline, aircraft built in or before 2007 are eligible for accelerated fleet renewal. Again taking a period of 4 years, this should be completed by 2026. Without early retirement, these aircraft would have been replaced by 2029.

In this case, the accelerated replacement of existing by upcoming aircraft does affect the next phase of fleet renewal, in which upcoming aircraft are replaced by future types. Specifically, an additional 4.5% of the upcoming fleet of aircraft will have to be replaced by a future aircraft by 2050.[55] This moves a 18B€ investment anticipated in 2051 (and thereby out of scope of the main study) to 2050.

Early replacement of upcoming by future aircraft

Alternatively to accelerating the replacement of existing by upcoming aircraft, accelerated fleet renewal towards future aircraft is considered. Anticipated reductions in CO_2 emissions are more substantial for the transition from upcoming to future aircraft (30% or more) than for existing to upcoming aircraft (between 15 and 25% depending on class, per van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 30).

The analysis presented in Section 3.1.2 as well as Table B.3 in Appendix B, indicated that by 2050, about 1/3rd of all aircraft will be of the upcoming generation, built between 2028 and 2035. Again using a maximum age of 15 years would mean that this entire share of the fleet – encompassing 2820 airframes – would be eligible for accelerated fleet renewal. This would move an investment of 251B€, otherwise occurring between 2050 and 2057, forward. With that, it would accelerate decarbonisation substantially in the period between 2043 and 2050 – and/or reduce reliance on out-of-sector compensation measures.

Accelerated fleet renewal might be especially interesting for that part of the fleet that can be replaced by hybrid-electric regional turboprops (reducing CO_2 by 50% compared to upcoming aircraft) and zero-carbon hydrogen-powered single-aisle aircraft. In the former class, 450 aircraft would be eligible for a total investment of 14B€. In the latter, 670 aircraft would meet the eligibility criteria, which could be early-replaced by investing some 65B€.

Box C.1 Decelerated fleet renewal – an alternative means to the same end?

Alternatively to replacing upcoming aircraft built between 2028 and 2035 early, the lifetimes of aircraft built between 2006 and 2012 could be extended. If these aircraft would not be retired after the typical 22.5 year period but could remain operational until future aircraft are introduced into service, they could immediately be replaced by future aircraft – rather than being first replaced by upcoming aircraft as an 'intermediate' solution. This will slow the pace of decarbonisation between 2028 and 2035, but the fact that the reduction in CO_2 emissions realised by future aircraft compared to upcoming types is larger than that by upcoming compared to existing models makes good for this. Again, that especially holds for aircraft to be replaced by hybrid-electric regional turboprops or hydrogen-powered single-aisle aircraft.

[55] Computed from 1 / 22.5 = 4.5%.

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seo • amsterdam economics

Roeterstraat 29
1018 WB, Amsterdam
The Netherlands

+31 20 525 1630
secretariaat@seo.nl
www.seo.nl