Hydrogen-based fuels for European aviation

A prospective life cycle assessment applying scenario analysis

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TU Delft

Universiteit Leiden

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by

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Cover image: Large ‘H_2’ and smaller aircraft against blue background. Design by the author.

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Abstract

Through exploratory scenario development, this study delves into the environmental impacts of European commercial aviation. Climate targets and the adoption of alternative aviation fuels (AAF) following ReFuelEU Aviation are assessed, considering e-fuel produced from direct air capture (DAC) and hydrogen aircraft. A novel method is applied, combining the generation of prospective life cycle inventories based on integrated assessment models with technology forecasting, system dynamics, and scenario development. This enables reflection on not only aircraft performance, but also fuel production, aircraft manufacturing, and fleet dynamics. Although there are limitations, including the relatively simple approach to system dynamics and limited data availability, clear conclusions can be drawn. Even for high-growth trajectories of air traffic, the total fuel demand of aviation could stagnate by 2035 under highly ambitious circumstances. Lower air traffic would require less ambitious circumstances. Combined with the reduced impact of AAF on aviation-induced cloudiness modelled here, the radiative forcing associated with aviation could reach a peak by 2050. However, the current scope of ReFuelEU Aviation does not prevent this peak from being eclipsed again by 2070. To prevent this, the mandate for a 70% share of AAF by 2050 should be followed up with a mandate for a 100% share. Thereby, warming neutrality is within reach – provided the necessary technologies can be implemented at scale. Hydrogen propulsion makes more efficient use of resources than e-fuel does, which is relevant for some impact categories, but less so for climate change as assessed here. When considering the magnitude of radiative forcing, present projections fall short. Estimating a budget of CO_2 emissions through a grandfathering approach of the targets set by ICAO and IATA, the budget is exceeded by 2070, even with the most optimistic technological advancements. Critical here is the high use of fossil fuel leading up to 2035, for which there are no timely technological solutions. Lacking offsetting opportunities that are reliable, large-scale, and long-term, the only option is to restrict the volume of air traffic. Reducing traffic to 70% of the 2019 passenger-kilometers can be sufficient to respect the CO_2 limit, even without optimistic developments in aircraft technology. This challenges conventional narratives, which advocate against demand management, claiming this would limit technological innovation. Thereby, evidence is created in support of the degrowth discourse which has gained momentum in recent decades. To ensure that aviation can provide long-term societal benefits, near-future flight activity must be redistributed to future generations. Given the boundaries and uncertainties of the presented scenarios, a much-needed discussion is encouraged: what share of global environmental limits is aviation – and within that, European aviation – entitled to?

Preface

The process of forming, adapting, and combining the disparate ideas which are at the foundation of this thesis took several months. The supervisors of my master thesis in Aerospace Engineering, Irene Fernandez Villegas and Bernhard Steubing, played no small part in shaping what direction I would go in next. It was a wonderful coincidence that, as I continued to work with Bernhard, Nils Thonemann became the second supervisor for this thesis. Nils' experience with aviation and ambition for methodological innovation made for great conversations. Starting before my internship at CE Delft, colleagues there were influential in forming the study, from early exploration to the later refinement of its methods and presentation. Thank you all. I am especially grateful for the guidance of Isabel Nieuwenhuijse, whose insights in the content and in project management proved extraordinarily valuable. I must also thank Wei Shijie, from CML. As I was orienting myself, Shijie continuously made time to support my research and share his own work. Finally, my gratitude extends to Amelie Müller, Bram Peerlings, Julien McTighe, Liam Megill, and Romain Sacchi for discussing their research with me. I hope that it is evident that my work is only possible because of efforts in and outside of the scientific community, but personal correspondence has always been particularly meaningful to me.

It is only in hindsight that I realise how transformative this period was for me. At the time of my Aerospace Engineering thesis defence, in September 2023, I had not expected much to change as I completed my studies in Industrial Ecology. As I started at CE Delft, I found a warm welcome. It was great to be involved in such a considerate and tight-knit organisation. I especially valued the talks over lunch, even though this came at the cost of my lunch walks at 2.56. This everyday support brought life, even as the world turned grey. And as the collaboration with Bernhard and Nils continued, I become much more familiar with the workings and research of CML. Now, with the completion of this master thesis, I continue in the field of prospective life cycle assessment as a PhD candidate at CML. Reflecting on how I have developed over the years, I am grateful for the communities I have found, the friendships made – old and new, for the presence and support of my family, and for Kristie, who continues to be a centre of kindness, love, and generosity in my life.

Thomas Arblaster
Delft, January 2024

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Nomenclature

This page lists a number of symbols and abbreviations which are used throughout this document.

Abbreviation	Definition
ATAG	Air Transport Action Group
AAF	Alternative aviation fuel
AC	Aircraft
AIC	Aviation-induced cloudiness
CCD	climb/cruise/descent
CH_4	Methane
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct air capture
EFTA	European Free Trade Association
EU	European Union
FT	Fischer-Tropsch (process)
GHG	Greenhouse gas
H_2	Molecular hydrogen
HC	Hydrocarbon
IAM	Integrated assessment model
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LH_2	Liquid hydrogen
LHV	Lower heating value
LTO	landing and take-off
NO_x	Nitrogen oxides
PEM	Proton exchange membrane electrolysis
PtL	Power-to-liquid
RF	Radiative forcing
RPK	Revenue passenger-kilometer
SAF	Sustainable aviation fuel
SMR	Steam methane reforming
SOEC	Solid oxide electrolysis
SSP	Shared Socioeconomic Pathway
UNFCCC	United Nations Framework Convention on Climate Change

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Introduction

Today, the global economy is largely reliant on abundant, energy-dense fossil resources. The resulting greenhouse gas (GHG) emissions have brought about a warming of global surface temperatures of around 1.09°C (IPCC, 2022). Through the Paris Agreement, the international community aims to limit this warming "to well below 2°C" to mitigate environmental catastrophe (UNFCCC, 2015, p. 3). Far-reaching socio-technical transitions are required to realise the required decrease in GHG emissions. This thesis explores what this means for the aviation sector. First, the present situation is described alongside a discussion of research performed so far (Section 1.1). Based on this, the research question is formulated (Section 1.2).

1.1. Problem situation and previous work

Among climate change mitigation efforts, one prominent area of focus is energy systems. Electricity from renewable energy sources, notably including wind and solar, is already on track to make a large contribution to decarbonisation (IEA, 2022b). However, many sectors cannot be decarbonised through electrification alone. This is where molecular hydrogen (H_2) might come in. Hydrogen from renewable sources can replace hydrogen generated from fossil methane (CH_4), but also has further potential as a link in novel low-carbon process chains (IEA, 2022a). In the transportation sector – most critically, aviation and shipping – this creates a promising route to synthetic and bio-based fuels (Barke et al., 2022; IEA, 2022a).

The air transport sector has become a linchpin of the global economy, but it is also a large contributor to environmental degradation (Grobler et al., 2019; Lee et al., 2021). The European Parliament and the Council recently agreed on the ReFuelEU Aviation proposal – part of the Fit-for-55 package – which outlines that alternative fuels should form 70% of use by 2050 (European Parliament & Council of the European Union, 2023). A number of industry reports have been published, which describe similar – or more ambitious – developments (see, e.g., ATAG, 2021; ICAO, 2022d; NLR and SEO, 2021). Such ambitions raise concerns regarding the availability of sustainable energy sources, particularly when considering the growth in air traffic currently projected. Many have argued for curbing this growth at a regional or global level, including Jaramillo et al. (2022), Sacchi et al. (2023), Kito et al. (2023), and the IEA (2023). However, industry reports point towards reductions in air traffic leading to reduced investment towards new technologies (ICAO, 2022a; NLR & SEO, 2021) and argue that technological development is "more nuanced and effective" than demand management in reducing emissions (ATAG, 2021, p. 39).

To understand these challenges and explore possible solutions, an interdisciplinary approach is required. Industrial ecology is a field of research concerned with the material and energy flows which make up society's metabolism, extending to the effects which these flows have on the natural world. Among the tools employed by industrial ecologists is life cycle assessment (LCA): a framework through which the environmental impacts of a product or service system can be quantified from cradle to grave (Guinée et al., 2002; ISO 14040:2006; ISO 14044:2006). In recent years, strides have been made in adapting this framework to the evaluation of emerging technologies and socio-technical transitions through so-called prospective LCA (see, e.g., Sacchi et al., 2022; Thonemann et al., 2020; van der Giesen et al., 2020). Such techniques have successfully been used to scale-up and evaluate a novel technology in a future setting (see, e.g., Ballal et al., 2023; Barke et al., 2022; Delpierre et al., 2021).

However, studies on aviation fuels typically present considerable knowledge gaps in understanding the impact and uncertainty of their respective technologies. For many studies, scenarios are limited to a variety of sources for electricity or production feedstock. They do not contextualise the wider development and implementation of the technologies at hand, which greatly depend on scaling up technologies such as water electrolysis, direct air capture (DAC), carbon capture and storage (CCS), and carbon capture and utilisation (CCU) (Ballal et al., 2023; Leblanc et al., 2022; van der Giesen et al., 2014). When a single, best-guess scenario is analysed, the resulting analysis cannot account for unexpected developments (positive or negative) in these technologies' adoption. In this light, Delpierre et al. (2021) stand out, as both optimistic and pessimistic scenarios are formulated. Ballal et al. (2023) recommend further work in this direction, suggesting that aviation fuels are analysed in the context of wider societal scenarios. Knowledge gaps are not limited to fuel production. Kossarev et al. (2023) point out the further work that can be done in evaluating future aircraft. Bicer and Dincer (2017) and Ratner et al. (2019) recommend further investigation into necessary changes to (local) infrastructure.

Uncertainty in the performance of technologies in a future setting is underexplored, which extends to understanding how these technologies might affect environmental impacts over time, over the course of their implementation. There have been several studies which model how the impact of aviation on climate change might progress, as aircraft technology, operations, and fuels change. However, these typically only focus on the immediate emissions of flight, greatly simplifying the impacts of fuel production (see, e.g., Grewe et al., 2021) or excluding this stage entirely (see, e.g., Klöwer et al., 2021). This ignores signals from technology-level research, which illustrates a wide breadth of outcomes based on the background system alone. Possible alternatives in the background system are included in the AeroMAPS tool (formerly CAST) ("AeroMAPS", 2023; Planès et al., 2021). It is notable that this tool allows the user to change and combine a variety of settings, including air traffic, technology, fuel supply, and operations. It appears that the only work considering a sector-level perspective over time with a fully documented LCA is that of Sacchi et al. (2023). The present work aims to combine a rigorous LCA methodology, following Sacchi et al. (2023), with the approach to scenario exploration demonstrated by Planès et al. (2021).

1.2. Research question

To contribute to the societal challenges laid out in Section 1.1 while making a scientific contribution to the knowledge gaps described, the following two-part research question is formulated:

Considering hydrogen-based fuels for European commercial aviation, (1) to what extent can environmental impacts be reduced and (2) under what conditions are climate targets met?

This research question enables a broad exploration of possible futures for the commercial aviation sector, from the perspective of hydrogen-based fuels. To answer it, the potential conditions of the sector are defined. This includes determining ranges for technological improvement of established technologies, such as conventional hydrocarbon (HC) aircraft, as well as emerging technologies, such as hydrogen aircraft. Additionally, how the demand for air transport evolves over time and how this is translated into yearly flight movements plays an important role. To define these dimensions more precisely, Section 1.3 elaborates on the key concepts of the research question.

1.3. Definition and scoping of key concepts

This section elaborates on several key concepts in the main research question. This way, a definition and scope is provided for how these concepts are understood within the context of this research.

1.3.1. European commercial aviation

International agreements generally define the aviation emissions allocated to a particular region based on the flights departing from that region. This approach is used here as well. In the context of this research, 'Europe' is defined as a selection of countries closely aligned in their approach to reducing GHG emissions, being the European Union (EU), the European Free Trade Association (EFTA), which includes Iceland, Norway, Switzerland, and Liechtenstein, and additionally, the United Kingdom. This geographical definition is adopted from the Destination 2050 report (NLR & SEO, 2021). This is referred to here as EU+.

To evaluate commercial aviation, the scope is limited to passenger transport on scheduled flights. It can therefore be described in terms of revenue passenger-kilometres (RPK). Non-scheduled flights and all-cargo flights are excluded primarily for pragmatic reasons. Scheduled passenger transport is the largest and most-discussed section of air transport. By choosing this scope, the assumptions required for this study are restricted to only this section. Further information on how this concept is operationalised is provided in Section 2.3.

1.3.2. Hydrogen-based fuels

Several technologies are emerging to enable the transition away from fossil-kerosene-based aviation fuel. Broadly, these can be divided into drop-in fuels; non-drop-in fuels, the most discussed of which is liquid hydrogen; and battery-electric propulsion (Detsios et al., 2023). Drop-in and non-drop-in fuels can be grouped under the labels alternative aviation fuels (AAFs) or sustainable aviation fuels (SAFs), although some reserve the latter for drop-in fuels alone.

Ongoing research has resulted in several promising production pathways for SAFs. The most technologically mature are those based on hydroprocessed esters and fatty acids (HEFA) – which use feedstock such as vegetable oils and waste cooking oil or animal fats – followed by other biomass processes based on the Fischer-Tropsch process (FT) or the alcohol-to-jet route (AtJ), which can accept a range of woody or agricultural biomass (Detsios et al., 2023). These SAFs still have limited production capacity, but are furthermore limited by the availability of appropriate feedstock, also in the future (Habermeyer et al., 2023; Krogh et al., 2022). Because of this, there is an interest in promoting fuels based on renewable electricity: e-fuels. In their purest form, e-fuels are synthesised based on direct air capture (DAC) of carbon dioxide and hydrogen obtained from water electrolysis (van der Giesen et al., 2014). This pathway is also known as power-to-liquid (PtL). However, the definition typically extends to synthetic fuels where hydrogen from electrolysis is combined with carbon from a point source (such as industrial flue gas) or excess carbon from a biomass process (Ballal et al., 2023). Because of the limitations of biomass, this thesis focuses on the role of electricity to produce alternative aviation fuels. The scope is further limited to e-fuel production using carbon from DAC. For the sake of simplicity, carbon from point sources is also excluded, as it is a form of delayed (generally) fossil emission.

Hydrogen (H_2) itself, particularly when stored in liquid form (LH_2), is also considered as a sustainable fuel for aviation. It is not a drop-in fuel: hydrogen has a distinctly different molecular makeup compared to currently used hydrocarbons, therefore requiring that storage and use on aircraft is adapted accordingly (Kossarev et al., 2023). The first narrow-body hydrogen-powered aircraft is thought to enter the market in 2035 (Airbus, 2023). Other non-drop-in fuels have also been proposed, such as liquid natural gas (LNG) or ammonia (NH_3) (Bicer & Dincer, 2017; Gangoli Rao et al., 2020), but these have not received the rapidly growing attention that LH_2 has, and are excluded from the scope of this study.

This study therefore considers hydrocarbon e-fuel and hydrogen propulsion as the two alternatives to fossil kerosene. Here, the term "hydrogen-based fuels" will be used to refer to these alternatives. This term is not part of the typical nomenclature surrounding alternative aviation fuels, nor is it suggested here that it should be. The term is merely used to differentiate the energy carriers of interest from the broader collection of alternative fuels. The production of these fuels as considered in this research is described in more detail in Section 2.5.

1.3.3. ReFuelEU Aviation

After a multi-year process, legislative bodies of the European Union came to an agreement on new rules for the aviation sector, titled ReFuelEU Aviation (European Parliament & Council of the European Union, 2023). Most importantly, this regulation prescribes a number of increasing SAF shares that must be met when considering at least 95% of departures from airports in the European Union[1]. These shares are described in Table A.7 (European Parliament & Council of the European Union, 2023, article 4). The regulation also provides additional provisions, in order to maintain the competitiveness of European aviation and to avoid burden shifting[2]. It is important to highlight that only hydrogen-based fuels are included in this study. In reality, a combination of routes can be expected. Technical maturity currently favours certain bio-fuels, which are imagined to contribute the vast majority of AAF required in the coming decades. For the reasons given in Section 1.3.2, these fuels are excluded from this study. This limitation is discussed in Section 4.2.2.

1.3.4. Aviation climate targets

In contemporary aviation roadmaps, a recurring concept is that of achieving so-called climate-neutral aviation by 2050. This has multiple possible definitions. Sacchi et al. (2023) define flight-CO_2 neutrality, warming neutrality, and climate-neutrality. Warming neutrality "requires that the [radiative] forcing is stabilized at the 2050 level" (Sacchi et al., 2023, p. 2). This is broader than flight-CO_2 neutrality, which only considers warming from fossil CO_2 emissions during flight, neglecting greenhouse gas emissions elsewhere in the system, as well as the non-CO_2 climate forcers associated with flight emissions. The definition of Sacchi et al. (2023) for climate-neutrality is stricter, requiring that radiative forcing is not stabilised, but rather brought to net-zero by implementing additional negative-emissions technologies. Such use of negative-emission technologies is outside of the scope of the present study, so the focus will be on warming neutrality, assessing warming both with and without the inclusion of non-CO_2 effects.

In addition to the *trend* in warming beyond 2050, which the above definitions consider, there is the question of what *magnitude* of warming the aviation sector should remain within. This has become a subject of discussion (see, e.g., Delbecq et al., 2023), but this discussion is still emerging, and challenging to fully operationalise. Therefore, the approach of Kito et al. (2023) is used, who quantify a climate budget for Japanese aviation based on the emission limits for CO_2 of the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA), leaving other climate forcers outside of the scope of this target. This is a grandfathering approach, assuming that the historical share of aviation emissions can be maintained into the future. The limits are based on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). In short, this scheme aims to offset CO_2 emissions from international aviation which exceed the yearly limit, which is quanti-

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[1] Therefore, the geographic scope of this study is not precisely aligned with the scope of ReFuelEU Aviation. However, the relevance of the regulation to the EU Emissions Trading System (EU ETS) means that Iceland, Liechtenstein, Switzerland, and Norway are also affected. The United Kingdom has left the EU ETS, but might link its emissions trading scheme to EU ETS in the future ("Participating in the UK ETS", 2023). However, the 2023 update of the roadmap to decarbonise aviation in the United Kingdom, put forward by industry actors, drastically increases the ambitions regarding SAF, to 75% of fuel by 2050 (Sustainable Aviation, 2023, p. 6) – in line with the 70% of ReFuelEU Aviation.

[2] For example, by discouraging fuel tankering – where an operator coming from outside the EU could minimise the purchase of relatively expensive SAF blends within the EU, by carrying a surplus of relatively cheap fossil kerosene from its departure airport, thereby increasing the share of fossil kerosene, while also causing additional emissions in transporting this additional fuel (European Parliament & Council of the European Union, 2023, article 5).

fied as 85% of such emissions in 2019 (ICAO, 2023, p. 5). Note that other greenhouse gasses are only considered to a limited extent (ICAO, 2022c). This scheme extends to 2035, after which the aspiration is to achieve net-zero by 2050 (IATA, 2022). Although CORSIA is an offsetting scheme, rather than a means to physically limit aviation emissions, there are clear challenges to effective, large-scale offsetting, such as their present efficacy (see, e.g., Badgley et al., 2022; Unearthed, 2021) and their proposition for long-term impact reduction (see, e.g., Stuart et al., 2019). Therefore, offsets are excluded from the present analysis, but are discussed in Section 4.2.4.

In order to further operationalise these targets, the temporal scope is defined, starting in 2024 and ending in 2070. For the purpose of this study, all European aviation is considered, including domestic flights. Furthermore, although "one-time construction and manufacturing activities" are explicitly excluded from CORSIA (ICAO, 2022c, p. 4), this study includes the life cycles of fuel production plants and aircraft manufacturing, as well as their respective end-of-life phases, as such activities are expected to become increasingly relevant in the coming decades (see, e.g., Arblaster, 2023). Airport activities (construction, ground operations, amenities, etc.) are excluded in these policies as well as in the present research. How the climate impact of aviation is quantified and assessed is elaborated on further in Section 2.8.

1.4. Thesis structure

The methods and materials of this research are explained in Chapter 2. To improve reproducibility further, additional information is provided in Appendix A and Appendix B. The results, including sensitivity analyses, are presented and briefly discussed in Chapter 3, with additional results being included in Appendix C. This leads to Chapter 4, where the key findings and limitations are discussed. Finally, conclusions and recommendations are presented in Chapter 5.

2

Methods and materials

To answer the research question, an LCA is conducted by coupling temporally explicit inventory data to a system of stock-and-flow models. Section 2.1 describes the general workflow of this system. Scenarios are developed as described in Section 2.2. The system is then broken down further, first describing how the demand element of the reference flow is defined (Section 2.3), followed by the system dynamics (Section 2.4), and then how these translate to the LCA inventories and impact assessment. Finally, the approach to sensitivity analysis is presented (Section 2.9).

2.1. General approach

The prospective life cycle assessment has the functional unit of providing air transport to all passengers departing from EU+ countries each year from 2024 to 2070 inclusive. Section 1.3 described the scope of this functional unit. Reference flows can be defined as providing this function in the context of a particular scenario. The general approach to this is illustrated in Figure 2.1. The structure of the service system, from a life cycle inventory perspective, is illustrated in Figure 2.2. Many of the unit processes are quantified using stock-and-flow models (see Section 2.4). In short, these stock-and-flow models quantify activities based on the dynamic demand for aircraft and aviation fuels, passing information to each other in a manner reflecting conventional LCA logic. The economic flows feeding into these stock-and-flow models are evaluated using version 2.9.2 of the Activity Browser (Steubing et al., 2020). The stock-and-flow models and subsequent impact assessment are performed using custom python scripts. Foresight principles, as explained in Section 2.2, are used to define the scenario dimensions (Table 2.1), the value of which directly influences elements of the life cycle inventories and/or stock-and-flow models.

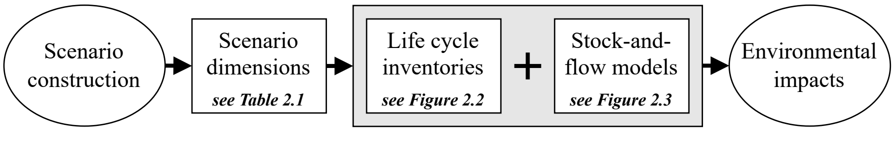

Figure 2.1: Flowchart of the approach, illustrating how the environmental impacts of a certain scenario are quantified by feeding the scenario dimensions into a connected system of life cycle inventories and stock-and-flow models. Elements are labelled with the table or figure which expands on their content.

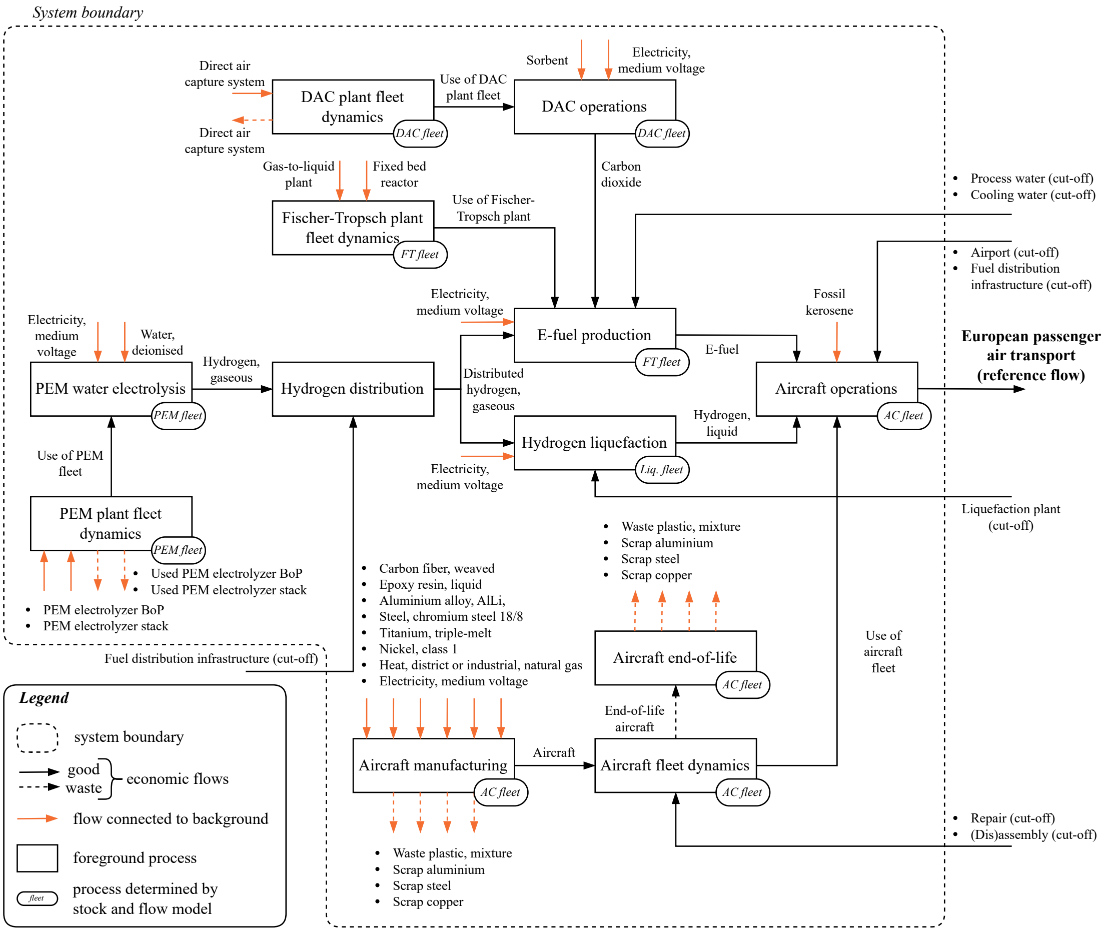

Figure 2.2: Flowchart of the LCA model. Unit processes with a "fleet" label are quantified with the connected stock-and-flow model. AC: aircraft, DAC: direct air capture, FT: Fischer-Tropsch process, liq.: liquefaction, PEM: proton exchange membrane.

2.2. Scenario development

The development of scenarios is primarily inspired by the work of Delpierre et al. (2021) and Langkau et al. (2023). Their frameworks are simplified to reduce the dependence on participatory methods, which are beyond the scope of the present research, although being important to the field of foresight. The initial probability space is constructed through an iterative approach, by determining which processes contributed the most to the results, and secondly, what uncertainty ranges could be identified for the inventory parameters of these processes. This leads to a number of dimensions with possible values (Table 2.1). Here, these possible values can lead to a total of 7776 scenarios. Several steps are taken in order to reduce this to a more manageable number. Combinations of variables which are judged to be inconsistent with each other are ruled out. Additionally, each dimension is considered based on its influence on the results. Dimensions with little influence on the results are relegated to sensitivity analysis. Reviewing the remaining scenario field, a small number of scenarios are selected for further discussion. These scenarios are selected considering distinctiveness in dimensions and results. Furthermore, their internal consistency is motivated through a causal loop diagram (Figure A.4) and brief narrative description (Section 3.1).

2.3. European air transport demand

As described in Section 1.3.1, European aviation is defined based on the scheduled passenger flights departing from the EU+ geographic scope. Following Grewe et al. (2021), the whole sector is approximated based on narrow-body

Table 2.1: Overview of all scenario dimensions considered and their possible values. For each value, an indication is given of its meaning. For dimensions describing a difference in fuel or energy demand, this refers to the energy content of fuel used per revenue passenger-kilometer (RPK). AAF: alternative aviation fuel, gen.: generation, w.r.t.: with respect to, GMST: global mean surface temperature, HC: hydrocarbon.

Dimensions and related section(s)	Possible values	Indication of meaning
AAF volume	No ReFuelEU Aviation	Current AAF share (0.05%) is maintained
Section 2.5	ReFuelEU Aviation as-is	AAF share increases to 70% in 2050 and stagnates
	ReFuelEU Aviation extended	AAF share increases to 70% in 2050 and 100% in 2060
Air traffic volume	High growth	Yearly RPK for 2070 is 2.77 times 2019 value
Section 2.3	Base growth	Yearly RPK for 2070 is 1.96 times 2019 value
	Low growth	Yearly RPK for 2070 is 1.37 times 2019 value
	Degrowth	Yearly RPK for 2070 is 0.70 times 2019 value
HC aircraft technology	Business as usual	2050 gen. has 22% fuel saving w.r.t. present-day gen
Sections 2.6.1 and 2.6.3	Optimistic improvements	2050 gen. has 34-38% fuel saving w.r.t. present-day gen.
	Breakthrough improvements	2050 gen. has 50% fuel saving w.r.t. present-day gen.
H_2 aircraft technology	No hydrogen aircraft	H_2 aircraft do not see any commercial entry into service
Sections 2.6.1 and 2.6.3	Low performance	120-140% energy demand of contemporary HC aircraft
	Medium performance	100-115% energy demand of contemporary HC aircraft
	High performance	95-90% energy demand of contemporary HC aircraft
AAF production technology	Worst-case performance	Low-end values and improvements over time
Section 2.6.2	Base performance	Mid-range values and improvements over time
	Best-case performance	High-end values and improvements over time
Operational performance	Business as usual	Payload load factor stagnates at 80%
Section 2.6.4	Optimistic improvements	Payload load factor increases to 90% by 2050
Hydrogen source	Water electrolysis with wind energy	0.5-0.6 kg CO_2-eq per 1 kg H_2 in 2040
Section 2.7	Water electrolysis with grid mix	0.6-1.7 kg CO_2-eq per 1 kg H_2 in 2040
	Prospective hydrogen market mix	3.3-10.5 kg CO_2-eq per 1 kg H_2 in 2040
Background system	~2.5°C GMST increase by 2100	33 g CO_2-eq per 1 kWh grid electricity in 2040
Section 2.7	~1.7°C GMST increase by 2100	32 g CO_2-eq per 1 kWh grid electricity in 2040
	~1.3°C GMST increase by 2100	12 g CO_2-eq per 1 kWh grid electricity in 2040

aircraft and wide-body aircraft. Segments are created to divide traffic based on aircraft type, distance flown, and destination (intra-EU+ or extra-EU+), based on flight data from 2019 (EUROCONTROL, 2022a). This results in eight segments serviced by narrow-body aircraft and five segments serviced by wide-body aircraft (see Section A.2). Each of these segments is given a reference flight distance and an estimate for the share of RPK that could be serviced with hydrogen aircraft, should these be introduced (Table A.1).

For the sake of simplicity, 2019 is the only year with bottom-up construction of the segments. For subsequent years, the segments are multiplied by historical and projected trends (EUROCONTROL, 2022b, 2023). Note that this approach to future traffic means that the relative distribution of air traffic among segments is kept constant. This limitation is discussed in Section 4.2.1. EUROCONTROL bases its trends on factors such as airport capacity and economic forecasts, with uncertainties such as environmental pressure, resulting in a 'low' traffic projection with low growth after 2024. However, there have also been calls for a decrease in total air traffic, rather than a mere reduction in growth. A recent example of this can be found in the report commissioned by the Dutch House of Representatives of Populytics (2023). In their panel consultation of the Dutch population on how to achieve national climate targets, some of the most favoured options related to restricting aviation. On average, participants chose to reduce the number of flights by 30% and, additionally, to ban flights to destinations within 600 km (Populytics, 2023, p. 19). Extrapolating these findings to the EU+, a fourth scenario is added in which RPK decreases from 2024 through 2034, before stagnating at 70% of the 2019 RPK[1] (Figure A.3, Table A.2).

2.4. Fleet dynamics

There are several functions present in the system which are not met by a singular unit process, but by a combination of many units, potentially including in a mix of characteristics across units (Figure 2.2). In this study, such a group of units is referred to as a fleet. At any given time, there is an aircraft fleet serving each demand section (see Section 2.3), each fleet consisting of multiple types and generations (see Section 2.6.1). Such fleets are also constructed for various functions in the fuel production chain, which are similarly given generations (see Section 2.6.3).

There are multiple approaches possible in the characterisation of fleets. Two main approaches are distinguished. The fleet can consist of persistent units. This way, the characteristics of the fleet can be defined entirely by its inflows and outflows (see, e.g., Kito et al., 2023; NLR and SEO, 2021). New technologies affect the fleet through these flows. Another approach is to forego persistent units and to parametrically describe the fleet itself as a function of time, rather than doing so based on its inflows and outflows. This can be done by defining a progression in the composition of the fleet (see, e.g., Delbecq et al., 2022; Grewe et al., 2021), or by directly representing the fleet composition through a singular process (see, e.g., Sacchi et al., 2023). In the present research, the choice is made for persistent units. One benefit of this approach is that, once the persistent units which make up the fleet are defined, it becomes relatively straightforward to attach their respective cradle-to-gate and end-of-life phases. Another benefit is that it allows for some discussion of efficiency improvement as a function of fleet dynamics. However, at the same time, inflows and outflows determined through a simple set of rules might deviate more strongly from the patterns observed or expected from reality, when compared to an approach which described the fleet composition directly (see Section 4.2.1).

For each of the fleets constructed (see Section 2.1), some basic rules are used in a stock-and-flow model (Figure 2.3). These rules utilise certain characteristics, such as the year from which a generation of units can enter the fleet, how much a unit can contribute to the function of the fleet per time interval, and at what age the unit will retire. Precise descriptions of these values are presented in Appendix A. For each time interval, units which

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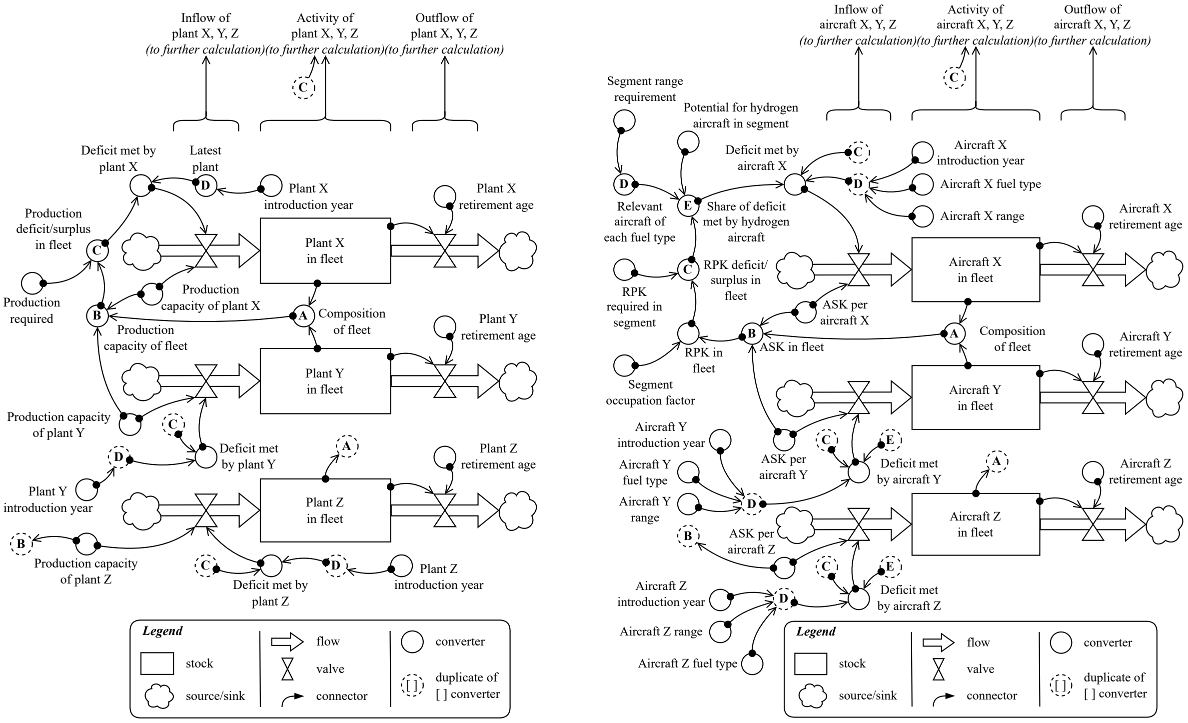
[1] As with other scenarios, the development of air traffic is applied equally to all segments. The simplification is made that any shift towards larger aircraft and further destinations stemming from the 30% reduction is balanced out by the short distance ban not being directly implemented to short distance segments.



(a) Stock-and-flow diagram for the AAF fleets.

(b) Stock-and-flow diagram for the aircraft fleets.

Figure 2.3: Stock-and-flow diagrams. The stock-and-flow models are connected to each other in order to quantify life cycle inventories. To illustrate the working of the model, only three stocks are shown for each diagram. In practise, the number of stocks depends on the assumed number of generations. These diagrams are shown on a larger scale in Section A.1. ASK: available seat-kilometers, RPK: revenue passenger-kilometer.

have reached their retirement age leave the fleet[2], at which point enough new units enter in order for the fleet to meet its function for the present time interval. The new units always come from the most recent generation. There are additional rules for the introduction of hydrogen aircraft (Figure 2.3b). Segments of passenger transport (see Section 2.3) are co-defined by what share of the segment could be satisfied with hydrogen aircraft. Both hydrogen aircraft and hydrocarbon aircraft are introduced according to this share[3]. In several cases, this results in a decrease in e-fuel required (see Section 2.5). If, after retirement, there are more units in a fleet than required to meet the present function, only a portion of this fleet is deployed for that time interval.

Fleets are initiated in the first year of the analysis based on a distribution of ages for the starting year, the values of which are reported in Section A.3 and Section A.4. This distribution is then used to determine the generational composition of the fleet, again using the most recent generation available for each year. Subsequently, this composition is scaled in order to supply the fleet's function for the starting year. From this starting fleet, the rules of the previous paragraph can be applied. This is done iteratively until the final year of the analysis is reached, being 2070. Note that this approach to temporal scope is different from its usual implementation: the temporal scope also sets a strict boundary for when environmental flows are accounted. Impacts occurring outside of this temporal scope, but which do enable the product system somehow are effectively cut off[4]. Beyond this technicality,

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[2] Note that an aircraft leaving a fleet is not necessarily synonymous with its retirement. It is common for airlines from more economically developed countries to replace aircraft well before their retirement age, selling on the older aircraft to another airline (see, e.g., Cox et al., 2018; Kito, 2021). In this study, the simplification is made that aircraft leaving the fleet immediately enter end-of-life.

[3] For example: if a segment is described as being able to accommodate 50% of RPK with hydrogen aircraft, 50% of the RPK deficit will be met with hydrogen aircraft, provided there is a generation of hydrogen aircraft with suitable introduction year (i.e., not an introduction year in the future) and suitable range. Using this approach, the demand for both hydrocarbon and hydrogen aircraft does not radically shift within one generation.

[4] For example, the majority of aircraft used in the first time interval of the simulation were manufactured previously. The impacts of their cradle-to-gate phase (and use prior to this time interval) are excluded. Another example is aircraft and AAF production plants introduced for

the extent of the analysis can be considered cradle-to-grave. However, there are some notable cut-offs, which are included in Figure 2.2. These include the construction and operations of airport buildings, as well as the construction of fuel distribution and storage infrastructure, both of which were excluded due to a lack of data that aligns with the temporal scope considered. Further cut-offs are discussed alongside the processes they are cut off from, in Section 2.6.

2.5. Fuel supply

As introduced in Section 1.3.3, the introduction of AAF is modelled here based on the ReFuelEU Aviation rules. These describe the minimum volume of compliant AAF that must be used in a given period, mostly relating to a specific calendar year. The fuels considered here are fossil kerosene, e-fuel, and liquid hydrogen. ReFuelEU Aviation specifies that hydrogen should be considered based on energy content, but does not specify this for drop-in fuels (European Parliament & Council of the European Union, 2023, article 4). As each of these fuels has a different energy density, they are evaluated based on their lower heating value (LHV)[5] when determining the share of AAF in the total fuel supply.

In addition to the ReFuelEU Aviation timeline, two additional possibilities are considered (Table A.7). One is a reference case, where there is no increase to the present volume of AAF, being around 0.05% (EASA, 2022). Another extends the ReFuelEU Aviation volumes beyond their current scope of 2050, to align with the temporal scope extending to 2070. Following the general trend of the rules as-is, fossil kerosene is phased out completely by 2060.

The logical order applied when quantifying the fuel supply starts from the reference flow, with the air traffic demands being used to construct the aircraft fleets (Figure 2.3b). For each time interval, the activity of the aircraft fleet requires a certain volume of hydrocarbon fuels (here, fossil kerosene and e-fuel) and liquid hydrogen. In scenarios that comply to a certain minimum volume of AAF, all liquid hydrogen forms a contribution to this minimum, with the remainder being achieved by defining the quantity of e-fuel required within the total hydrocarbon demand. The number of hydrogen aircraft is, in principle, independent from this minimum: if hydrogen aircraft are available, they are added to the fleet for their full potential. E-fuel and liquid hydrogen requirements are met by the respective AAF infrastructure fleets (see Section A.4). As mentioned in Section 2.4, it is possible for the introduction of hydrogen aircraft to outpace increases to the minimum AAF share, in which case only a fraction of the AAF infrastructure fleets which experience a surplus are deployed.

2.6. Unit processes modelling

The general logic and dynamics of the simulation have been described so far. The following sections describe how, within this framework, the inventories are created which quantify the total environmental flows across the service system.

2.6.1. Aircraft

The aircraft modelled to construct the fleets described in Section 2.4 are first based on existing reference aircraft, after which future aircraft are imagined. The existing aircraft are the Airbus A320 and A320neo, representing generation 0 and generation 1 for narrow-body aircraft in this study, and the Boeing 777-300 and Airbus A350-900, representing generation 0 and generation 1 for wide-body aircraft. This choice of reference aircraft is adopted

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use in the final time interval. The full impacts of their cradle-to-gate phases are included, but only see a fraction of their lifetime use within the temporal scope. This approach is different from how unit processes are typically determined, which might consider that since these systems only see a fraction of their lifetime use within this scope, their cradle-to-gate impacts should also only be accounted for a fraction of the total. The choice is made against this convention, as even this partial use requires the existence of the full system at that point in time.

[5] This is taken to be $43\,\mathrm{MJ\,kg^{-1}}$ for fossil kerosene, $45\,\mathrm{MJ\,kg^{-1}}$ for e-fuel, and $120\,\mathrm{MJ\,kg^{-1}}$ for liquid hydrogen.

from Grewe et al. (2021). Future aircraft adjust the inventories created for these aircraft in some way. The fuel use and emissions of aircraft are determined based on a variety of sources and, in the case of future aircraft, depend on the scenario values considered (see Section 2.6.3). For the sake of simplicity, the aircraft cradle-to-gate and end-of-life processes are considered to be constant across scenarios – although, within the logic of the scenarios, there would be considerable differences in the design and manufacture of future aircraft.

Both the cradle-to-gate and end-of-life processes of aircraft are based primarily on Cox et al. (2018), who construct inventories based on the (assumed) material composition of the aircraft (Table B.1) and adding to this flows of electricity, heat, and dust, parameterised to aircraft operating empty weight – rather than considering the production of specific components such as the airframe, electrical systems, or interior furnishing. Two notable changes are applied to these inventories. First, Cox et al. (2018) exclude the so-called buy-to-fly ratio, effectively assuming that no manufacturing waste is created. However, the creation and disposal of waste are influential metrics for the manufacturing phase (Arblaster, 2023). This is therefore incorporated based on industry estimates (Bachmann et al., 2017; Orefice et al., 2019; Timmis et al., 2015; see Section B.1). Secondly, to account for hydrogen aircraft likely having a relatively higher empty operating weight than contemporary hydrocarbon aircraft, their mass is increased by 10%, based on Kossarev et al. (2023). However, no change to their relative material composition is considered. End-of-life processes are adapted directly from Cox et al. (2018). Inventories for each aircraft generation are provided in Section B.6.

2.6.2. Fuel well-to-tank

The required supply of fossil kerosene, e-fuel, and liquid hydrogen for each scenario is determined as described in Section 2.5. These values are used to quantify the production chains of these three fuels. For fossil kerosene, this is simply done by connecting a relevant background process (see Section 2.7). For the AAFs, the main plants required along their production chain are treated as dynamic fleets (see Section 2.4). The following paragraphs briefly describe how the performance of these fleets is determined across scenarios, with further information in Sections B.2, B.3, and B.4, and with inventories in Section B.6. Inventories for construction and end-of-life phases of plants are generated using premise (see Section 2.7). This is the case for all background flows, which includes the sorbent used for direct air capture.

The scenarios which consider all hydrogen to be produced from water electrolysis use proton exchange membrane (PEM) electrolysers. Three scenarios are defined for technological performance, based on estimates reported by the IEA (2019), with some adjustments (Delpierre et al., 2021; Sacchi et al., 2022). Hydrogen taken from a market mix is generated using the work of Wei et al. (in preparation) – in these cases, the market composition changes according to the background scenario considered, but there is no longer a distinction between performance scenarios. Hydrogen distribution is based on Sacchi et al. (2023). For use on hydrogen aircraft, hydrogen is liquefied after distribution (Smith & Mastorakos, 2023). Liquefaction is represented by its operational energy demand alone. Transportation and boil-off losses are each estimated as 1%, resulting in the emission of hydrogen to air.

The sorbent-based direct air capture (DAC) system considered is based on the inventories of Terlouw et al. (2021). The worst-case scenario does not consider any improvements over time, while learning rates for the base and best-case scenarios are developed by comparing and combining a number of sources (Fuss et al., 2018; Hanna et al., 2021; Qiu et al., 2022). Note that these inventories are strictly affected by the AAF performance scenario dimension. As a deployment rate for DAC is assumed in the calculation of the learning rates, one can reflect on the consistency between this dimension and the dimension of the background system, which incorporates the degree of climate change mitigation.

The performance of e-fuel production is determined by comparing the work of Atsonios et al. (2023), König et al. (2015), and Rojas-Michaga et al. (2023). Each of these reports a plant design focused on the production of synthetic kerosene. Plants utilising a Fischer-Tropsch process are multifunctional, so some assumptions are required in order to arrive at mono-functional processes. To this end, physical allocation centred around lower heating value (LHV) is applied, in line with literature. The production process is simplified to flows of CO_2, H_2, and electricity. Due to a lack of data, cooling water and waste water are cut off. Because the Fischer-Tropsch process itself is well-established, these inventories are not considered to change over time.

2.6.3. Fuel tank-to-wing

The fuel tank-to-wing phase (i.e., combustion) distinguishes between the three fuels, while also accounting for the aircraft using the fuel and aspects of the flight itself. The flight is split up into the landing and take-off cycle (LTO), where emissions are relatively low to the ground, and climb/cruise/descent (CCD), where emissions are higher up. Inventories for hydrocarbon fuels are based on Winther and Rypdal (2023), with the addition of metal impurities of fossil kerosene, which are taken from the ecoinvent 3.9.1 database (Wernet et al., 2016). E-fuel is assumed to not have these metal impurities, nor sulphur impurities, meaning that no sulphur oxides (SO_x) are formed – the same assumptions as made in earlier work (Arblaster, 2023). The combustion of hydrogen is modelled based on Mitchell and Hobson (2023). Note that the emissions of hydrogen aircraft are based on a gas turbine, rather than a fuel cell-driven electric powertrain, while their fuel consumption considers both as possibilities. This simplification is discussed in Section 4.2.3. The inventories are reported in Section B.6. Inventories are expressed per 1 MJ fuel use, with separate inventories for LTO and CCD. Fuel use for LTO is assumed to be consistent across flights, while CCD scales with the flight distance (see Section A.2). For each fuel, the inventories per 1 MJ are the same for each aircraft type, based on the recent reference aircraft (see Section 2.6.1). The exception to this is the old reference aircraft, which have separately generated inventories.

The fuel use of future hydrocarbon aircraft is estimated by combining a number of different sources. Grewe et al. (2021) combine insights from various experts to determine the improvements to conventional aircraft concepts that could be realised, although they recognise that this would be challenging to achieve. This forms the optimistic scenario. Some speculate that even larger improvements are possible, for example when introducing new aircraft concepts (see, e.g., ICAO, 2022b). To simulate this, the optimistic values of Cox et al. (2018) are adopted, named here the breakthrough scenario. Finally, the business-as-usual case of Cox et al. (2018), based on historical trends, is adopted as third scenario (Table A.5). Values for fuel use of future hydrocarbon aircraft are applied directly to LTO and CCD fuel uses and their respective inventories (Table A.4). For hydrogen aircraft, the estimations reported by ICAO (2022b, pp. 88-89) are used. These express three scenarios for the fuel use of hydrogen aircraft, relative to their contemporary conventional aircraft[6], while accounting for payload capacity (Table A.6). These values align with estimates reported elsewhere (see, e.g., NLR, 2022; Smith and Mastorakos, 2023; Adler and Martins, 2023; or the review of Delbecq et al., 2023). The assumption that wide-body hydrogen aircraft could enter the market in 2050 is also adopted (see Section A.2).

2.6.4. Operational improvements

With the exception of the COVID-19 pandemic, the load factor of passenger aircraft has historically improved to reach around 80%. Under optimistic conditions, this can reach 90% (Cox et al., 2018). Increasing the load factor increases the mass to be transported – and therefore, the required fuel. However, there is considerable deviation among values quantifying this relationship (Arblaster, 2023). Another trend in commercial aviation, particularly in Europe, is the focus on inefficiencies stemming from air traffic management – optimising how the aircraft is flown (see, e.g., EUROCONTROL, 2022b). Both of these factors should not be ignored, but they are also challenging to quantify, as well as playing a smaller role overall when compared to aircraft technology or

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[6] Note that ICAO (2022b) report performance of hydrogen aircraft relative to contemporary tube-and-wing aircraft. It is unlikely that efficiencies assumed for hydrocarbon aircraft in the breakthrough case can be achieved with a tube-and-wing concept, considering the optimistic efficiencies reported by Grewe et al. (2021). Therefore, the fuel efficiency of hydrogen aircraft is overestimated in the breakthrough scenario.

alternative fuels. Therefore, these operational improvements are simplified into a single metric: if improvements are introduced, the load factor gradually increases from 80% in 2024 to 90% by 2050, without any additional fuel requirements. Any increases to fuel use stemming from the increasing load factor are thereby assumed to be balanced out by improvements to traffic efficiency.

2.7. Prospective background LCI data

The inventories created through the methods described above make use of economic activities not modelled within this work, but directly adopted from another source. It is through these activities that the service system connects itself to the background. The background databases used here are each generated using the python library premise (Sacchi et al., 2022), version 1.8.0. This library enables the transformation of an ecoinvent database – in this case, ecoinvent 3.9.1 with the cut-off system model (see Wernet et al., 2016)[7] – to align with the regions and scenarios of an integrated assessment model (IAM), while furthermore creating a number of additional inventories, not present in the original database. IAMs link human processes, such as the energy system, to environmental processes, such as climate change, through a series of key attributes (e.g., Stehfest et al., 2014). Such models can inform policy makers on how policy responses might affect society and its impacts on the environment (Stehfest et al., 2014). To frame the use of these models, the scientific community has created so-called Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017). These are narratives which each describe plausible societal pathways. Together, the SSPs facilitate the exploration of, and subsequent understanding of, the uncertainty the future holds. An early example of applying the output of an IAM to transform the background database used for prospective LCA is the work of Mendoza Beltran et al. (2020). The premise library makes the generation of such databases more accessible.

Background databases are generated following three future pathways, following the approach of Wei et al. (in preparation): the pathways “SSP2-NDC”, “SSP2-PkBudg1150”, and “SSP1-PkBudg500” of the REMIND model (Luderer et al., 2022) are used, representing scenarios with a global mean surface temperature (GMST) increase by 2100 of around 2.5°C, 1.7°C, and 1.3°C, respectively[8]. To approximate the timeline of these pathways, databases are generated with a time interval of five years (i.e., for 2020, 2025, 2030, etc.). Flows exported from these background databases to connect to the foreground are then linearly interpolated to align with the one-year time interval maintained in this work. The “EUR” region of REMIND is assumed to be representative of the geographic region considered.

2.8. Impact assessment

Aviation has several environmental effects, noise, air quality degradation, and climate change being among the most prevalent. The focus of the present research is on climate change. A topic of increasing interest in this regard is the non-CO_2 effects of aviation. The most prevalent of these are caused by nitrogen oxides (NO_x) and by condensation of water into contrails, resulting in aviation-induced cloudiness. Both of these, when introduced at high altitudes, have both warming and cooling components to their effects (Lee et al., 2021). Although climate targets are mostly geared towards CO_2, with a minor focus on other greenhouse gasses (see Section 1.3.4), such additional climate forcers should not be ignored. However, despite being increasingly well-understood, their short lifespan when compared to CO_2 makes it challenging to assess their warming impacts holistically (see, e.g., the discussion of Ballal et al., 2023). In response to observing this same challenge when comparing CO_2 and methane (CH_4), Allen et al. (2021) develop the linear-warming-equivalent (LWE) metric, which transforms a time series of

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[7] Note that there is an exception to this: the prospective hydrogen markets used in the sensitivity analysis are those produced by Wei et al. (in preparation), who use ecoinvent 3.8 as input.

[8] Thereby, the SSP2-PkBudg1150 scenario achieves the goal of the Paris Agreement, the SSP1-PkBudg500 scenario achieves an ambitious interpretation of it (to limit GMST increase to below 1.5°C), and the SSP2-NDC scenario implements the nationally determined contributions (NDCs) set in the context of international climate action, although these still fall short of meeting the Paris Agreement. Note that for each of these scenarios, ambitious climate policy is required beyond what has been implemented so far.

emissions into the radiative forcing expected over that same time period and into the future. Sacchi et al. (2023) adapt this metric to aviation non-CO_2 effects. This approach is much less robust than the dynamic models used, for example, by Grewe et al. (2021) and Grobler et al. (2019), but greatly reduces computational demand.

An additional impact to consider here is contrail formation. Sacchi et al. (2023) evaluate this based on the distance flown, rather than any specific environmental flow. Doing so, they also consider how particulate matter emissions affect the formation of ice crystals, based on Burkhardt et al. (2018), as these factors are influenced by fuel properties – as synthetic fuels contain less impurities and result in less nucleation sites – which in turn influence the radiative forcing of contrails. The impact model of Sacchi et al. (2023) is applied to quantify the LWE impact of emissions, with some adaptions to the quantification of ice crystals, as well as the scope and impact of NO_x emissions (motivated and detailed in Section B.5). Three cases are considered: evaluating all climate forcers, excluding aviation non-CO_2 effects, and only considering CO_2 itself. This third approach is used to determine whether the CO_2 emission limit is respected. In principle, the first approach – considering all climate forcers – indicates whether the warming-neutrality target is achieved, although it must be noted that there is much uncertainty regarding non-CO_2 effects, especially when evaluating future technologies. This is why the other two approaches are included too. The ICAO/IATA limits for CO_2 emissions are also evaluated using the LWE metric. Since these limits are expressed relative to the CO_2 emissions of 2019 (see Section 1.3.4), the model created is run for 2019 flight activity. This results in the target and the future emissions being generated using the same assumptions.

To the best of the author's knowledge, climate change is the only impact category for which LCA-adapted metrics have been developed to consider the cumulative impact of emissions over time. Still, it is valuable to consider how the environmental flows quantified for each time interval affect other impact categories. This is done by calculating the impact for each year in the analysis, obtaining a time series of impacts. No discount rates or prospective characterisation factors are applied. The midpoint characterisation models used here are those of the EF family (v3.1), as recommended by the European Commission (2021). However, the "water use" impact category is excluded, as the emission of water to air plays a prominent role in its calculation. In the context of this research, water is primarily emitted because of fuel combustion, rather than the abstraction of water resources. This choice is further motivated by data limitations on the water flows of e-fuel plants (see Section 2.6.2).

2.9. Sensitivity analysis

Due to the nature of this research, a broad range of possible future values is assessed. However, as described in Section 2.1, not all of the possible values identified are included in the main results. A number of dimensions of Table 2.1 are left out of the main discussion for the sake of simplicity. The focus of the sensitivity analysis is therefore on how these parameters affect the results and what might be overlooked by the choices made. This consists of exploring the operational improvements, fuel production technology, the background system, and the source of hydrogen used.

3

Results

Executing the methods described in Chapter 2 provides a wide array of results. This chapter highlights the key outcomes relevant to the research question in Section 3.4.1. To better understand the system dynamics of this work, additional results have been generated (Section 3.2), including results for impact categories other than climate change (Section 3.5). Finally, there is the sensitivity analysis (Section 3.6). Each of the following sections includes a brief discussion of the results. This lays the foundation for the discussion presented in Chapter 4.

3.1. Representative scenarios

As described in Section 2.2, the initial array of possible scenarios is reduced step by step. Concerning the internal consistency of scenarios, scenarios which do not include ReFuelEU Aviation are considered to be incompatible with scenarios which do include hydrogen aircraft. If environmental ambitions are too low to set requirements for AAF volumes, it stands to reason that the ambition to develop commercially viable hydrogen aircraft is also too low. Hydrogen produced from water electrolysis using the grid mix is combined with a background system in line with a $\sim$1.7°C increase to global mean surface temperature by 2100 (i.e., in line with the Paris Agreement). This choice is made to be consistent with the context of ReFuelEU Aviation. The existing legislature aims to produce the hydrogen-based fuels discussed here using renewable energy. However, arguments can be made regarding what constitutes a fair or representative assessment of the energy system. The additional electricity required for e-fuels could delay the phasing out of fossil resources across the electricity market as a whole – a relationship not quantified within the scope of this research. By using a Paris-compliant background scenario, the full electricity system is considered, while still having the AAF produced almost entirely from renewables. For the sake of simplicity and to facilitate the comparison between scenarios, these values are set for all scenarios outside of the sensitivity analysis. Finally, only the base-performance of AAF infrastructure and the business-as-usual operational performance are considered for now. This is because these dimensions were found to have a limited influence on the results (see Section C.4). After these steps, there are four dimensions differentiating the scenarios remaining: the AAF volume, the air traffic volume, and the technological performances of hydrocarbon and hydrogen aircraft.

From the four remaining dimensions, three sets of representative scenarios are selected based on air traffic: high growth, low growth, and degrowth. The choice is made to couple the air traffic volume to the performance of future aircraft technologies. This relationship is illustrated in a causal loop diagram (Figure A.4) and narrative description in the following paragraph. Each set is given three fuel scenarios. The first fuel scenario serves as a reference. It sees no increase in the AAF volume share compared to 2025. The other two scenarios implement the extended version of ReFuelEU Aviation: once with the introduction of hydrogen aircraft, and once without. This way, the three scenarios in each set have counterparts with a similar fuel supply in the other sets, resulting in a total of nine scenarios (Table 3.1).

A supporting narrative for these scenarios is as follows: in the high-growth scenario, the fuel efficiency imperative of the aviation sector enabled it to maintain its substantial growth, which in turn provided space for revolutionary aircraft technologies to mature. In combination with broad public support, this enabled the construction of AAF infrastructure at rates thought impossible. Conversely, in the degrowth scenario, a lack of resources reinforces the slow development of AAF infrastructure and halts technological breakthroughs. This, in turn, limits the traffic that can be achieved within stringent environmental regulations, further restricting available resources. The low-growth scenario finds itself in between these two extremes. Note that it is not a given that the relationships illustrated by these narratives hold true, but that efficiency improvements in transportation are considered to stimulate demand (see, e.g., Devezas, 2020; Font Vivanco et al., 2015). These basic narratives could be approached in a more robust way, but are sufficient within the scope of the present research.

3.2. Fleet activity

The introduction of new aircraft depends on the progression of air traffic and on whether hydrogen aircraft are introduced or not (Figure 3.1). Since hydrogen aircraft were modelled to have the same number of seats and lifetime use as their hydrocarbon equivalents (see Section A.3), whether hydrogen aircraft are introduced or not does not affect the number of aircraft in the fleet, but one-to-one displaces hydrocarbon aircraft with a hydrogen equivalent, dependent on the potential attributed to the air traffic segments.

It can be observed from Figure 3.1 that, under a constant growth rate, there is little difference in how quickly a new generation becomes the majority of the fleet. However, when observing the degrowth scenario (Figure 3.1e and f), the step change in growth that air traffic sees around 2035 results in a corresponding change in required aircraft deliveries. By 2045, the second-generation aircraft make up a notably larger portion of the fleet when compared to the other scenarios. The low demand for new aircraft in 2024-2034 can be imagined as aircraft manufacturers primarily delivering to growing markets, with these markets slowing down by the time that European aviation has stopped shrinking. The pattern created in this period repeats itself twenty years later, resulting in a relatively slow uptake of third-generation aircraft. This is a consequence of the simplifications governing the system dynamics.

The number of aircraft corresponds to the growth in air traffic, but fuel use is also closely related to the progression of aircraft technologies. Observing the scenarios without ReFuelEU Aviation (Figure 3.2a), these factors balance each other out such that, although the yearly fuel use differs across scenarios, their trends after 2035 are quite similar. This illustrates the stark contrasts between low-end and high-end projections for aircraft efficiency. The differences in total fuel use can be explained by the diverging traffic realised up to 2035, when aircraft efficiencies are similar across scenarios. There is also a considerable range in the efficiency of future hydrogen aircraft (see Table A.6), which is reflected in the yearly demand for AAF (Figure 3.2b). However, even though hydrogen aircraft require more fuel, these scenarios show that this does not translate to an increased demand for hydrogen, even when assuming low-performance hydrogen aircraft (Figure 3.2c). This is because, in this study, the use of liquid hydrogen displaced some of the e-fuel that is required within the ReFuelEU rules. The production of 1 MJ e-fuel requires more hydrogen than the production of 1 MJ liquid hydrogen[1].

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[1] Accounting for losses, fuelling an aircraft with 1 MJ liquid hydrogen required that around 1.02 MJ hydrogen is produced. For base-case performance of AAF infrastructure, 1 MJ e-fuel requires around 1.61 MJ hydrogen. Note that other inputs across the system are not considered in this comparison.

Table 3.1: Overview of the nine representative scenarios selected. Each column corresponds to a scenario, the construction of which is motivated in Section 3.1. Scenarios are defined and labelled into three sets (HG, LG, DG), where each set contains three scenarios for the fuel supply (I, II, III). **HG**: high-growth air traffic with high-performance aircraft technologies; **LG**: low-growth air traffic with medium-performance aircraft technologies; **DG**: degrowth of air traffic with low-performance aircraft technologies; **I**: no ReFuelEU Aviation; **II**: ReFuelEU Aviation extended, no introduction of hydrogen aircraft; **III**: ReFuelEU Aviation extended with the introduction of hydrogen aircraft. AAF: alternative aviation fuel, HC: hydrocarbon.

Dimensions	**Possible values**	**Combination of values selected for each scenario**								
AAF volume	No ReFuelEU Aviation	HG.I			LG.I			DG.I		
	ReFuelEU Aviation as-is									
	ReFuelEU Aviation extended		HG.II	HG.III		LG.II	LG.III		DG.II	DG.III
Air traffic volume	High growth	HG.I	HG.II	HG.III						
	Base growth									
	Low growth				LG.I	LG.II	LG.III			
	Degrowth							DG.I	DG.II	DG.III
HC aircraft technology	Business as usual							DG.I	DG.II	DG.III
	Optimistic improvements				LG.I	LG.II	LG.III			
	Breakthrough improvements	HG.I	HG.II	HG.III						
H_2 aircraft technology	No hydrogen aircraft	HG.I	HG.II		LG.I	LG.II		DG.I	DG.II	
	Low performance									DG.III
	Medium performance						LG.III			
	High performance			HG.III						
AAF production technology	Worst-case performance									
	Base performance	HG.I	HG.II	HG.III	LG.I	LG.II	LG.III	DG.I	DG.II	DG.III
	Best-case performance									
Operational performance	Business as usual	HG.I	HG.II	HG.III	LG.I	LG.II	LG.III	DG.I	DG.II	DG.III
	Optimistic improvements									
Hydrogen source	Water electrolysis with wind energy									
	Water electrolysis with grid mix	HG.I	HG.II	HG.III	LG.I	LG.II	LG.III	DG.I	DG.II	DG.III
	Prospective hydrogen market mix									
Background system	$\sim$2.5°C GMST increase by 2100									
	$\sim$1.7°C GMST increase by 2100	HG.I	HG.II	HG.III	LG.I	LG.II	LG.III	DG.I	DG.II	DG.III
	$\sim$1.3°C GMST increase by 2100									

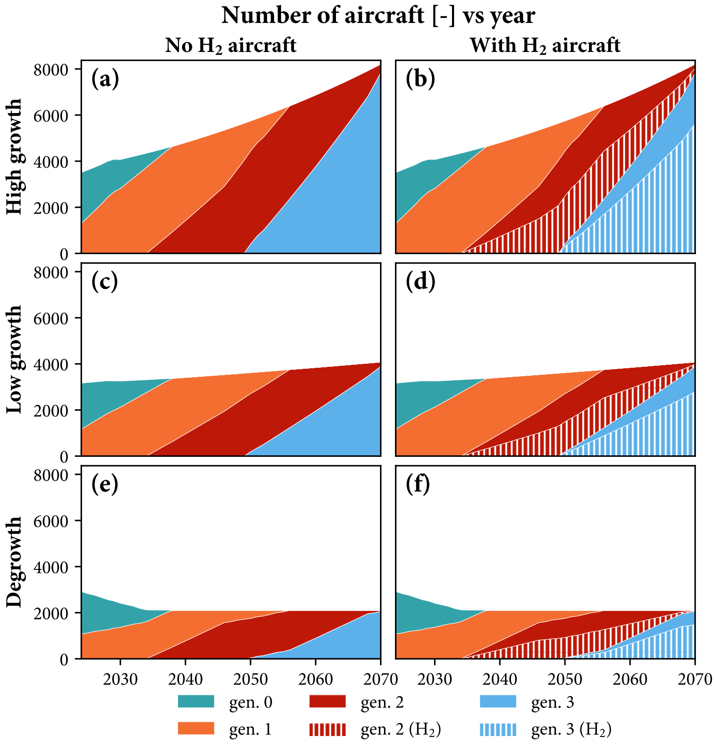

Figure 3.1: Results for the representative scenarios in the progression of fleet size, in number of aircraft, and of fleet composition, illustrating **(a, c, e)** scenarios which have no introduction of hydrogen aircraft (with or without ReFuelEU Aviation), and **(b, d, f)** scenarios which do see the introduction of hydrogen aircraft. Note that this is a visualisation of the number of aircraft and that, due to differences between aircraft types, a visualisation of distance flown by each generation (gen.) would be different.

3.3. Climate impacts

Across scenarios, the evolution of yearly CO_2 emissions aligns closely with the yearly use of fossil kerosene (compare Figure 3.2a and Figure 3.3a). The alternative aviation fuels show no improvement initially compared to cases without ReFuelEU, but as their share increases, the share of renewable electricity in the grid mix increases too. This low-carbon grid mix also explains, in part, why the differences in impact between scenarios with and without hydrogen aircraft are very limited, only showing noticeable difference in CO_2 emissions after 2050 (Figure 3.3a). Despite these minimal differences, the introduction of hydrogen aircraft does bring an advantage when it comes to the yearly demand for hydrogen (see Figure 3.2c). Comparing air traffic scenarios in 2070, there are stark contrasts in radiative forcing (Figure 3.3b), although all scenarios succeed in greatly reducing CO_2 emissions by 2060 (Figure 3.3a). The low-growth and high-growth scenarios overshoot the CO_2 target, as discussed in Section 3.4.2.

3.4. Climate targets

The climate impact of the representative scenarios were reviewed in Section 3.3. Now, the climate targets described in Section 2.8 are evaluated, considering all main scenario dimensions.

3.4.1. Warming neutrality

Around half of the scenarios shown fit some definition of warming neutrality (Figure 3.4), which was defined by comparing the radiative forcing of the years 2050 and 2070, as described in Section 2.8. This is particularly the case when including non-CO_2 effects of flight, where all but two scenarios in which ReFuelEU Aviation is extended display a decrease in radiative forcing from 2050 to 2070. This can be attributed in particular to the decrease in

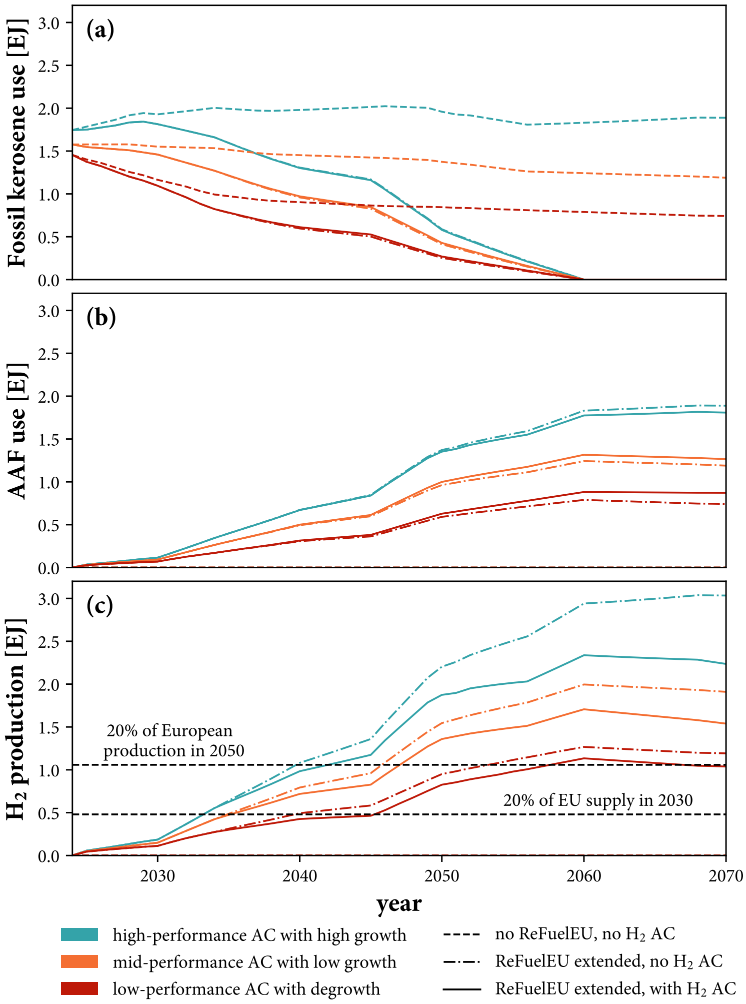

Figure 3.2: Results for nine reference scenarios on timeline for **(a)** fossil kerosene use, **(b)** use alternative aviation fuels, and **(c)** the demand for hydrogen production. Note the near-overlap of ReFuelEU scenarios within the same air traffic scenario in **(a)** and of all scenarios without ReFuelEU in **(b)** and **(c)**. Yearly demand for hydrogen is contextualised based on the supply of hydrogen (10 million tonnes production and 10 million tonnes import) that the European Commission has set as target for 2030 (European Commission, 2023) and production in Europe in 2050 estimated based on the IEA "net zero emissions" scenario (Wei et al., in preparation). Energy content of fuels is expressed in terms of lower heating value. AC: aircraft, AAF: alternative aviation fuels.

cloudiness associated with AAF. Even without increasing the AAF share to 100%, a few of the degrowth scenarios illustrate that the decreases in cloudiness and the fuel use of future aircraft could outweigh the long-term warming of CO_2. However, it bears repeating that there is much uncertainty surrounding these short-term climate forcers. When only considering CO_2 emissions (Figure 3.4b), the effect of the fuel supply is less pronounced, with fuel efficiency standing out more. These graphs show that warming neutrality, as it was defined here, can be achieved for each growth scenario, provided the described aircraft technologies and low-impact fuel supply can be achieved.

3.4.2. Cumulative CO_2 emissions

As described in Section 1.3.4, the yearly CO_2 limit until 2035 is defined as 85% of the applicable 2019 emissions. Running the model created based on 2019 flight activity, a value of 150×10^9 kg CO_2 is obtained[2]. Evaluating the target based on this value, only a handful of scenarios stay within the limit (Figure 3.4a). In any case, the degrowth

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[2] This is slightly higher than the relevant emissions determined by EASA (2022), who report 147×10^9 kg CO_2 for 2019. Note that some additional factors are considered in the present study, while others – such as all-cargo transport – were excluded. This is why a figure generated using these assumptions is used, rather than the one reported by EASA.

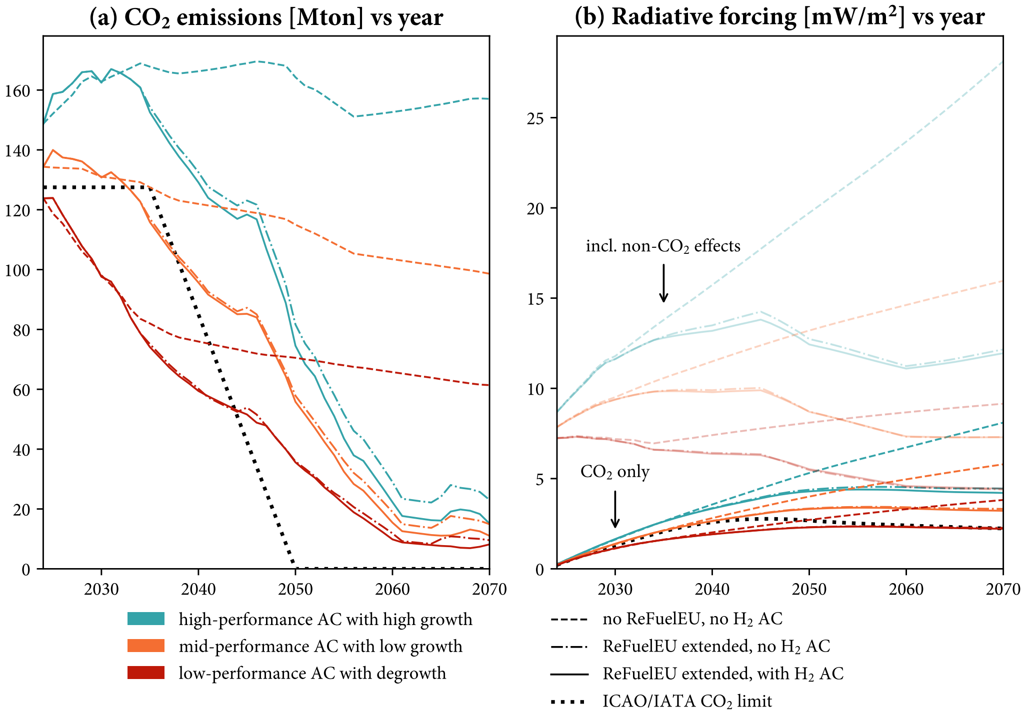


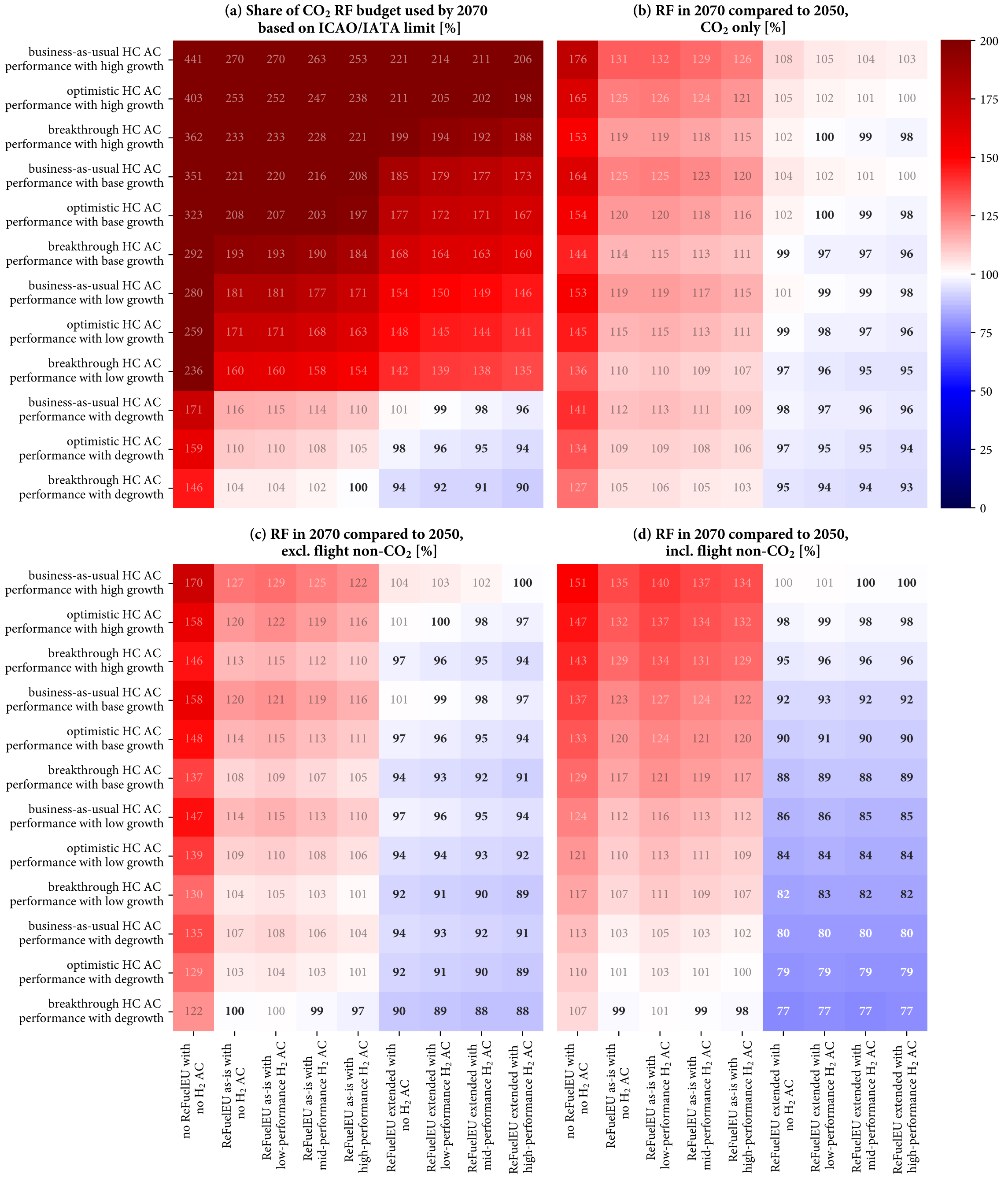
Figure 3.3: Results for nine reference scenarios on timeline for **(a)** CO_2 emissions and **(b)** radiative forcing, showing lines for both all climate forcers (originating above) and CO_2 only (originating below). AC: aircraft, incl.: including.

demand scenario is required. If ReFuelEU Aviation is implemented as-is, the high-end technological development is required for both hydrocarbon aircraft and hydrogen aircraft. If the introduction of AAF is increased further after 2050, all degrowth scenarios manage to stay within the limit to varying degrees, except when hydrocarbon aircraft see business-as-usual improvements and hydrogen aircraft are excluded, in which case the limit is missed by less than 1%. The other demand scenarios overshoot the limit by a minimum of 35%, many cases seeing an overshoot of over 100%, even when implementing ReFuelEU Aviation.

As can be observed from Figure 3.3, that all conventional growth scenarios overshoot the CO_2 target is a result of their high emissions prior to 2060. These are driven by a high use of fossil kerosene. Fossil kerosene's share of the fuel supply is a feature of ReFuelEU Aviation, so without assuming a sizeable decrease in traffic, these impacts can only be avoided with AAF deployment far beyond the regulatory minimum. This has clear implications for narratives surrounding future aviation, to be discussed in Section 4.1.

3.5. Additional impact categories

The quantification of environmental flows can not only be used to determine impacts on climate change, but also for other impact categories (see Section 2.8). Quantifying these impacts year-by-year – without adjustments to the LCIA methods – a variety of trends emerges (Figure C.4). A selection of impact categories are shown in Figure 3.5 to discuss these trends. Across impact categories, there is no substantial increase or decrease in yearly impacts if no increase in AAF is implemented. The curves generally follow a shape similar to the fossil kerosene demand (compare to Figure 3.2a), indicating the contribution of the fuel system. If a version of ReFuelEU Aviation is implemented, some impact categories still generally follow this trend, while a few show notable co-benefits, and several others show clear trade-offs, increasing as a result of large-scale AAF production. An example from this first group is "eutrophication: terrestrial" (Figure 3.5b), as this is tied to in-flight NO_x emissions. For the same reason, clear co-benefits can be observed for this impact category with the introduction of hydrogen aircraft. The second group,



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	441	270	270	263	253	221	214	211	206
optimistic HC AC performance with high growth	403	253	252	247	238	211	205	202	198
breakthrough HC AC performance with high growth	362	233	233	228	221	199	194	192	188
business-as-usual HC AC performance with base growth	351	221	220	216	208	185	179	177	173
optimistic HC AC performance with base growth	323	208	207	203	197	177	172	171	167
breakthrough HC AC performance with base growth	292	193	193	190	184	168	164	163	160
business-as-usual HC AC performance with low growth	280	181	181	177	171	154	150	149	146
optimistic HC AC performance with low growth	259	171	171	168	163	148	145	144	141
breakthrough HC AC performance with low growth	236	160	160	158	154	142	139	138	135
business-as-usual HC AC performance with degrowth	171	116	115	114	110	101	**99**	**98**	**96**
optimistic HC AC performance with degrowth	159	110	110	108	105	**98**	**96**	**95**	**94**
breakthrough HC AC performance with degrowth	146	104	104	102	**100**	**94**	**92**	**91**	**90**

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	131	132	129	126	108	105	104	103
optimistic HC AC performance with high growth	165	125	126	124	121	105	102	101	100
breakthrough HC AC performance with high growth	153	119	119	118	115	102	**100**	**99**	**98**
business-as-usual HC AC performance with base growth	164	125	125	123	120	104	102	101	100
optimistic HC AC performance with base growth	154	120	120	118	116	102	**100**	**99**	**98**
breakthrough HC AC performance with base growth	144	114	115	113	111	**99**	**97**	**97**	**96**
business-as-usual HC AC performance with low growth	153	119	119	117	115	101	**99**	**99**	**98**
optimistic HC AC performance with low growth	145	115	115	113	111	**99**	**98**	**97**	**96**
breakthrough HC AC performance with low growth	136	110	110	109	107	**97**	**96**	**95**	**95**
business-as-usual HC AC performance with degrowth	141	112	113	111	109	**98**	**97**	**96**	**96**
optimistic HC AC performance with degrowth	134	109	109	108	106	**97**	**95**	**95**	**94**
breakthrough HC AC performance with degrowth	127	105	106	105	103	**95**	**94**	**94**	**93**

(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	127	129	125	122	104	103	102	**100**
optimistic HC AC performance with high growth	158	120	122	119	116	101	**100**	**98**	**97**
breakthrough HC AC performance with high growth	146	113	115	112	110	**97**	**96**	**95**	**94**
business-as-usual HC AC performance with base growth	158	120	121	119	116	101	**99**	**98**	**97**
optimistic HC AC performance with base growth	148	114	115	113	111	**97**	**96**	**95**	**94**
breakthrough HC AC performance with base growth	137	108	109	107	105	**94**	**93**	**92**	**91**
business-as-usual HC AC performance with low growth	147	114	115	113	110	**97**	**96**	**95**	**94**
optimistic HC AC performance with low growth	139	109	110	108	106	**94**	**94**	**93**	**92**
breakthrough HC AC performance with low growth	130	104	105	103	101	**92**	**91**	**90**	**89**
business-as-usual HC AC performance with degrowth	135	107	108	106	104	**94**	**93**	**92**	**91**
optimistic HC AC performance with degrowth	129	103	104	103	101	**92**	**91**	**90**	**89**
breakthrough HC AC performance with degrowth	122	**100**	100	**99**	**97**	**90**	**89**	**88**	**88**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	135	140	137	134	100	101	**100**	**100**
optimistic HC AC performance with high growth	147	132	137	134	132	**98**	**99**	**98**	**98**
breakthrough HC AC performance with high growth	143	129	134	131	129	**95**	**96**	**96**	**96**
business-as-usual HC AC performance with base growth	137	123	127	124	122	**92**	**93**	**92**	**92**
optimistic HC AC performance with base growth	133	120	124	121	120	**90**	**91**	**90**	**90**
breakthrough HC AC performance with base growth	129	117	121	119	117	**88**	**89**	**88**	**89**
business-as-usual HC AC performance with low growth	124	112	116	113	112	**86**	**86**	**85**	**85**
optimistic HC AC performance with low growth	121	110	113	111	109	**84**	**84**	**84**	**84**
breakthrough HC AC performance with low growth	117	107	111	109	107	**82**	**83**	**82**	**82**
business-as-usual HC AC performance with degrowth	113	103	105	103	102	**80**	**80**	**80**	**80**
optimistic HC AC performance with degrowth	110	101	103	101	100	**79**	**79**	**79**	**79**
breakthrough HC AC performance with degrowth	107	**99**	101	**99**	**98**	**77**	**77**	**77**	**77**

Figure 3.4: Heat map depicting the results for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** warming neutrality when considering all surface-level GHGs, and **(d)** warming neutrality when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft, HC: hydrocarbon, RF: radiative forcing.

for which both AAFs considered results in co-benefits, includes “ecotoxicity: freshwater” (Figure 3.5d), although no impact categories benefit as much as climate change and the “energy resources: non-renewable” category. Further attention needs to be given to the impact categories which see moderate or large increases over time, such as “material resources: metals/minerals” (Figure 3.5a) and “particulate matter formation” (Figure 3.5c). These impacts originate in the background system and are largely caused by the large quantities of electricity required by hydrogen-based fuels.

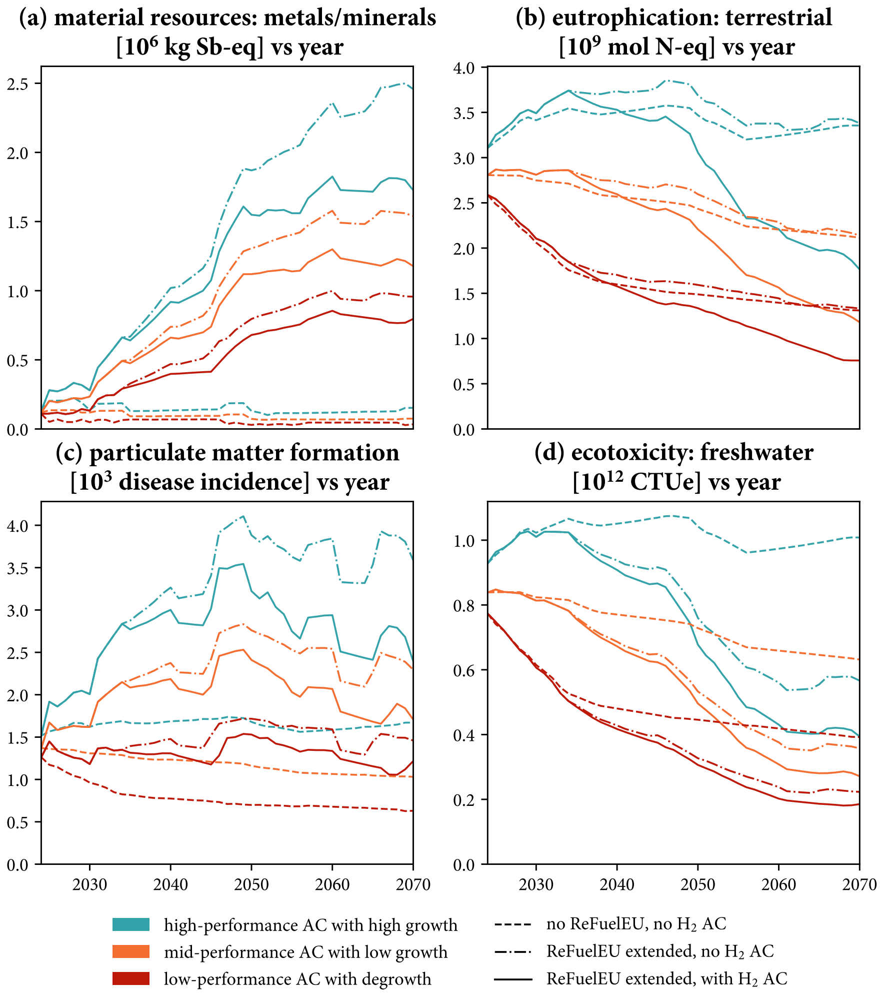


Figure 3.5: Results for nine reference scenarios on timeline for additional impact categories from the EF 3.1 method, showing **(a)** material resources: metals/minerals, **(b)** eutrophication: terrestrial, **(c)** particulate matter formation, and **(d)** ecotoxicity: freshwater. Impact categories are evaluated year-by-year, without considering environmental flows from prior years. AC: aircraft, CTUe: comparative toxic units for ecotoxicity, N-eq: nitrogen-equivalent, Sb-eq: antimony-equivalent.

This variety of trends is indicative of insights that cannot be obtained by evaluating climate change alone. The array of technological solutions considered within this study do not mitigate damages in these impact categories, but in some cases exacerbate them, resulting in burden shifting. However, as the majority of these impacts are created somewhere in the background system, they should be considered alongside the limitations of the prospective background databases used. For example, these do not incorporate future metal economies and opportunities to improve recycling (see Steubing et al., 2023). Although these impact categories warrant further investigation, this is beyond the scope of this thesis.

3.6. Sensitivity analyses

The sensitivity analyses described in Section 2.9 are conducted and presented as two sets, each with a focus on the climate targets (i.e., to be compared with Section 3.4). First, the factors which were excluded due to their limited influence on the results are discussed, being operational improvements and the technological performance of AAF production. Next, the dimensions concerning the hydrogen source and background system are explored. The corresponding figures can be found in Section C.4.

3.6.1. Minor dimensions

Which performance level of AAF technology is considered has some influence. Particularly when considering the low-performance end of the spectrum, several scenarios no longer meet the climate targets (Figure C.5 and, e.g., Figure C.7). Scenarios which entirely rely on e-fuel to replace fossil kerosene appear to be the most affected. Logically so, as the low-end performance of Fischer Tropsch plants identified from literature is considerably different from the base-case (see Appendix B). On the other hand, the difference between base-case and best-case performance is much less pronounced in the results. It should be noted that these ranges were determined for a narrow selection of technologies. Should entirely different technologies be considered instead, the range of values would consequently be broader.

Implementing the operational improvements described in Section 2.6.4 does result in a clear decrease in CO_2 emissions (Figure C.5). However, concerning the CO_2 limit, this only affects a few of the degrowth cases to push them below the maximum. Since the improvements were assumed to be realised to their maximum extent by 2050, they have little effect on the warming trend from 2050 to 2070, although there are a few edge cases where this change is relevant (Figure C.6).

3.6.2. Background system and hydrogen source

Section 3.1 discussed how a background aligned with the Paris Agreement and hydrogen production together from the grid mix forms a consistent setting for the ReFuelEU Aviation narratives considered. Alternative hydrogen sources – i.e., replacing grid electricity with electricity from offshore wind or by implementing the prospective hydrogen production mixes described by Wei et al. (in preparation) – and alternative background systems – i.e., SSP2-NDC or SSP1-PkBudg500 (see Section 2.7) – can considerably alter the results. Even the most optimistic progression of the hydrogen production mix drastically narrows the conditions under which climate targets are achieved (Figure C.11). For less optimistic mixes, the CO_2 limit is fully out of reach, with only warming neutrality being potentially possible when considering all climate forcers (Figure C.13 and Figure C.16). The mix created for the SSP2-NDC scenario even shows the possibility of hydrogen-based fuels producing a worse outcome than simply sticking with fossil kerosene (Figure C.16a). However, it should be noted that these less optimistic mixes assume that overall hydrogen production sees limited growth in the coming decades – an assumption which is incompatible with the volumes required for ReFuelEU Aviation as modelled here (see Figure 3.2c). Still, the observation can be made that hydrogen-based fuels using steam methane reforming – even to a limited extent – face a much larger challenge in meeting climate targets (Figure C.11a).

When comparing Section 3.4 to grid mixes and wind electricity across scenarios, changes are generally limited. The most extreme differences can be observed from wind energy in the $\sim$1.3°C scenario (Figure C.9) and from grid electricity in the $\sim$2.5°C scenario (Figure C.15). In both cases, the general trends observed in Section 3.4 are unaffected, primarily affecting groups of scenarios where only a fraction meet the targets, to increase/decrease the share of this fraction. Overall, it is clear that the metrics illustrated here do not reward efficient use of hydrogen if hydrogen production has a near-zero climate impact[3]. As such, additional impact categories should not be neglected in the assessment of hydrogen-based fuels (see Section 3.5).

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[3] It is even the case that the introduction of low-performance hydrogen aircraft can be detrimental to the overall targets compared to hydrocarbon aircraft (see, e.g., scenarios for ReFuelEU as-is in Figure C.9). This is because the method through which ReFuelEU Aviation is implemented means that the increases to the total fuel supply of low-efficiency hydrogen aircraft can be translated into a larger volume of fossil kerosene being used while still meeting the minimum AAF share. This relationship holds true for all scenarios, but is only detrimental to hydrogen aircraft when hydrogen has a near-zero climate impact.

4

Discussion

Having presented the results in Chapter 3, the following sections reflect on the key findings (Section 4.1), and discuss some of the main limitations of this work (Section 4.2).

4.1. Key findings

Observing the scenarios presented in Chapter 3, several findings stand out. The progression of aircraft technologies considered could offset growth in air traffic, meaning a stagnation or decrease in the yearly demand of aviation fuels beyond 2035. Because of this, warming neutrality can be achieved when comparing 2050 to 2070 (Figure 3.4d). However, for this to be the case, the adoption of AAF must be continued after 2050, beyond 70%. These relationships align with the findings of Grewe et al. (2021), but are not obvious from the work of Sacchi et al. (2023), who disregard technological improvements beyond 2050.

Whether hydrogen is used to fuel liquid hydrogen aircraft or in the production of e-fuel bears little consequence to the overall trend of the results. The relatively low efficiency of e-fuel production has little impact, due to the low climate impact of hydrogen production modelled here (compare Figure 3.2c and Figure 3.3b). However, this finding does not hold true if these systems are not overwhelmingly powered by renewable energy, in which case overall impacts are larger, with the introduction of hydrogen aircraft resulting in more pronounced benefits (e.g., Figure C.13a). The potential advantages of hydrogen aircraft become even more apparent when considering additional impact categories, such as material resources: metals/minerals and eutrophication: terrestrial (Figure 3.5). So, hydrogen aircraft could make a substantial impact by 2070, but benefits with respect to e-fuels are context-dependent. Such benefits are particularly pronounced for high-performance hydrogen aircraft, but even low-performance hydrogen aircraft show overall gains.

Despite the result that technological breakthroughs could balance out high growth in traffic, all scenarios with positive growth fall short of respecting the CO_2 limit. Central here is the use of fossil kerosene, which cannot be decoupled from growth prior to 2035 (Figure 3.2a). Leading up to 2035, the CO_2 emissions of scenarios with positive growth consume the budget to such a degree that, even under the most optimistic conditions considered, they far surpass the CO_2 limit by 2070. An absolute decrease in emissions prior to 2035 is required in order to respect this limit. Hypothetically, one way to achieve this is if the deployment of AAF far outpaces the regulatory minimum. However, the aviation sector is unlikely to achieve this on its own accord. Concerning past environmental targets, Jamie and Keith (2022) determined that the aviation sector has often "replaced or abandoned its commitments and targets without explanation, and, since the targets are voluntary, faced no consequences for doing so" (p. 52). A particular trend that is repeating itself now is the promise that future technologies will achieve certain efficiencies, while emissions grow in the short and medium term. Given that such past promises have fallen short, it would be unwise to expect the current generation of voluntary promises to unfold differently. Therefore, decreasing emissions prior to 2035 must rely on air traffic demand management.

The degrowth narrative described in Section 3.3 is by no means universally desired, yet a decline in air traffic could be a step towards a prosperous, just, and joyful society, rather than a diversion. The societal value of the sector in its current form is debatable[1]. Beyond aviation, there is increasing evidence that economic growth cannot be aligned with environmental objectives (see, e.g., Hickel and Kallis, 2020)[2]. The mitigation of growth brings disadvantages to some stakeholders in the short term, but could be advantageous to all in the long term. Kito et al. (2023) frame this trade-off as "intergenerational equity" (p. 11): if aviation uses up its climate budget in the coming decades, future generations cannot enjoy the same benefits of flight enjoyed by some so far. In order to avoid this inequity, a drastic temporal redistribution of flight activity is required. Delbecq et al. (2023) frame the conversation differently, focusing on what a "fair share" of societal budgets for aviation looks like. Perhaps, some growth might be justifiable with regards to the climate budget, but can the same then be said about the demand for biomass or renewable electricity? Figure 3.2c indicates that hydrogen availability could certainly be a concern, especially after 2050.

One could argue that the growth of the aviation sector is a direct result of the technological advancements in aircraft technology achieved over the past century (see, e.g., Devezas, 2020). Perhaps, the case could be made that these achievements would not have existed, had air transport demand historically been much lower. Even though the existence of this relation is not a given, this research shows that the trend in demand is more critical to the safeguarding of climate targets than the development of breakthrough aircraft technologies is. However, the rapid deployment of low-impact fuels remains a high priority, regardless of other factors. These findings enable a necessary discussion on the value of aviation to current and future generations.

4.2. Limitations

This research is limited. The following sections describe a number of key limitations and how these relate to what conclusions can (or cannot) be drawn.

4.2.1. Simplification of trends

The system dynamics and scenario development explored in this work relied on a number of simplifications. These narrowed the scope of the research and limit to what extent the findings can be generalised. Two of the trends that were left out of the scope are the shift towards larger aircraft and the shift towards longer flights (see, e.g., Cox et al., 2018; NLR and SEO, 2021). These trends could slightly reduce the impacts per RPK. However, since RPK trajectories were in part based on projections for the number of flights (see Section 2.3), it is more likely that neglecting these trends results in underestimating the total impacts.

Another trend that has been observed is the shift towards shorter aircraft lifetimes (see, e.g., Kito, 2021). Shorter aircraft lifetimes speed up the introduction of new generations. Thereby, fuel efficiency improves more rapidly – this has a substantial benefit, but becomes economically disadvantageous before its full environmental

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[1] In their statistical analysis of British households, Baltruszewicz et al. (2023) conclude that there is "no association between air travel and improved mental health, loneliness, or subjective well-being" (p. 7). However, they do find considerable inequality in air traffic energy footprints, linked primarily to the financial situation of the households analysed. Köves and Bajmócy (2022) describe how the current "eco-modernist" narratives surrounding aviation are logical to stakeholders in the sector itself, but prevent the influence of alternative – perhaps, necessary – narratives.

[2] The alternative narrative – gearing the economy towards well-being, foregoing the pursuit of increasing consumption and production – dates back at least to the Limits to Growth report (Meadows et al., 1972). This report shows how overshoot in pollution and resource use could lead the system to collapse. Empirical data from the 50 years since this report shows the same basic behaviour (see, e.g., Nebel et al., 2023).

potential is reached (Kito et al., 2023). In the present study, aircraft lifetimes were consistently set to 22 years (see Section A.3). Reducing this to 15 or 10 years would have a substantial influence on the results. This is not represented within the scenario space. However, for this trend and the ones discussed in the previous paragraph, it must be pointed out that the purpose of this study is exploratory. As such, a broad range of possible scenarios was considered, with the most optimistic scenarios for fuel efficiency going beyond optimistic expert judgement (see Section 2.6.3). Considering the potential impact of additional scenario dimensions can be done by reflecting on the spaces between scenarios and by consulting the sensitivity analyses (Section 3.6).

A different factor not considered is the possibility of substitution or rebound effects, such as an air-to-rail shift. Although this is beyond the scope of this thesis, it can reasonably be assumed that scenarios with lower air traffic would see such an effect to a certain extent. However, this concept is perhaps less relevant than one might imagine. A majority of aviation traffic cannot be substituted by an attractive rail journey and substituting those which can has a limited effect (Dobruszkes et al., 2022; ICCT, 2022; Kito et al., 2023). The difference in long-distance flights between air traffic scenarios should therefore not be imagined as being replaced by an equivalent journey by rail or road. This also has consequences for what recommendations can be provided (see Chapter 5).

4.2.2. Aviation bio-fuels

This study considered the transition from fossil kerosene to hydrogen-based fuels. However, as introduced in Section 1.3.2, bio-based aviation fuels are also expected to play a large role. Acknowledging this, the results presented here require some additional discussion. Firstly, scaling up bio-kerosene within the framework used here would not change the total fuel demand (Figure 3.2a and b), but it would mean that less additional hydrogen is required for each of the scenarios (Figure 3.2c), due to the biogenic hydrogen conserved in bio-fuel processes. Both hydrogen production capacity and biomass availability could be limiting factors, so a trade-off between these two cannot be made when only evaluating hydrogen-based fuels. However, the focus of this study – being, environmental impacts and climate targets of aviation – can still be discussed despite this limitation in scope. Although the present-day electricity mix makes hydrogen-based fuels unattractive when compared to bio-kerosene (see, e.g., Ballal et al., 2023; Habermeyer et al., 2023), provided there is abundant electricity from renewable sources available, e-fuels can be expected to have a lower climate change impact than bio-fuels (see, e.g., Penke et al., 2021; van der Giesen et al., 2014). Therefore, the sensitivity analyses based on wind energy are representative of the most optimistic case regarding the climate impact of AAF (Figures C.9, C.12, and C.14). As discussed in Section 3.6, these sensitivity analyses show limited influence on the overall results. It can therefore not be claimed that the findings of this study rely on an overestimation of impacts. Still, this limitation should be kept in mind: no scenario generated in this study can be taken as a prediction of future impacts. Rather, the range of scenarios considered collectively give some insight into the breadth of possible future impacts.

4.2.3. Non-CO_2 effects of flight

Non-CO_2 climate forcers play a large role in the total warming caused by aviation. Figure C.2 breaks this down, showing that aviation-induced cloudiness in particular has a high contribution. This figure shows uncertainty ranges for the radiative forcing impact of the estimated emissions, adopted from Lee et al. (2021) via Sacchi et al. (2023). However, a number of additional assumptions are made, which increase the uncertainty regarding these impacts further. These are addressed in the following paragraphs.

As described in Section 2.6, all impacts from flight emissions (with the exception of aviation-induced cloudiness) were assumed to scale linearly with fuel use. This does not reflect reality, as the formation of NO_x, CO, and particulate matter – to name a few examples – is tied to combustion properties which are changing along with engine technology. Cox et al. (2018) find that, for the period 1970-2020, NO_x emissions decreased faster than fuel use, resulting in a decrease of the NO_x emission index (EI; emission mass per mass fuel use) which they project to continue in coming decades. Quadros et al. (2021), however, observe that choices in technological development have lead to an increase in the NO_x EI. They expect that it will take decades for this trend to fully reverse, driven by a decrease in EI from wide-body aircraft, while the EI continues to increase for narrow-body aircraft. Grewe et al. (2021), on the other hand, expect the reverse: a decrease in NO_x EI for narrow-body aircraft and an increase for wide-body aircraft. Because of this uncertainty among experts, the choice was made to maintain a constant EI for all substances.

The atmospheric influence of substances such as NO_x is also simplified. In reality, these are time and location dependent (Dahlmann et al., 2016; Grobler et al., 2019). The radiative efficiencies adopted from Lee et al. (2021) are not region-specific, but global. They are also not temporally universal, as background changes to atmospheric composition – and resulting responses – are not accounted for.

Recall that the in-flight emissions of hydrogen aircraft were modelled here assuming hydrogen combustion, although the fuel efficiency explicitly does consider the possibility of an electric powertrain powered by a hydrogen fuel cell. A fuel cell would completely eliminate NO_x and would affect contrail formation. While it is expected that all hydrogen aircraft would produce contrails more frequently than hydrocarbon aircraft, this is thought to be offset by a much lower optical depth and reduced lifetime of the resulting cloudiness (see, e.g., Gierens, 2021). An important factor here is the reduction in soot created, resulting in much lower nucleation of ice crystals (see Section B.5). Note that the present quantification in this regard is relatively optimistic when compared to other work (see, e.g., Kossarev et al., 2023). These factors should be kept in mind when considering the results, but have limited impact on what conclusions can be drawn beyond the limitations already evident from the present approach to quantifying non-CO_2 impacts.

It is for the above reasons that results which exclude these non-CO_2 effects are also shown and discussed. Although there is confidence that non-CO_2 effects have a strong warming effect, their particular magnitudes and trends must be approached with caution in the context of the present research. In the same vein, note that warming itself can trigger additional climate forcers (see, e.g., Armstrong McKay et al., 2022), which should be kept in mind when reflecting on warming neutrality as it was evaluated here.

4.2.4. Economic measures and offsetting

Important to understanding the implications of this research is that the aviation sector does not commit itself to meeting the climate targets evaluated here by reducing its own emissions. CORSIA is an offsetting scheme. Broadly, the idea is that the aviation sector contributes to preventing emissions in other sectors, or enables negative emissions directly (see, e.g., ATAG, 2021). As these measures were not included here, it is not surprising that the conventional scenarios do not meet the emission limit. If one assumes that, at any given time, the aviation sector has economic measures at its disposal with which to balance excess emissions, naturally, any scenario could meet the emission limit. However, such an assumption cannot be justified. For one, the efficacy of existing offsetting programs is questionable (see, e.g., Badgley et al., 2022; Unearthed, 2021). A cap-and-trade arrangement can, in principle, be effective, but requires either enough sectors to emit below their cap, or the introduction of negative-emission technologies. This makes the narrative of the aviation sector particularly volatile, as it relies on a narrow imagining of the future, undermining alternative futures and policies (see, e.g., Köves and Bajmócy, 2022; Stuart et al., 2019). Furthermore, an element of the present research that should not be overlooked is its geographical scope. Can it be justified that European aviation appropriates a large share of the limited capacity for offsetting, ahead of regions which are less prepared for the large-scale deployment of AAF? It might be feasible to maintain compliance with CORSIA in this way for some time, but this raises the same questions of equity brought up in Section 4.1, rather than rendering these questions moot. In short, the possibility of effective economic measures can add an additional dimension to the discussion of Section 4.1, but it does not invalidate its core observations and, in any case, remains uncertain.

5

Conclusions and recommendations

This thesis aimed to contribute to how the future of commercial aviation in Europe is envisioned and discussed. This was done by considering a two-part research question:

Considering hydrogen-based fuels for European commercial aviation, (1) to what extent can environmental impacts be reduced and (2) under what conditions are climate targets met?

This research questions was answered through a detailed exploration of the recent ReFuelEU Aviation rules, while considering other measures to mitigate the environmental impacts of aviation. By focusing on hydrogen-based fuels – here meaning e-fuel and hydrogen aircraft – the intricacies of bio-kerosene were avoided, while still arriving at a robust discussion of the AAF supply, potential levels of technological improvements, and possible trajectories for the air traffic volume. Observing that there is a lack of extensive scenario exploration which utilises a detailed LCA method, a novel method was applied, which combined best practises in prospective LCA with a temporally explicit approach to the LCI and LCIA phases – adapting elements from Grewe et al. (2021), Langkau et al. (2023), and Sacchi et al. (2023), among others. Inventories for future technologies were introduced using a system dynamics approach. The scope and combination of methods allows for a dialogue with industry road maps, particularly, Destination 2050 (NLR & SEO, 2021). These methods are appropriate for the study at hand, although with clear limitations. Due to restrictions to the practical scope, participatory elements typical to forecasting were excluded, the scenario field and subsequent quantification were simplified, and economic measures to balance excess emissions were excluded. Combined, this means that there is still much uncertainty between a particular description of future trends and what impacts the model created here describes. This is to be expected. Within the exploratory context of this research, salient observations can be made none the less.

To answer the first part of the research question, it is clear that commercial aviation can greatly reduce its emission of GHGs, provided that it can utilise hydrogen-based fuels based on water electrolysis with renewable electricity on a large scale. High-performance future aircraft technologies can play an important role in this as well: a majority of impacts stay within the fuel lifecycle, although shifting from fuel use to fuel production. In the same vein, the introduction of liquid hydrogen aircraft could be preferred over hydrocarbon aircraft powered by e-fuel. This assumes that there are no strong differences in non-CO_2 effects between a hydrogen aircraft and one powered by e-fuel. In general, the benefit of fuel efficiency is less pronounced for climate change than it is for other impact categories. When considering the progression of climate impacts over time – as was also done for the second part of the research question – warming neutrality from 2050 to 2070 appears possible, especially if the AAF share keeps increasing beyond the 2050 timeline of ReFuelEU Aviation. The ambition of the aviation sector to become "climate neutral" therefore seems, by some definition, attainable. Additionally, the warming from CO_2 emissions over time was compared to CO_2 limits described by ICAO and IATA. This revealed that none of the scenarios using an air traffic projection based on EUROCONTROL forecasts stayed within this limit, even in the most optimistic cases. In the absence of a reliable mechanism to permanently offset excess emissions, this necessitates a drastic increase in the ambitions for AAF deployment of ReFuelEU and/or a progression of air traffic below the low-growth EUROCONTROL forecast. Here, it was found that, if supplementing ReFuelEU Aviation with a 100% AAF target for 2060, a reduction to 70% of the 2019 RPK volume by 2035 could be sufficient to respect the emission limit, even if aircraft performance follows a business-as-usual trajectory – rather than the optimistic or breakthrough trajectories often imagined.

Future research on this topic should consider the limitations highlighted in Section 4.2. These limitations were the most influential to contextualising this specific study. Looking more broadly, a range of additional recommendations can be formulated. In the representative scenarios presented here, a dependency between air traffic and technological improvement was incorporated. Such dependencies emerge from subjective narratives. This illustrates the value of participatory research to forecasting. In this light, the stock-and-flow models constructed could also benefit from such co-creation, as stakeholders might disagree with the relevance, direction, or magnitude of relationships modelled[1]. Such considerations are particularly relevant for functional units such as the one used here – quantifying all air traffic within the scope, rather than a service-level value (i.e., per revenue passenger-kilometer). The present work shows the disparities between these two approaches to the functional unit (see Section C.2). This is relevant to considering that technologies are introduced over time and can have effects beyond the product level (see, e.g., Font Vivanco et al., 2015). As such, a service-level perspective does not allow any reflection on cumulative impacts or climate budgets. Sector-level assessments are by no means a novel concept, but have only received limited attention in the discussion of (prospective) LCA so far (see, e.g., Laurent et al., 2018; Rupcic et al., 2023). As best-practises take shape, this perspective should not be neglected.

Considering the future of the aviation sector, it is clear that the presumption of growth must be challenged, as discussed above (see also, e.g., Delbecq et al., 2023; Gössling and Humpe, 2024; Köves and Bajmócy, 2022; Sacchi et al., 2023). Pursuing technological breakthrough might be alluring, but should not distract from the urgency of impact mitigation. In short, shared imaginations of possible futures should draw from more diverse perspectives than the one promoted by the aviation sector. Considering a lack of solutions to mitigating the near-term impacts of aviation, demand management should be considered. The report by Populytics (2023) which inspired the degrowth pathway for air traffic shows that such policies could see popular support. There, a reduction of air traffic was framed as one potential lever among many to achieve the desired climate targets, and was tied to expanding high-speed rail infrastructure. However, as discussed in Section 4.2.1, the difference in air traffic scenarios cannot be explained based on a direct air-to-rail shift for the same destination. Demand management must be considered more broadly: substituting a transatlantic holiday destination with one closer to home. Furthermore, focusing on reducing short-distance flights could have an adverse effect, shifting airport and airspace capacity towards additional long-distance flights, creating a net increase in emissions. Therefore, it is critical to focus on metrics such as the total fuel used, rather than the number of (short-distance) flights. Still, a relatively sharper reduction in short-distance flights when compared to other distance segments might be a logical step towards mitigating the short-term social cost of demand management. This should also be considered alongside (the mitigation of) the social costs of climate change. Promoting an equitable distribution of flight activity within and between regions for present and future generations will require creative policy solutions. This work illustrates the urgency with which these solutions are required.

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[1] For example, while this work treats the air traffic volume as an input variable, which contributes to defining the fuel use, Gössling and Humpe (2024) consider the possibility that air traffic depends on the availability of fuel. Such an approach is further removed from the typical logic of LCA, but might be a (more) relevant perspective to stakeholders.

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A

Extended description of system modelling

In this appendix, the descriptions of the modelling approach provided in Chapter 2 are supplemented.

A.1. Stock-and-flow diagrams

In Figure A.1 and Figure A.2, the stock-and-flow diagrams introduced in Figure 2.3a and Figure 2.3b are displayed on a larger scale.

A.2. Air traffic demand segments

The research database of EUROCONTROL (2022a) is used, which lists each flight recorded in its airspace for four months of the year (March, June, September, and December). Each of these flights is filtered and divided into segments using the characteristics market segment, departing airport, arrival airport, actual distance flown, and aircraft type. To approximate the use of narrow-body and wide-body aircraft types, the most-used types reported by the ICCT (2022) are filtered from the data. Regional aircraft and commuter aircraft, which contribute a small minority of emissions, are excluded from the analysis. Next, the number of seats reported by the ICCT (2022) for these aircraft are used as a basis to determine the available seat-kilometers (ASK), which are converted to revenue passenger-kilometers (RPK) assuming an occupation factor of 80%. Recognising that there is a trade-off between analytical resolution and computational burden, the choice is made to group these RPK values into a few bins, based on flight distance. This results in a number of segments, each of which is defined by a reference distance, its quantity of revenue passenger-kilometers (RPK) estimated for 2019, and an estimate for the share of RPK that could be serviced with hydrogen aircraft, should these be introduced (Table A.1). The assumption that hydrogen aircraft could, in theory, foresee all intra-EU+ flights is taken from NLR and SEO (2021). Consider here that hydrogen aircraft are introduced gradually, so not all airports would require adapted infrastructure in 2035 already. As wide-body hydrogen aircraft are unlikely to enter the market prior to 2050, they are not typically represented in road maps. Here, the assumption is made that by 2050, some airports outside of the EU+ will have hydrogen infrastructure, allowing for a gradual introduction of wide-body hydrogen aircraft equivalent to a potential of 0.5. In principle, this would mean that narrow-body extra-EU+ segments should also be given a non-zero potential after 2050, but this is neglected here.

Until 2029, values from EUROCONTROL (2023) for en-route service units (an expression of aircraft size and payload) are adopted. From 2030 onward, the values from EUROCONTROL (2022b) for flight numbers are used,

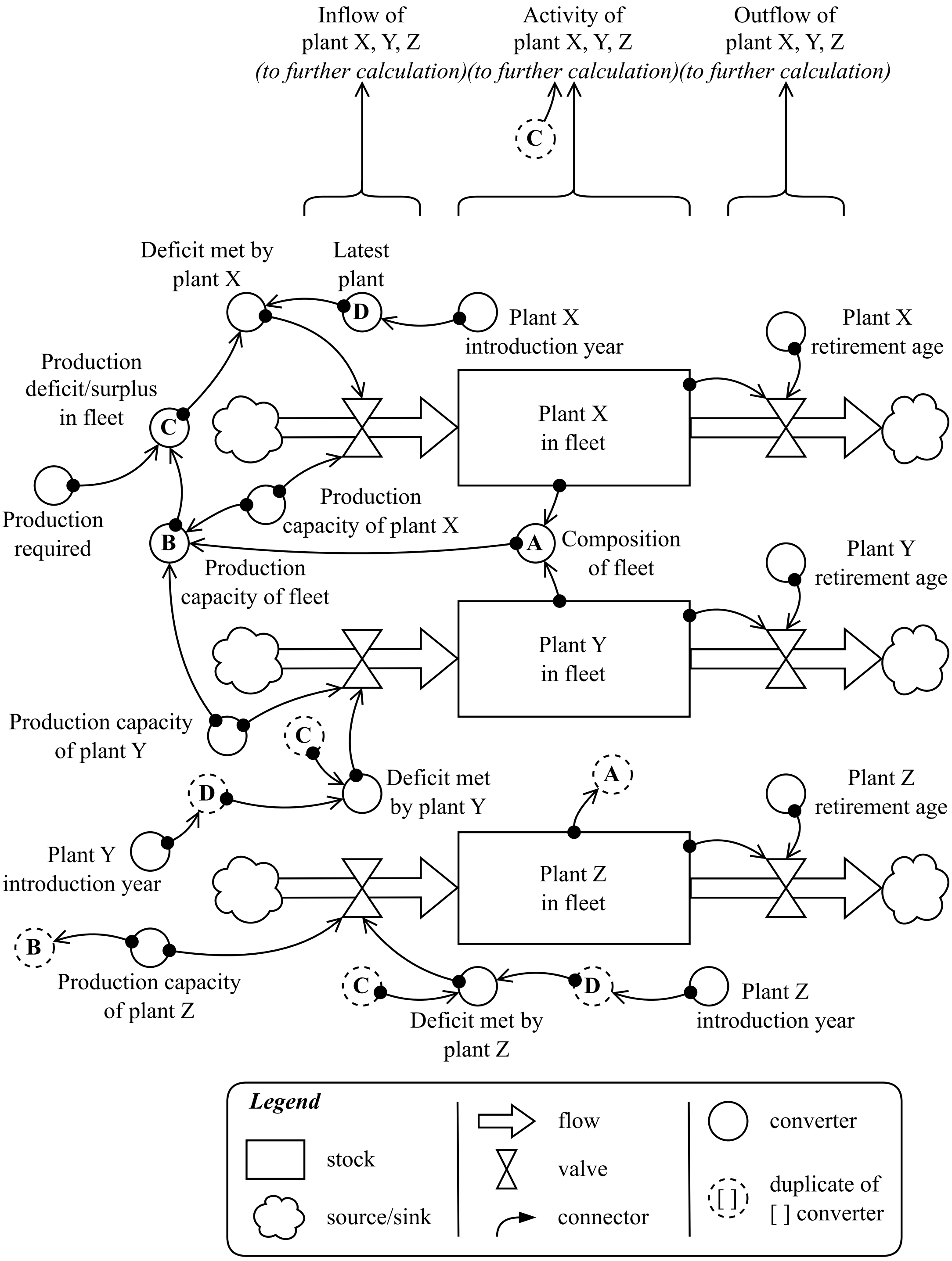

Figure A.1: Stock-and-flow diagram for the AAF fleets. The AAF fleets are connected to each other and to the aircraft operations through further calculations in order to determine the production required from each fleet.

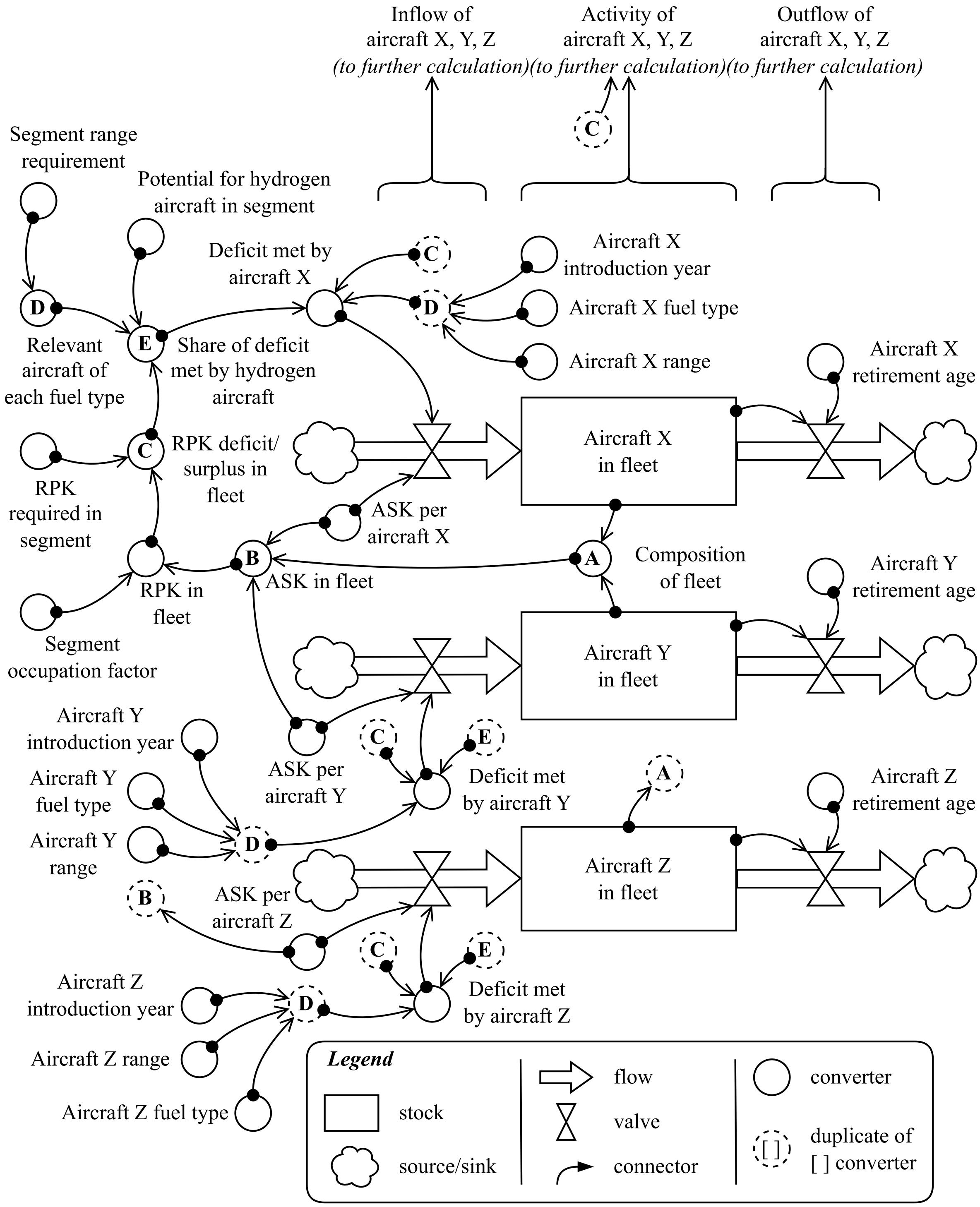

Figure A.2: Stock-and-flow diagram for the aircraft fleets. For each segment of flights, a fleet is generated, the results of which are used for further calculation. ASK: available seat-kilometer, RPK: revenue passenger-kilometer.

Table A.1: Characteristics and initial conditions of air traffic segments.

Aircraft type	Destination	Bin [km]	Reference flight [km]	Air traffic in 2019 [RPK]	H_2 aircraft potential [-]
Narrow-body	Intra-EU+	(0, 1000]	500	1.71×10^{11}	1
Narrow-body	Intra-EU+	(1000, 2000]	1500	3.58×10^{11}	1
Narrow-body	Intra-EU+	(2000, 3000]	2500	1.24×10^{11}	1
Narrow-body	Intra-EU+	>3000	3500	2.34×10^{10}	1
Narrow-body	Extra-EU+	(0, 1000]	500	4.39×10^{9}	0
Narrow-body	Extra-EU+	(1000, 2000]	1500	3.95×10^{10}	0
Narrow-body	Extra-EU+	(2000, 3000]	2500	7.47×10^{10}	0
Narrow-body	Extra-EU+	>3000	3500	6.58×10^{10}	0
Wide-body	Intra-EU+	(0, 4000]	2000	9.85×10^{9}	1
Wide-body	Extra-EU+	(0, 4000]	2000	1.49×10^{10}	0.5
Wide-body	Extra-EU+	(4000, 6000]	5000	1.21×10^{11}	0.5
Wide-body	Extra-EU+	(6000, 8000]	7000	1.80×10^{11}	0.5
Wide-body	Extra-EU+	>8000	9000	2.27×10^{11}	0.5

as no en-route service units values are provided. Note again that the approach used here couples the overall trend to that of each of the individual segments, but that these trends can differ in reality. The trend towards larger aircraft and further flight distances means that the projected flight numbers would mean a larger increase in RPK than portrayed here.

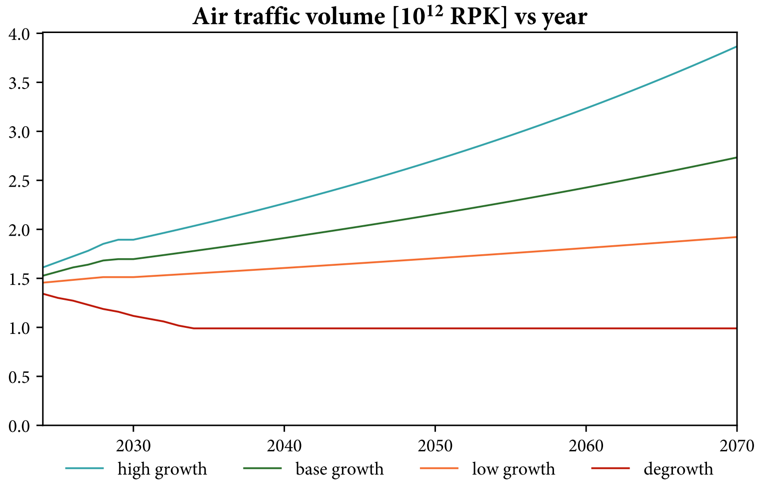

Figure A.3: Visualisation of the air traffic scenarios for temporal scope of 2024-2070. RPK: revenue passenger-kilometers.

A.3. Aircraft stock-and-flow model

This section expands on some of the elements described in Section 2.4, specific to aircraft fleets. In order to create these fleets, an initial age distribution is defined, as well a retirement age. In 2018, the mean age of aircraft was around 11 years, but distributed in a way such that new aircraft (0-5 years old) were almost twice as common as older aircraft (15-20 years old) (Grewe et al., 2021). However, in the meantime, the COVID-19 pandemic has disrupted the aviation sector. Furthermore, there are a number of factors influencing aircraft lifetime, and the general trend seems to be towards a relatively short lifetime, when compared to the design lifetime of 25-30 years

Table A.2: Overview of revenue passenger-kilometers (RPK) in air traffic scenarios, shown relative to RPK in 2019.

Year	High-growth traffic	Base-growth traffic	Low-growth traffic	Degrowth traffic
2019	1.00	1.00	1.00	1.00
2025	1.18	1.11	1.04	0.92
2030	1.36	1.22	1.08	0.79
2035	1.49	1.29	1.11	0.70
2040	1.62	1.37	1.14	0.70
2050	1.94	1.55	1.22	0.70
2060	2.32	1.74	1.29	0.70
2070	2.77	1.96	1.37	0.70

Table A.3: Characteristics of reference aircraft used in fleet construction and the generation of inventories. OEW: operating empty weight, NB: narrow-body, WB: wide-body, gen.: generation.

	Introduction [year]	Seating capacity [-]	Yearly operations [km/year]	OEW [kg]
NB gen. 0	1988	180	2.26×10^6	4.26×10^4
NB gen. 1	2016	189	2.26×10^6	4.26×10^4
NB gen. 2	2035	189	2.26×10^6	3.96×10^4
NB gen. 2 (H_2)	2035	189	2.26×10^6	4.36×10^4
NB gen. 3	2050	189	2.26×10^6	3.71×10^4
NB gen. 3 (H_2)	2050	189	2.26×10^6	4.09×10^4
WB gen. 0	1995	360	4.07×10^6	1.61×10^5
WB gen. 1	2015	350	4.07×10^6	1.42×10^5
WB gen. 2	2035	350	4.07×10^6	1.33×10^5
WB gen. 3	2050	350	4.07×10^6	1.26×10^5
WB gen. 3 (H_2)	2050	350	4.07×10^6	1.38×10^5

(see, e.g., Kito, 2021). Due to the structure of the stock-and-flow model, the initial distribution of ages assumed can have a profound influence on the progression of fleet turnover. In order to limit the cascading effect the initial age distribution can have, a uniform distribution is opted for, assuming a maximum age of 22 years – keeping the mean age around 11 years, with turnover faster than the maximum design lifetime, but still longer than more optimistic projections (see, e.g., Delbecq et al., 2022). This maximum age is also used to determine when aircraft retire as the fleet progresses.

In addition to aircraft age, the stock-and-flow model illustrated in Figure A.2 uses variables such as the ASK per aircraft per year (see also Section A.2) and the introduction year of each aircraft. ASK is determined by multiplying the seats of an aircraft by its yearly distance flown. An overview of these variables is provided in Table A.3. Seat capacity and introduction years of reference aircraft are taken from NLR and SEO (2021), with the introduction of future aircraft generally aligning with works such as Delbecq et al. (2022), EUROCONTROL (2022b), Grewe et al. (2021), ICAO (2022d), and NLR and SEO (2021). For the sake of simplicity, the seat capacity of future aircraft is set equal to that of their respective present-day counterpart. In a sense, this neglects the trend of increasing seat densification (see, e.g., Cox et al., 2018; NLR and SEO, 2021), but this assumption also justifies the method through which efficiencies from literature are adopted, which are described as a factor of energy per ASK (see Section 2.6.3). The distances per year are adopted from Cox et al. (2018). These are also used for hydrogen aircraft, although in reality, these have more complicated ground operations, likely increasing the time that must be spent between flights. This assumption results in an underestimation of impacts related to the production of hydrogen aircraft.

Table A.4: Performance of the reference aircraft used for the landing and take-off (LTO) phase and the climb/cruise/descent (CCD) phase of reference flight distances. NB: narrow-body, WB: wide-body, gen.: generation.

Flight phase	**NB gen. 0 (Airbus A320)**	**NB gen. 1 (Airbus A320neo)**
Fuel use LTO	3.23×10^4	2.60×10^4
Fuel use CCD, 500km	7.19×10^4	6.40×10^4
Fuel use CCD, 1500km	1.90×10^5	1.64×10^5
Fuel use CCD, 2500km	3.09×10^5	2.66×10^5
Fuel use CCD, 3500km	4.30×10^5	3.70×10^5
Flight phase	**WB gen. 0 (Boeing 777-300)**	**WB gen. 1 (Airbus A350-900)**
Fuel use LTO	1.02×10^5	8.42×10^4
Fuel use CCD, 2000km	7.11×10^5	5.84×10^5
Fuel use CCD, 5000km	1.77×10^6	1.44×10^6
Fuel use CCD, 7000km	2.46×10^6	2.01×10^6
Fuel use CCD, 9000km	3.32×10^7	2.59×10^6

A.4. AAF infrastructure stock-and-flow model

This section expands on some of the elements described in Section 2.4, specific to AAF infrastructure fleets. First, the step from aircraft fleets to fuel demand is explained (Section A.4.1), followed by its conversion to the required AAF supple (Section A.4.2), leading to characteristics specific to AAF infrastructure used in creating its fleets (Section A.4.3).

A.4.1. Total fuel demand

The fuel demand of the reference aircraft is determined using the EMEP/EEA calculation sheet for aviation emissions (Winther & Rypdal, 2023). Fuel use and emissions for the four existing reference aircraft are determined for a number of distances. The emissions per unit fuel are determined separately for LTO and CCD phases (see Section B.6), but these in any case still require the fuel quantity per phase. For CCD phases, this is determined for each reference distance by assuming a linear progression between the two closest distances available in the calculation sheet. The results of this process are presented in Table A.4.

As described in Section 2.6.3, the fuel efficiency of reference aircraft also serves as input for the fuel demand of future aircraft. The differences in fuel efficiency for each of the three hydrocarbon aircraft scenarios is shown in Table A.5. The efficiencies for future hydrogen aircraft with respect to contemporary hydrocarbon aircraft – adopted from ICAO (2022b) – are reproduced in Table A.6. From these tables, the fuel demand of each aircraft modelled can be determined for each reference flight. This way, the total fuel demand for each time step is calculated in terms of the energy content required as liquid hydrogen and as hydrocarbon aviation fuel.

A.4.2. Required AAF supply

Having calculated the total volume of aviation fuels required (see Section A.4.1), the demand for liquid hydrogen is known. Next, the share of hydrocarbon fuel that is met by AAF is determined (Table A.7). Related fleets are constructed and deployed to match these shares precisely. The compliance per time interval is modelled by assuming a linear progression between the left and right milestones shown in Table A.7. To illustrate, minimum shares at t_1 and t_3 of 5% and 10% respectively are assumed to result in a share of 7.5% at t_2. The remaining hydrocarbon fuel demand is met by fossil kerosene.

Table A.5: Scenarios for the fuel use of future hydrocarbon aircraft. Fuel use is expressed relative to the first generation of aircraft in the same type (e.g., performance of WB gen. 3 is reported relative to WB gen. 1). NB: narrow-body, WB: wide-body, gen.: generation.

Type and generation	Business as usual	Optimistic improvements	Breakthrough improvements
NB gen. 1	1.00	1.00	1.00
NB gen. 2	0.87	0.78	0.70
NB gen. 3	0.78	0.62	0.50
WB gen. 1	1.00	1.00	1.00
WB gen. 2	0.87	0.82	0.70
WB gen. 3	0.78	0.66	0.50

Table A.6: Scenarios for the fuel use of future hydrogen aircraft. Fuel use is expressed relative to the performance of their contemporary hydrocarbon generation (e.g., WB gen. 3 (H_2) is reported relative to WB gen. 3), see Table A.5. NB: narrow-body, WB: wide-body, gen.: generation.

Type and generation	Low-performance	Mid-performance	High-performance
NB gen. 2 (H_2)	1.2	1.15	0.95
NB gen. 3 (H_2)	1.2	1.15	0.95
WB gen. 3 (H_2)	1.4	1	0.9

Table A.7: Minimum share of AAF in the three AAF volume scenarios considered. Values represent the minimum share of AAF in the total fuel supply when evaluated based on LHV.

Year	No ReFuelEU	ReFuelEU as-is	ReFuelEU extended
2024	0.0005	0.0005	0.0005
2025	0.0005	0.02	0.02
2030	0.0005	0.06	0.06
2035	0.0005	0.2	0.2
2040	0.0005	0.34	0.34
2045	0.0005	0.42	0.42
2050	0.0005	0.7	0.7
2060	0.0005	0.7	1.00
2070	0.0005	0.7	1.00

Table A.8: Characteristics of AAF plants used in fleet construction and the generation of inventories.

Plant type	Unit of output	Yearly output capacity	Max. age [year]
PEM electrolysis plant	MJ H_2	1.78×10^{7}	20
DAC plant	kg CO2	1.00×10^{8}	20
Fischer-Tropsch plant	MJ e-fuel	2.35×10^{11}	30
Hydrogen liquefaction plant	MJ H_2	9.90×10^{7}	20

A.4.3. Characteristics of AAF infrastructure

As described in Section 2.4, each element of AAF infrastructure was given certain characteristics in order to construct the related fleets, as was done for aircraft in Section A.3. In contrast to the discussion on the starting age distribution for aircraft, this variable is much less relevant for AAF infrastructure, since only a small fraction of the total fuel supply is met with AAF at the start of the temporal scope. To reflect that even this small fraction is relatively young, the simplification is made that all AAF infrastructure in use during the first time interval was constructed in the interval prior. This assumption has a negligible effect on the analysis.

The performance of AAF plants is quantified in Appendix B. However, the construction of fleets requires a few additional features. Specifically, the maximum age of each plant and its yearly production capacity. These are provided in Table A.8 and are determined based on the same sources discussed in Appendix B.

A.5. Causal loop diagram

As introduced in Section 1.1, there is a perception that efficiency improvements in aviation are tied to an increase in air traffic. This work does nothing to prove or disprove this concept, but uses it as an input in the scenario construction and point of reflection. To illustrate this relationship, a causal loop diagram is created, based on perspectives observed in industry reports (ICAO, 2022a; NLR & SEO, 2021) (Figure A.4). As can be observed, the outer loop constitutes a reinforcing feedback (i.e., there is an even number of negative relations). Many additional variables and relations could be added to this image. For example, capital investment towards low-impact aviation and how this connects to the expenditure and revenue of the aviation sector is much more nuanced than depicted here, including policy dimensions and market dynamics.

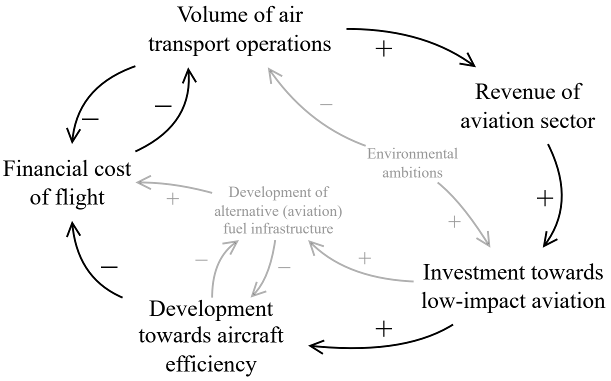

Figure A.4: Simple causal loop diagram illustrating the relations between the development of aircraft technology and the volume of air traffic. Several variables which do not contribute to this narrative are included in grey, to illustrate potential ways in which the diagram can be expanded.

B

Extended description of life cycle inventories and impacts

The following sections expand on the life cycle inventory analysis phase, described in Chapter 2. Note that Section B.6 includes an additional spreadsheet file in its contents, which is available alongside this thesis.

B.1. Aircraft manufacturing and disposal

As introduced in Section 2.6.1, the inventories for aircraft manufacturing and disposal were adopted from Cox et al. (2018) with a few adjustments. The aircraft material composition was maintained, but buy-to-fly ratios were introduced to quantify manufacturing waste (Table B.1). Based on estimates reported in literature, these are here assumed to be 8:1 for aluminium alloy (Timmis et al., 2015), 1.5:1 for composites (Bachmann et al., 2017), and 2.2:1 for other materials (Orefice et al., 2019). No conceptual distinction is made between manufacturing waste and end-of-life waste, besides their respective positioning in the aircraft life cycle. The assumptions of Cox et al. (2018) regarding what background data to use are largely adopted, using nickle as a proxy for the miscellaneous mass fraction and scrap copper as a proxy for miscellaneous and titanium waste. The names of the background inventories used are reported in Section B.6. Note that, instead of using the inventory for carbon fibre-reinforced composite (CFRP) included by Cox et al. (2018), background inventories generated by premise for carbon fibre and epoxy resin are included separately. This requires assuming a fibre mass fraction, which was chosen to be 68.5% – aligning with the common fibre volume fraction of 60% (see, e.g., Arblaster, 2023). No inventories for milling or composite forming were included, under the assumption that the heat and energy flows generalised by Cox et al. (2018) cover such activities to a sufficient degree.

Operating empty weights of future aircraft (Table A.3) were similarly correlated with the trend quantified by Cox et al. (2018). As discussed in Section 2.6.1, it is a simplification to assume that these are unaffected by the dimensions of aircraft performance. However, the small contribution of the aircraft system itself to the life cycle means that this assumption has little impact on the results.

B.2. Hydrogen production, distribution, and liquefaction

Three sources for hydrogen are considered. The market mix is adapted directly from the hydrogen production mixes described by Wei et al. (in preparation). These combine the typical hydrogen production process of steam

Table B.1: Material composition of reference aircraft, as share of operating empty weight. Within a given generation, all aircraft types are assumed to have the same composition. CFRP: carbon fibre-reinforced composite, gen.: generation.

Material	Gen. 0	Gen. 1	Gen. 2	Gen. 3
Aluminium alloy	0.68	0.48	0.29	0.15
CFRP	0.14	0.33	0.51	0.65
Steel	0.12	0.11	0.1	0.09
Titanium	0.04	0.05	0.06	0.06
Miscellaneous	0.02	0.03	0.04	0.05

methane reforming (SMR) with several water electrolysis technologies: alkaline electrolysers (AE), proton exchange membrane (PEM) electrolysers, and solid oxide electrolysis cells (SOEC), as well as a small volume of biomass gasification. At present, AE is the more common technology for water electrolysis, but PEM is expected to become the dominant technology in the coming decades. For the other two hydrogen scenarios, only PEM is considered, in one case powered by grid electricity and in the other case, powered by offshore wind[1]. For the market case, the technological progression described by Wei et al. (in preparation) is used. As this only generates inventories up to 2050, the 2050 inventories are reused for subsequent years. For the other two cases, three scenarios for technological progression are created by combining the efficiencies for electricity use reported by Delpierre et al. (2021) with those reported by the IEA (2019) for 2019, 2030, and 2050 (Table B.2). For plants constructed between these years, a linear progression between the two flanking years is assumed. No improvements beyond 2050 are considered. This general approach is used for all plants with a performance that evolves over time. For water use, the three scenarios are based on high- and low-end estimates found in literature. Ideally, water use is as low as $9\,\mathrm{kg\,kg^{-1}}$, however, a more typical value is around $10\,\mathrm{kg\,kg^{-1}}$ (Delpierre et al., 2021). Some report values as high as $14\,\mathrm{kg\,kg^{-1}}$ (in premise, see Sacchi et al., 2022). In principle, one could consider multi-functionality here, as oxygen is a co-product of water electrolysis. However, this is not considered as an additional functional flow here, and is excluded from the inventory.

Distribution of hydrogen is based on Sacchi et al. (2023), requiring $3.2\,\mathrm{kW\,h\,kg^{-1}}$ electricity for compression. Furthermore, a loss of 1% is considered, which contributes hydrogen emissions to the air. Although estimates for hydrogen transportation infrastructure exist (by truck, by ship, by natural gas pipeline, etc.) this element is excluded here due to high uncertainty.

For hydrogen aircraft, the hydrogen is liquefied. There is no inventory available for the construction of a liquefaction plant. This is therefore cut off. Smith and Mastorakos (2023) collect a variety of electricity demands for liquefaction, including the (future) year for which the value is reported. This results in three scenarios: a high-end and low-end, which are constant over time, and a mid-performance value which aligns with the improvement over time estimated by Smith and Mastorakos (2023) (Table B.2). An additional 1% loss occurs between liquefaction and fuel use. Much higher boil-off losses have been estimated, but it is considered that the majority of the boil-off could be recovered (see, e.g., IEA, 2019).

B.3. Direct air capture

Using premise, inventories for a sorbent-based direct air capture plant – and accompanying sorbent – are generated (see Section 2.7). The base performance of such a system is here modelled after Terlouw et al. (2021), using the values for a system using a heat pump, thereby only requiring input of sorbent and electricity (values for 2020 in Table B.3). For the best-case scenario, the assumption is made that waste heat can be sourced – for example by

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[1] As shown in Section B.6, the offshore wind cases use an inventory for a 1-3 MW turbine, localised to the Netherlands. The transformation from high voltage to medium voltage is accounted for.

Table B.2: Inputs for hydrogen production, compression, and liquefaction in the three performance scenarios. The transportation/boil-off losses are accounted after compression and after liquefaction. For some flows, the value changes depending on the construction year of the plant, as described in the text. PEM: proton exchange membrane.

Inputs per process [unit]	Year	Worst-case performance	Base performance	Best-case performance
PEM plant				
Electricity [kWh/MJ]	2019	4.96×10^{-1}	4.55×10^{-1}	4.15×10^{-1}
	2030	4.41×10^{-1}	4.28×10^{-1}	4.08×10^{-1}
	2050	4.15×10^{-1}	3.81×10^{-1}	3.75×10^{-1}
Water, deionised [kg/MJ]	all	1.17×10^{-1}	8.33×10^{-2}	7.50×10^{-2}
Hydrogen compression for transport				
Electricity [kWh/MJ]	all	2.67×10^{-2}	2.67×10^{-2}	2.67×10^{-2}
Hydrogen liquefaction				
Electricity [kWh/MJ]	2020	1.25×10^{-1}	8.67×10^{-2}	5.00×10^{-2}
	2050	1.25×10^{-1}	5.00×10^{-2}	5.00×10^{-2}

integration with other elements of the e-fuel production chain (see, e.g., Rojas-Michaga et al., 2023) – eliminating the need for a heat pump.

In the worst-case scenario, no improvements over time to the operational efficiency is assumed. For other cases, learning rates (LRs) are assumed. Based on expert judgement, Qiu et al. (2022) estimate a LR of 0-5% for energy and 5-15% for sorbent, with an optimal value of 18% and 50%, respectively. Using their method, at each time step, the operational performance (D_t) relative to the initial performance (D_0) can be described following Equation B.1, while accounting for the optimal value that can be attained (D_{min}). Here, $\log_2(X_t/X_0)$ represents how often the global capacity has doubled with respect to the initial capacity. Hanna et al. (2021) also estimate a LR for energy: 2%, without a maximum reduction, and without a LR for sorbent consumption. Based on these two works, optimal values of Qiu et al. (2022) are adopted, with base case LRs of 2.5% and 5% for energy and sorbent respectively, and best-case LRs of 5% and 15%, respectively. The capacity over time for these two cases is based on Fuss et al. (2018), who estimate a potential global capacity in 2050 of 0.5–5 GtCO_2/yr. In line with this range, an initial capacity of of 0.003 GtCO_2/yr in 2020 is linearly increased by 0.08 and 0.16 $\text{GtCO}_2/\text{yr}/\text{yr}$ for the base and best-case performance scenarios respectively. This leads to respective global capacities in 2070 of 4 and 8 GtCO_2/yr. These capacities are combined with the LRs following Equation B.1 for time intervals of five years (Table B.3).

$$D_t = (D_0 - D_{\text{min}}) \times (1 - \text{LR})^{\log_2(X_t/X_0)} + D_{\text{min}} \tag{B.1}$$

B.4. E-fuel production

The Fischer-Tropsch production route for e-fuel, using syn-gas (CO and H_2) as input, was modelled in detail by Van der Giesen et al. (2014). Using premise (see Section 2.7), inventories based on this work for the construction and demolition of the plants are generated. In contrast to other plants, where inventories for construction and demolition are created separately, these are combined here, meaning that the demolition phase is shifted back in time to coincide with the construction phase (see Section B.6). This has a limited influence on the results.

Sacchi et al. (2023) also base their inventories for the performance of gas-to-liquid plants on Van der Giesen et al. (2014). However, in recent years, life cycle inventories for such plants have become more robust. Although the basic principles have been around for decades, there is still much opportunity to fine-tune efficiencies, depending

Table B.3: Inputs for direct air capture in the three performance scenarios. DAC: direct air capture.

DAC plant	Year	Worst-case performance	Base performance	Best-case performance
Electricity [kWh/kg]	2020	1.13	1.13	5.00×10^{-1}
	2025	1.13	9.80×10^{-1}	3.75×10^{-1}
	2030	1.13	9.61×10^{-1}	3.61×10^{-1}
	2035	1.13	9.49×10^{-1}	3.53×10^{-1}
	2040	1.13	9.42×10^{-1}	3.48×10^{-1}
	2045	1.13	9.36×10^{-1}	3.43×10^{-1}
	2050	1.13	9.31×10^{-1}	3.40×10^{-1}
	2055	1.13	9.27×10^{-1}	3.37×10^{-1}
	2060	1.13	9.23×10^{-1}	3.35×10^{-1}
	2065	1.13	9.20×10^{-1}	3.33×10^{-1}
	2070	1.13	9.17×10^{-1}	3.31×10^{-1}
Sorbent [kg/kg]	2020	3.00×10^{-3}	3.00×10^{-3}	3.00×10^{-3}
	2025	3.00×10^{-3}	2.54×10^{-3}	1.98×10^{-3}
	2030	3.00×10^{-3}	2.49×10^{-3}	1.90×10^{-3}
	2035	3.00×10^{-3}	2.46×10^{-3}	1.87×10^{-3}
	2040	3.00×10^{-3}	2.44×10^{-3}	1.84×10^{-3}
	2045	3.00×10^{-3}	2.43×10^{-3}	1.83×10^{-3}
	2050	3.00×10^{-3}	2.41×10^{-3}	1.81×10^{-3}
	2055	3.00×10^{-3}	2.40×10^{-3}	1.80×10^{-3}
	2060	3.00×10^{-3}	2.40×10^{-3}	1.79×10^{-3}
	2065	3.00×10^{-3}	2.39×10^{-3}	1.78×10^{-3}
	2070	3.00×10^{-3}	2.38×10^{-3}	1.78×10^{-3}

Table B.4: Inputs for e-fuel production in the three performance scenarios.

Fischer-Tropsch plant	Worst-case performance	Base performance	Best-case performance
Electricity [kWh/MJ]	2.00×10^{-2}	2.00×10^{-2}	2.00×10^{-2}
H_2 [MJ/MJ]	2.30	1.59	1.37
CO_2 input [kg/MJ]	9.36×10^{-2}	8.62×10^{-2}	7.61×10^{-2}
CO_2 emissions [kg/MJ]	2.46×10^{-2}	1.72×10^{-3}	7.07×10^{-3}

on the assessment method and on what metrics are prioritised (see, e.g., Koj et al., 2019; van den Oever et al., 2022). Unlike hydrogen production or DAC, these efficiencies are rarely discussed as something that depends on technology improving over time, but more typically as something that depends on choices regarding process modelling and optimisation using existing technologies. Therefore, literature describing Fischer-Tropsch plants and reporting appropriate metrics are compared in order to understand the range of possible performances.

The works of Atsonios et al. (2023), König et al. (2015), and Rojas-Michaga et al. (2023) are consulted, for their detailed performance descriptions. Each of them report a carbon-utilisation (CU) factor, representing the share of carbon atoms entering the system which end up in a gaseous, liquid, or solid product. Assuming that e-fuel has a hydrogen-to-carbon ratio of 2.15 (van der Giesen et al., 2014), the CU can be used to determine the required input of CO_2 from DAC and the output of lost CO_2. As Fischer-Tropsch plants are multifunctional, the CU reported is assumed to hold for e-fuel as well. Multi-functionality could also be resolved by economic allocation, for example, but this would no longer ensure that carbon atoms present in each product are balanced exactly against carbon atoms entering the plant. Therefore, a physical allocation approach is taken, in line with literature (see, e.g., Ballal et al., 2023; van der Giesen et al., 2014). Synthesis gas that does not end up in the products is typically still recovered for energy. Some assume that this fulfils any electricity or heat inputs required (e.g., van der Giesen et al., 2014), but a small electricity input is typically included. The three levels of plant performance are defined by first assuming that each requires $0.02\,\mathrm{kW\,h\,MJ^{-1}}$ electricity across scenarios – this value is similar to those reported by Atsonios et al. (2023), König et al. (2015), and Rojas-Michaga et al. (2023). Next, the input of H_2 is determined based on a “hydrogen-to-liquid” efficiency, which is defined by combining the inputs of electricity, heat, and hydrogen (by LHV) and dividing this by the product outputs (by LHV). These were found to be 63.9% (König et al., 2015), 69.4% (Atsonios et al., 2023), and 42.2% (Rojas-Michaga et al., 2023). The outer values are used to determine the best-case and worst-case hydrogen use, while a value of 60% is selected for the base case (Table B.4). As with the CU, there is an assumption that performance reported for the plant in general holds when only considering the production of e-fuel. Cooling water and waste water are excluded from the inventories due to a lack of data.

B.5. Non-CO_2 effects

Burkhardt et al. (2018) create a model to consider how changing the number of soot particles generated influences the life cycle of aviation-induced cloudiness (AIC). Adapting their results, Sacchi et al. (2023) create a logarithmic expression for ice crystal formation based on the hydrogen content of the fuel (Equation B.2), assuming that the change in ice particles when compared to fossil kerosene (Equation B.3) correlates to a reduction in radiative forcing (Equation B.4). Sacchi et al. (2023) assume a hydrogen mass fraction in fossil kerosene of 13.73% and in e-fuel of 15.29%. This latter value aligns with the 2.15 H/C ratio considered in the present work (see Section 2.6.2). Note that this determines the change in radiative forcing by considering the ice particles expected from the average mixture of hydrocarbon fuels, while Sacchi et al. (2023) first calculate the ice particles, independent of the fuel mix – switching this around effectively makes more use of the logarithmic relation, resulting in relatively lower radiative forcing at small shares of e-fuel.

$$n_{\text{ice particles}} = 9.407 \times 10^{23} \times e^{\left(ln(0.2475) \times \frac{m_{\text{H}_2}}{m_{\text{total}}} \times 100\right)} \tag{B.2}$$

$$\Delta n_{\text{ice particles, fuel}} = 1 - \frac{n_{\text{ice particles, fuel}}}{n_{\text{ice particles, 100\% fossil kerosene}}} \tag{B.3}$$

$$\Delta \text{RF}_{\text{fuel}} = 1 - 0.048 \times 19.2^{\Delta n_{\text{ice particles, fuel}}} \tag{B.4}$$

These equations are geared towards e-fuel, but liquid hydrogen – with a hydrogen content of 100% – could show very different behaviour. Although the empirical evidence is limited, hydrogen aircraft are likely to produce contrails more frequently than those burning hydrocarbon fuels, but the shorter lifetime and lower optical depth of these contrails would result in an overall reduction in radiative forcing when compared to fossil kerosene (see, e.g., Gierens, 2021). Whether this reduction is larger than can be expected from e-fuel is unclear. Kossarev et al. (2023) choose to set the AIC of hydrogen aircraft equal to that of aircraft using synthetic fuels, although stating that this is a conservative estimate. The same approach is used here, thus setting the AIC impact of hydrogen aircraft to 34.05% of the AIC impact of flights fossil kerosene. Note, however, that Kossarev et al. (2023) only considered a reduction to 40% at most. The quantification applied in the present study is therefore particularly optimistic to AIC.

Sacchi et al. (2023) only consider the portion of flight above 9 km to contribute to contrail formation. However, the distance-based impacts described by Lee et al. (2021) already consider that some distances flown do not result in aviation-induced cloudiness, including the influence of altitude. To not double count these considerations, I apply all calculations of non-CO_2 effects to flight emissions at all altitudes. Furthermore, Sacchi et al. (2023) flip their logic around for NO_x, only considering emissions *below* 9 km. This does not reflect the altitude-dependent effects of NO_x. However, at the same time, their implementation of the LWE metric assumes that the short-term warming impact of NO_x persists for the same duration as its long-term influence on methane. These assumptions respectively greatly underestimate and greatly overestimate the impact of NO_x, possibly resulting in a net overestimation of radiative forcing [R. Sacchi, personal communication, 13 December 2023]. Here, the assumed lifetime of NO_x effects is changed to be 0.267 years, based on Fuglestvedt et al. (2010), although it should be noted that the implementation of LWE remains highly simplified.

B.6. Inventory spreadsheets

The attached spreadsheet file reports the foreground inventories, including the influence of related scenario dimensions. The background inventories used are generated by premise (see Section 2.7). This means that not all background processes listed are present in the ecoinvent 3.9.1 database. Note that further combination of the activities towards the reference flow (Figure 2.2) is not included in these spreadsheets, since these flows depend on additional models, rather than a single scenario dimension (see Section 2.4).

C

Additional results

This chapter includes figures which support the main text, but provide no direct insight to the understanding of the research question. This includes contribution analyses (Section C.1) and the figures generated for the sensitivity analyses (Section C.4).

C.1. Contribution analysis

Figure C.1 shows the contribution analysis of life cycle phases to the environmental flows of CO_2 emissions. Life cycle phases are defined by isolating various activities from the full life cycle. The manufacturing and disposal of aircraft are combined into the "aircraft system" and the construction and demolition of AAF plants are combined into "AAF infrastructure". As fossil kerosene is not modelled using a fleet of plats, but is directly connected from the background system, its well-to-tank activities are considered as a separate phase. As can be observed, fuel production and use dominates the contributions. CO_2 from the combustion of e-fuel is reflected in the negative y-axis by CO_2 drawn from the atmosphere by DAC, but as can be seen for the period 2060-2070, there are additional activities in the infrastructure and operations phases which result in a net positive balance of emissions. It is notable that infrastructure emissions (construction and demolition) form a sizeable share of these residual emissions, as these activities are (1) excluded from CORSIA (see Section 1.3.4) and (2) simplified and only partially reflected in the present inventories (see Section 2.6.2). This highlights that these activities should not be overlooked.

Figure C.2 shows the contributions to the LWE metric, broken down by climate forcer. As can be observed, the magnitude of both CO_2 and non-CO_2 radiative forcing is highly affected by the air traffic volume scenario, but also by whether or not the AAF share is increased. The difference between whether hydrogen aircraft are introduced or not is reflected in a shift in impact from NO_x to water (under "flight - other"), but both only form a limited contribution. However, it must be noted that the LWE model adapted from Sacchi et al. (2023) is a heavily simplified one, and that non-CO_2 effects in general are highly uncertain (see Section 4.2.3 and Section B.5).

C.2. System performance metrics

Figure C.3 illustrates a number of performance metrics for the nine representative scenarios. These metrics are relative to the volume of fuel supply or air traffic volume, thereby providing insight into how the differences in technological performance and fleet progression affect the scenarios. As can be observed, the differences in aircraft technologies have considerable effect (Figure C.3b), but this does not translate into notably different trends with

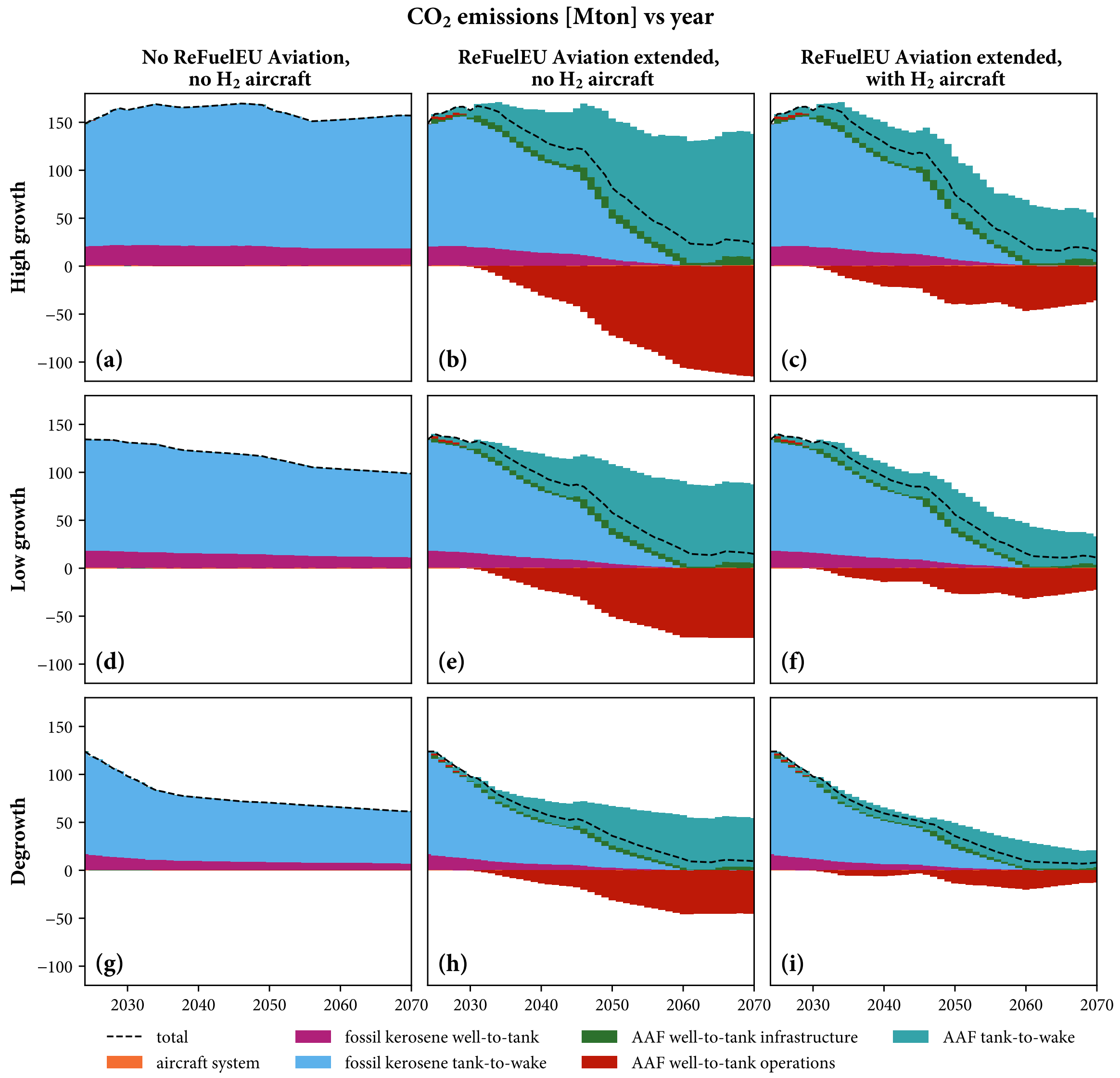


Figure C.1: Contributions to CO_2 emissions to the environment for nine reference scenarios, broken down by by life cycle phase. Since the e-fuel modelled uses CO_2 from direct air capture, there is a negative component to the contribution analysis. AAF: alternative aviation fuel.

respect to CO_2 intensity, provided ReFuelEU is implemented (Figure C.3a and Figure C.3c). In the scenarios modelled, a difference in the fuel intensity of flight of – for example – 50% in 2060 has little effect on the trend in CO_2 intensity (or in total CO_2 emissions) when examined with respect to the respective values of decades prior. However, this does not mean that such differences are trivial. Not only are the trends for other impact categories affected in considerably different ways (seeSection 3.5), but the meaning of such a difference in CO_2 emissions could be much more meaningful in 2060 than from a present-day perspective.

C.3. All other impact categories

Figure C.4 illustrates the progression of the EF 3.1 impact categories. A selection of these impact categories is highlighted and discussed in Section 3.5.

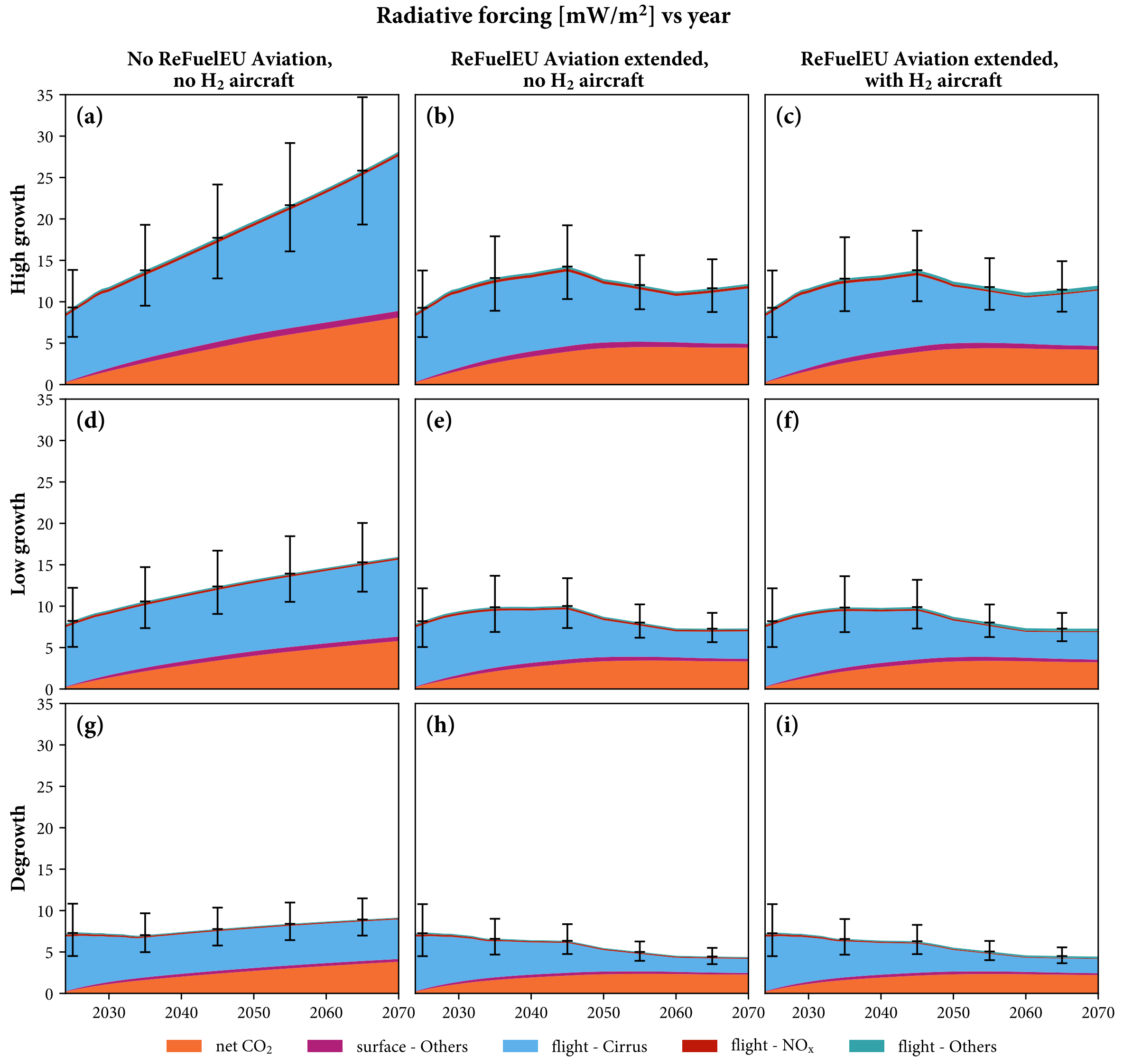


Figure C.2: Contributions to LWE for nine reference scenarios, broken down by climate forcer. Uncertainty ranges for radiative forcing efficiencies of emissions are given for 5% and 95% certainty, based on the values adapted from Lee et al. (2021) (see Section 2.8). Alongside near-surface and in-flight CO_2 emissions, aviation-induced cloudiness ("cirrus") is the largest contributor.

C.4. Sensitivity analyses

This section includes four figures demonstrating the influence of dimensions which were initially excluded due to their limited influence, as well as eight figures representing each of the alternative values for the source of hydrogen or the background system. These figures are discussed in Section 3.6.

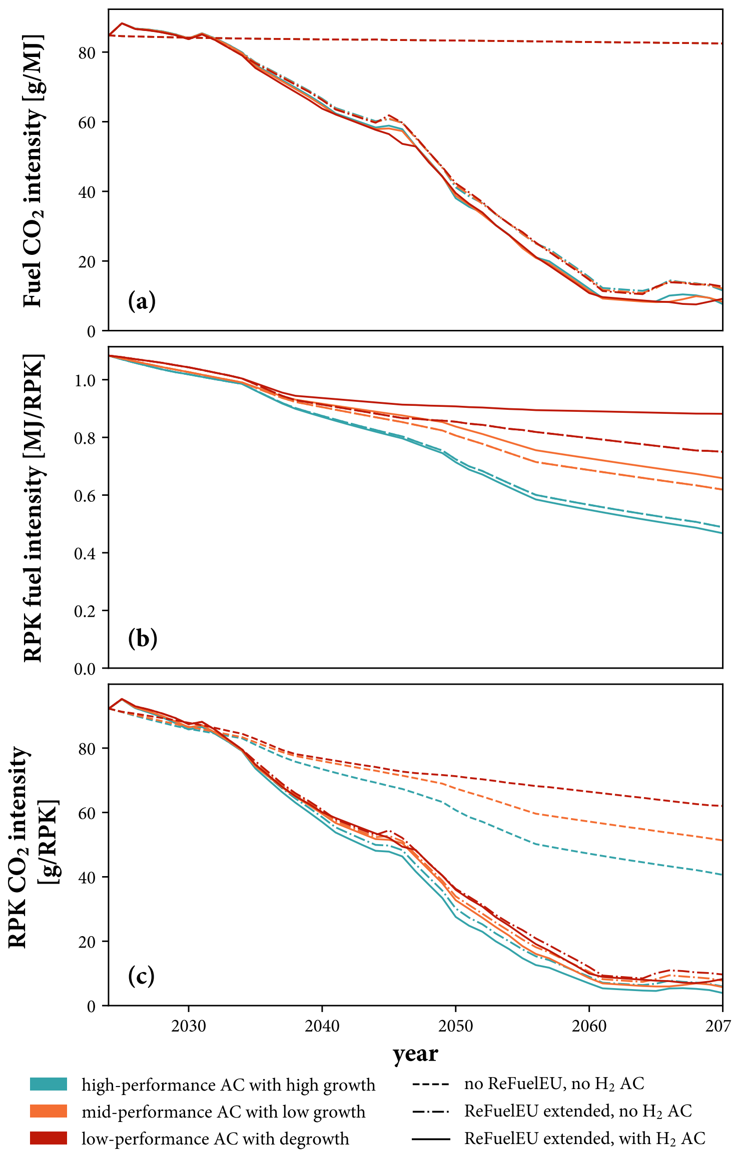


Figure C.3: Results for nine reference scenarios on timeline, showing the performance in **(a)** the CO_2-intensity of the fuel supply, considering fuel infrastructure, operations, and use (but excluding the aircraft system), **(b)** the fuel-intensity per revenue passenger-kilometer (RPK), and **(c)** the CO_2-intensity per RPK, considering all activities within the scope. Intensities per RPK were obtained by dividing the total fuel supply and CO_2 emissions, respectively, by the total RPK volume. Note that CO_2 is the only greenhouse gas considered in this figure. AC: aircraft.

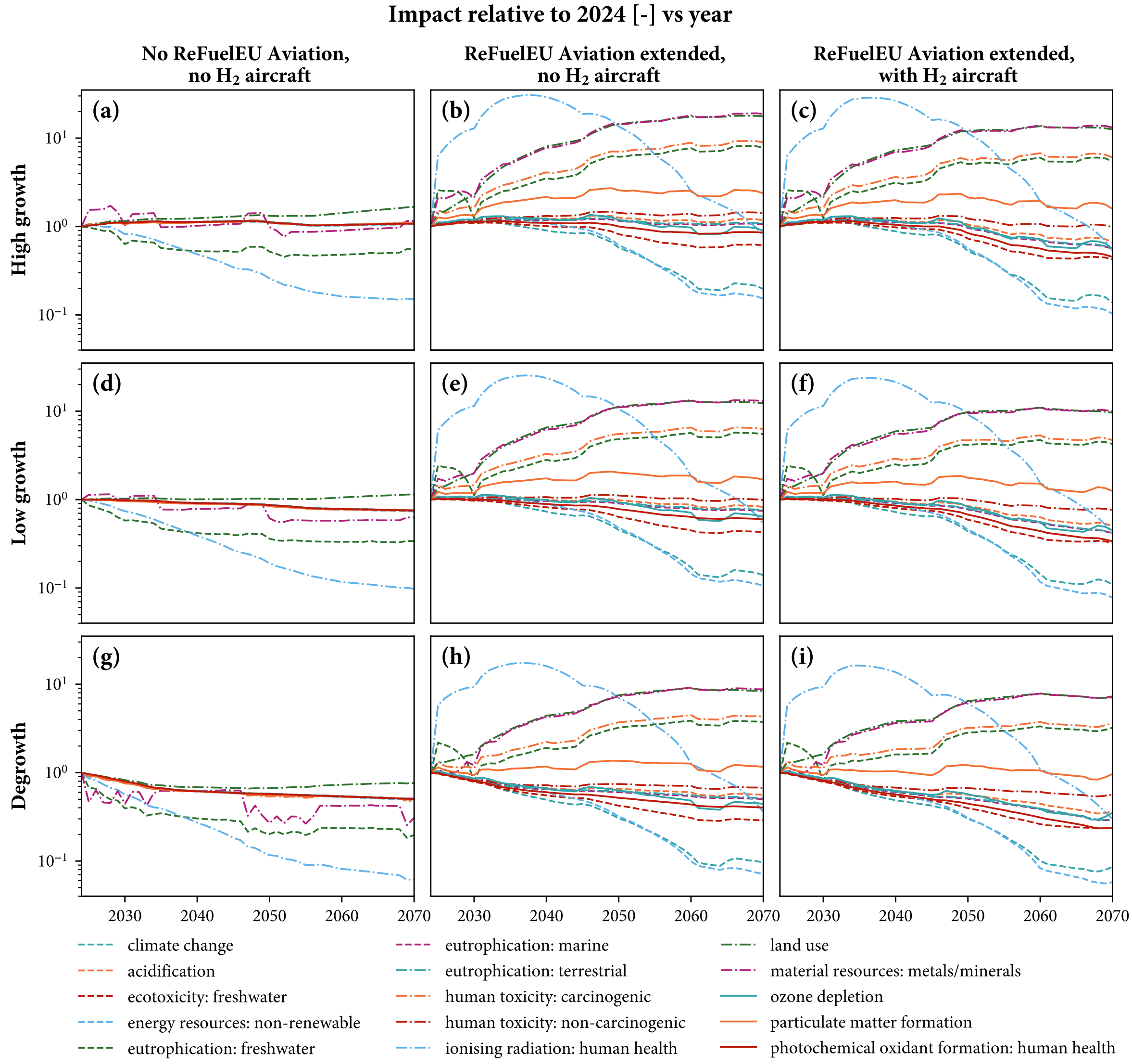
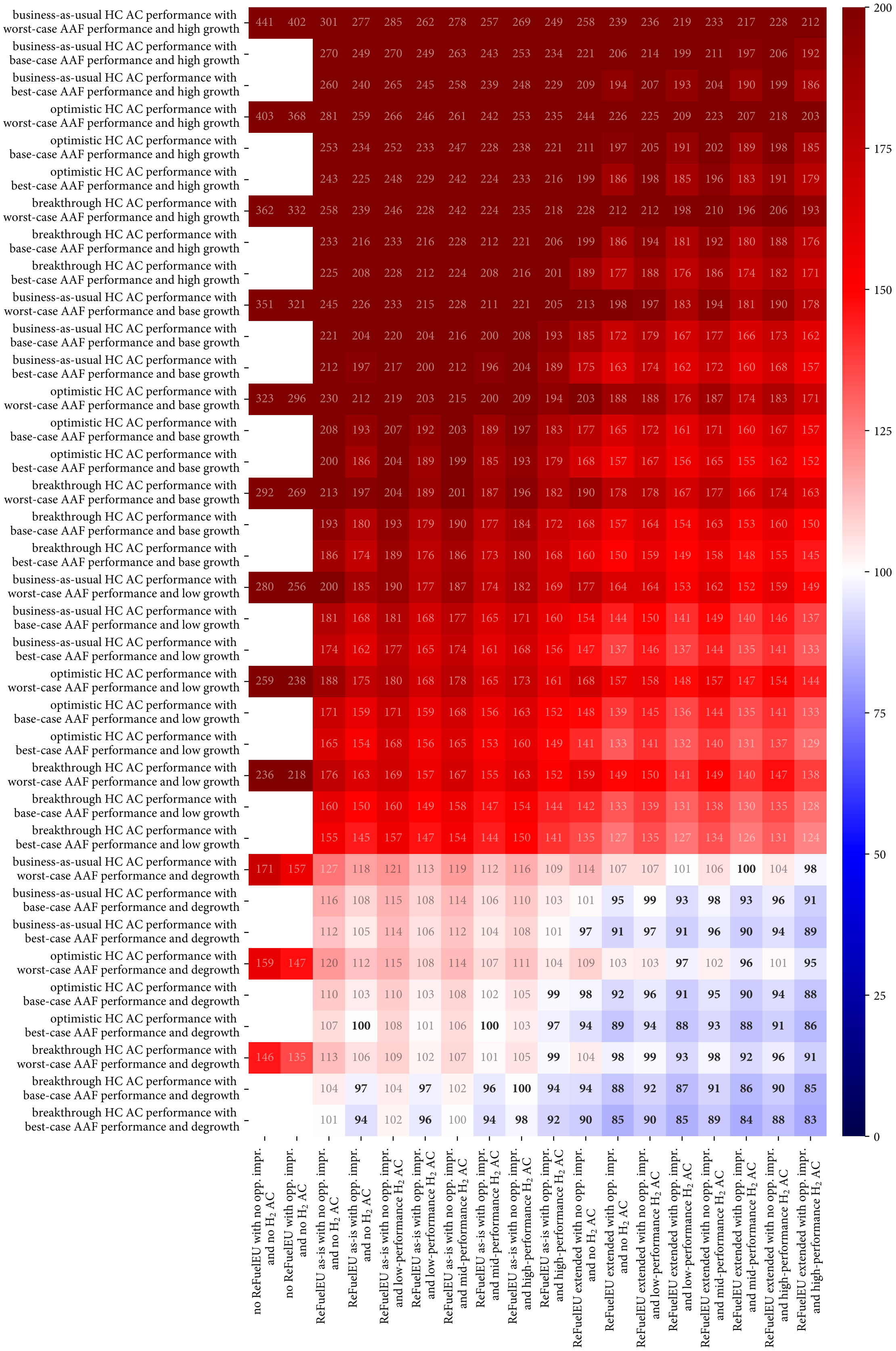
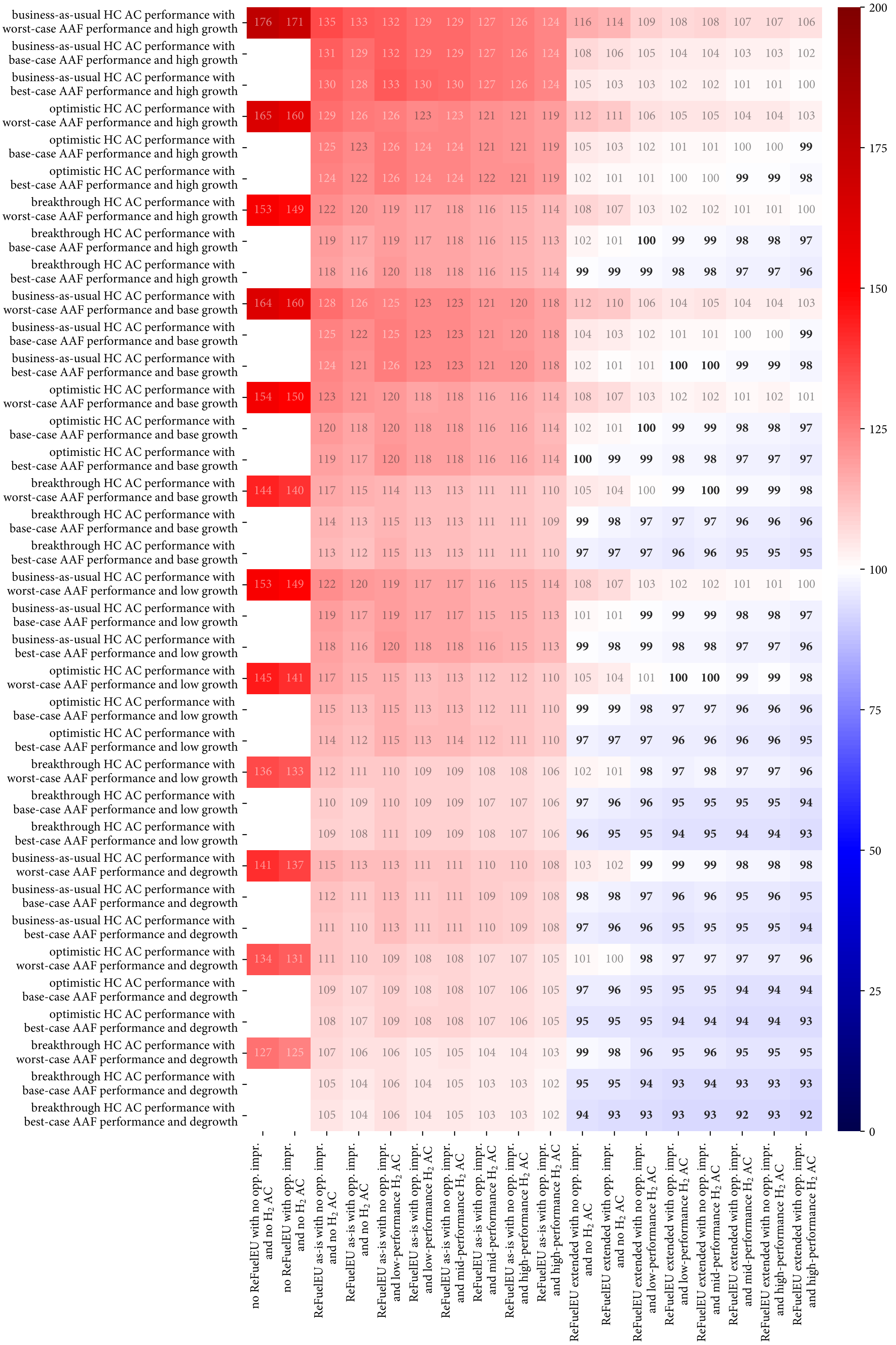


Figure C.4: Results for nine reference scenarios on timeline for all the impact categories of the EF 3.1 method, excluding water use. Impact categories are evaluated year-by-year, without considering environmental flows from prior years. Impacts are shown relative to the impacts in the initial year of the indicated scenario. They can therefore not be directly compared between sub-figures.



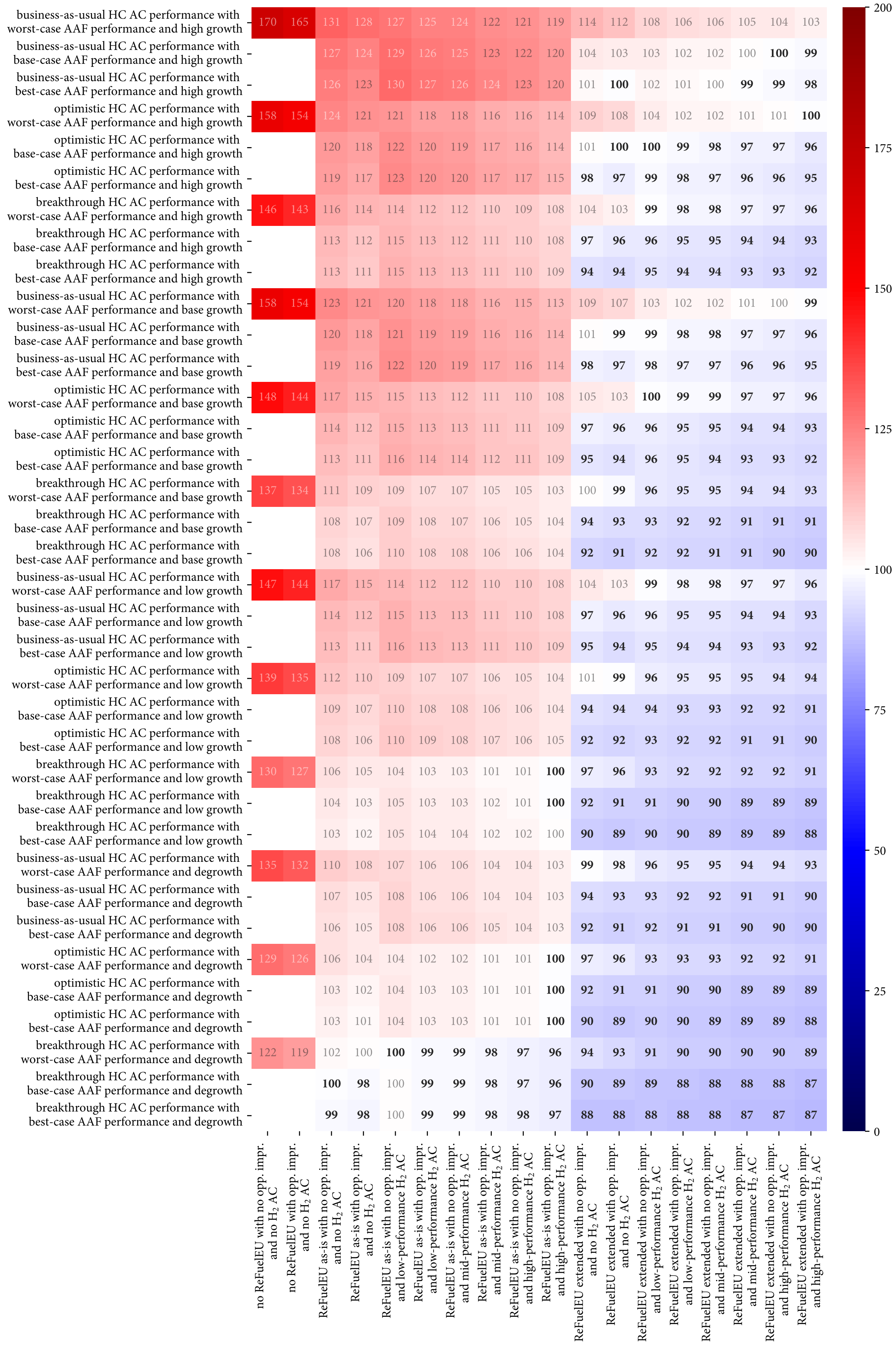
	no ReFuelEU with no opp. impr. and no H_2 AC	no ReFuelEU with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and no H_2 AC	ReFuelEU as-is with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and low-performance H_2 AC	ReFuelEU as-is with opp. impr. and low-performance H_2 AC	ReFuelEU as-is with no opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with no opp. impr. and high-performance H_2 AC	ReFuelEU as-is with opp. impr. and high-performance H_2 AC	ReFuelEU extended with no opp. impr. and no H_2 AC	ReFuelEU extended with opp. impr. and no H_2 AC	ReFuelEU extended with no opp. impr. and low-performance H_2 AC	ReFuelEU extended with opp. impr. and low-performance H_2 AC	ReFuelEU extended with no opp. impr. and mid-performance H_2 AC	ReFuelEU extended with opp. impr. and mid-performance H_2 AC	ReFuelEU extended with no opp. impr. and high-performance H_2 AC	ReFuelEU extended with opp. impr. and high-performance H_2 AC
business-as-usual HC AC performance with worst-case AAF performance and high growth	441	402	301	277	285	262	278	257	269	249	258	239	236	219	233	217	228	212
business-as-usual HC AC performance with base-case AAF performance and high growth			270	249	270	249	263	243	253	234	221	206	214	199	211	197	206	192
business-as-usual HC AC performance with best-case AAF performance and high growth			260	240	265	245	258	239	248	229	209	194	207	193	204	190	199	186
optimistic HC AC performance with worst-case AAF performance and high growth	403	368	281	259	266	246	261	242	253	235	244	226	225	209	223	207	218	203
optimistic HC AC performance with base-case AAF performance and high growth			253	234	252	233	247	228	238	221	211	197	205	191	202	189	198	185
optimistic HC AC performance with best-case AAF performance and high growth			243	225	248	229	242	224	233	216	199	186	198	185	196	183	191	179
breakthrough HC AC performance with worst-case AAF performance and high growth	362	332	258	239	246	228	242	224	235	218	228	212	212	198	210	196	206	193
breakthrough HC AC performance with base-case AAF performance and high growth			233	216	233	216	228	212	221	206	199	186	194	181	192	180	188	176
breakthrough HC AC performance with best-case AAF performance and high growth			225	208	228	212	224	208	216	201	189	177	188	176	186	174	182	171
business-as-usual HC AC performance with worst-case AAF performance and base growth	351	321	245	226	233	215	228	211	221	205	213	198	197	183	194	181	190	178
business-as-usual HC AC performance with base-case AAF performance and base growth			221	204	220	204	216	200	208	193	185	172	179	167	177	166	173	162
business-as-usual HC AC performance with best-case AAF performance and base growth			212	197	217	200	212	196	204	189	175	163	174	162	172	160	168	157
optimistic HC AC performance with worst-case AAF performance and base growth	323	296	230	212	219	203	215	200	209	194	203	188	188	176	187	174	183	171
optimistic HC AC performance with base-case AAF performance and base growth			208	193	207	192	203	189	197	183	177	165	172	161	171	160	167	157
optimistic HC AC performance with best-case AAF performance and base growth			200	186	204	189	199	185	193	179	168	157	167	156	165	155	162	152
breakthrough HC AC performance with worst-case AAF performance and base growth	292	269	213	197	204	189	201	187	196	182	190	178	178	167	177	166	174	163
breakthrough HC AC performance with base-case AAF performance and base growth			193	180	193	179	190	177	184	172	168	157	164	154	163	153	160	150
breakthrough HC AC performance with best-case AAF performance and base growth			186	174	189	176	186	173	180	168	160	150	159	149	158	148	155	145
business-as-usual HC AC performance with worst-case AAF performance and low growth	280	256	200	185	190	177	187	174	182	169	177	164	164	153	162	152	159	149
business-as-usual HC AC performance with base-case AAF performance and low growth			181	168	181	168	177	165	171	160	154	144	150	141	149	140	146	137
business-as-usual HC AC performance with best-case AAF performance and low growth			174	162	177	165	174	161	168	156	147	137	146	137	144	135	141	133
optimistic HC AC performance with worst-case AAF performance and low growth	259	238	188	175	180	168	178	165	173	161	168	157	158	148	157	147	154	144
optimistic HC AC performance with base-case AAF performance and low growth			171	159	171	159	168	156	163	152	148	139	145	136	144	135	141	133
optimistic HC AC performance with best-case AAF performance and low growth			165	154	168	156	165	153	160	149	141	133	141	132	140	131	137	129
breakthrough HC AC performance with worst-case AAF performance and low growth	236	218	176	163	169	157	167	155	163	152	159	149	150	141	149	140	147	138
breakthrough HC AC performance with base-case AAF performance and low growth			160	150	160	149	158	147	154	144	142	133	139	131	138	130	135	128
breakthrough HC AC performance with best-case AAF performance and low growth			155	145	157	147	154	144	150	141	135	127	135	127	134	126	131	124
business-as-usual HC AC performance with worst-case AAF performance and degrowth	171	157	127	118	121	113	119	112	116	109	114	107	107	101	106	**100**	104	**98**
business-as-usual HC AC performance with base-case AAF performance and degrowth			116	108	115	108	114	106	110	103	101	**95**	**99**	**93**	**98**	**93**	**96**	**91**
business-as-usual HC AC performance with best-case AAF performance and degrowth			112	105	114	106	112	104	108	101	**97**	**91**	**97**	**91**	**96**	**90**	**94**	**89**
optimistic HC AC performance with worst-case AAF performance and degrowth	159	147	120	112	115	108	114	107	111	104	109	103	103	**97**	102	**96**	101	**95**
optimistic HC AC performance with base-case AAF performance and degrowth			110	103	110	103	108	102	105	**99**	**98**	**92**	**96**	**91**	**95**	**90**	**94**	**88**
optimistic HC AC performance with best-case AAF performance and degrowth			107	**100**	108	101	106	**100**	103	**97**	**94**	**89**	**94**	**88**	**93**	**88**	**91**	**86**
breakthrough HC AC performance with worst-case AAF performance and degrowth	146	135	113	106	109	102	107	101	105	**99**	104	**98**	**99**	**93**	**98**	**92**	**96**	**91**
breakthrough HC AC performance with base-case AAF performance and degrowth			104	**97**	104	**97**	102	**96**	**100**	**94**	**94**	**88**	**92**	**87**	**91**	**86**	**90**	**85**
breakthrough HC AC performance with best-case AAF performance and degrowth			101	**94**	102	**96**	100	**94**	**98**	**92**	**90**	**85**	**90**	**85**	**89**	**84**	**88**	**83**

Figure C.5: Heat map depicting the results for cumulative CO_2 emissions, when considering the additional scenario dimensions of operational improvements (opp. impr.) and technological performance of AAF production. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft.



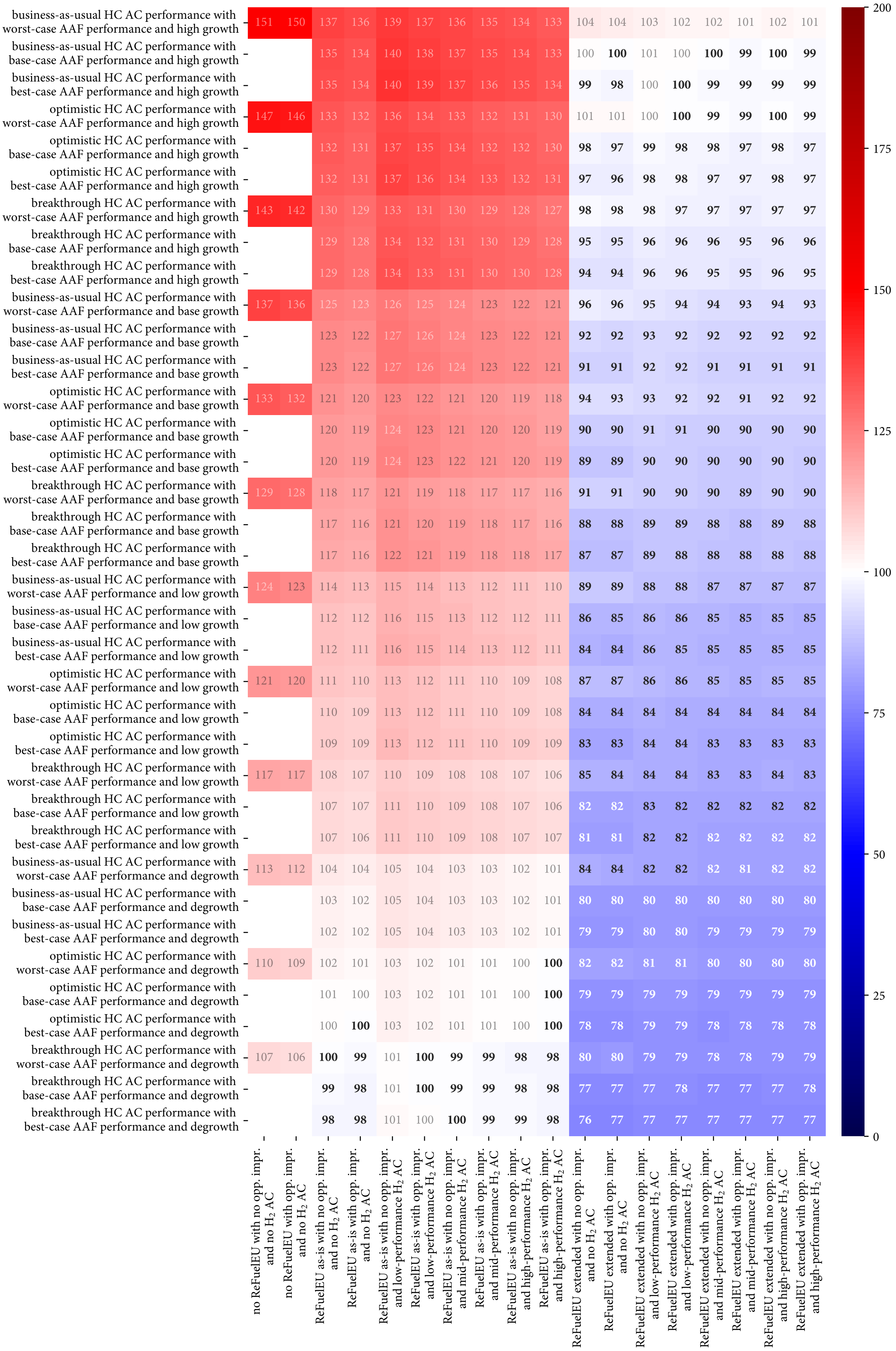
	no ReFuelEU with no opp. impr. and no H_2 AC	no ReFuelEU with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and no H_2 AC	ReFuelEU as-is with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and low-performance H_2 AC	ReFuelEU as-is with opp. impr. and low-performance H_2 AC	ReFuelEU as-is with no opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with no opp. impr. and high-performance H_2 AC	ReFuelEU as-is with opp. impr. and high-performance H_2 AC	ReFuelEU extended with no opp. impr. and no H_2 AC	ReFuelEU extended with opp. impr. and no H_2 AC	ReFuelEU extended with no opp. impr. and low-performance H_2 AC	ReFuelEU extended with opp. impr. and low-performance H_2 AC	ReFuelEU extended with no opp. impr. and mid-performance H_2 AC	ReFuelEU extended with opp. impr. and mid-performance H_2 AC	ReFuelEU extended with no opp. impr. and high-performance H_2 AC	ReFuelEU extended with opp. impr. and high-performance H_2 AC
business-as-usual HC AC performance with worst-case AAF performance and high growth	176	171	135	133	132	129	129	127	126	124	116	114	109	108	108	107	107	106
business-as-usual HC AC performance with base-case AAF performance and high growth			131	129	132	129	129	127	126	124	108	106	105	104	104	103	103	102
business-as-usual HC AC performance with best-case AAF performance and high growth			130	128	133	130	130	127	126	124	105	103	103	102	102	101	101	100
optimistic HC AC performance with worst-case AAF performance and high growth	165	160	129	126	126	123	123	121	121	119	112	111	106	105	105	104	104	103
optimistic HC AC performance with base-case AAF performance and high growth			125	123	126	124	124	121	121	119	105	103	102	101	101	100	100	**99**
optimistic HC AC performance with best-case AAF performance and high growth			124	122	126	124	124	122	121	119	102	101	101	100	100	**99**	**99**	**98**
breakthrough HC AC performance with worst-case AAF performance and high growth	153	149	122	120	119	117	118	116	115	114	108	107	103	102	102	101	101	100
breakthrough HC AC performance with base-case AAF performance and high growth			119	117	119	117	118	116	115	113	102	101	**100**	**99**	**99**	**98**	**98**	**97**
breakthrough HC AC performance with best-case AAF performance and high growth			118	116	120	118	118	116	115	114	**99**	**99**	**99**	**98**	**98**	**97**	**97**	**96**
business-as-usual HC AC performance with worst-case AAF performance and base growth	164	160	128	126	125	123	123	121	120	118	112	110	106	104	105	104	104	103
business-as-usual HC AC performance with base-case AAF performance and base growth			125	122	125	123	123	121	120	118	104	103	102	101	101	100	100	**99**
business-as-usual HC AC performance with best-case AAF performance and base growth			124	121	126	123	123	121	120	118	102	101	101	**100**	**100**	**99**	**99**	**98**
optimistic HC AC performance with worst-case AAF performance and base growth	154	150	123	121	120	118	118	116	116	114	108	107	103	102	102	101	102	101
optimistic HC AC performance with base-case AAF performance and base growth			120	118	120	118	118	116	116	114	102	101	**100**	**99**	**99**	**98**	**98**	**97**
optimistic HC AC performance with best-case AAF performance and base growth			119	117	120	118	118	116	116	114	**100**	**99**	**99**	**98**	**98**	**97**	**97**	**97**
breakthrough HC AC performance with worst-case AAF performance and base growth	144	140	117	115	114	113	113	111	111	110	105	104	100	**99**	**100**	**99**	**99**	**98**
breakthrough HC AC performance with base-case AAF performance and base growth			114	113	115	113	113	111	111	109	**99**	**98**	**97**	**97**	**97**	**96**	**96**	**96**
breakthrough HC AC performance with best-case AAF performance and base growth			113	112	115	113	113	111	111	110	**97**	**97**	**97**	**96**	**96**	**95**	**95**	**95**
business-as-usual HC AC performance with worst-case AAF performance and low growth	153	149	122	120	119	117	117	116	115	114	108	107	103	102	102	101	101	100
business-as-usual HC AC performance with base-case AAF performance and low growth			119	117	119	117	117	115	115	113	101	101	**99**	**99**	**99**	**98**	**98**	**97**
business-as-usual HC AC performance with best-case AAF performance and low growth			118	116	120	118	118	116	115	113	**99**	**98**	**99**	**98**	**98**	**97**	**97**	**96**
optimistic HC AC performance with worst-case AAF performance and low growth	145	141	117	115	115	113	113	112	112	110	105	104	101	**100**	**100**	**99**	**99**	**98**
optimistic HC AC performance with base-case AAF performance and low growth			115	113	115	113	113	112	111	110	**99**	**99**	**98**	**97**	**97**	**96**	**96**	**96**
optimistic HC AC performance with best-case AAF performance and low growth			114	112	115	113	114	112	111	110	**97**	**97**	**97**	**96**	**96**	**96**	**96**	**95**
breakthrough HC AC performance with worst-case AAF performance and low growth	136	133	112	111	110	109	109	108	108	106	102	101	**98**	**97**	**98**	**97**	**97**	**96**
breakthrough HC AC performance with base-case AAF performance and low growth			110	109	110	109	109	107	107	106	**97**	**96**	**96**	**95**	**95**	**95**	**95**	**94**
breakthrough HC AC performance with best-case AAF performance and low growth			109	108	111	109	109	108	107	106	**96**	**95**	**95**	**94**	**95**	**94**	**94**	**93**
business-as-usual HC AC performance with worst-case AAF performance and degrowth	141	137	115	113	113	111	111	110	110	108	103	102	**99**	**99**	**99**	**98**	**98**	**98**
business-as-usual HC AC performance with base-case AAF performance and degrowth			112	111	113	111	111	109	109	108	**98**	**98**	**97**	**96**	**96**	**95**	**96**	**95**
business-as-usual HC AC performance with best-case AAF performance and degrowth			111	110	113	111	111	110	109	108	**97**	**96**	**96**	**95**	**95**	**95**	**95**	**94**
optimistic HC AC performance with worst-case AAF performance and degrowth	134	131	111	110	109	108	108	107	107	105	101	100	**98**	**97**	**97**	**97**	**97**	**96**
optimistic HC AC performance with base-case AAF performance and degrowth			109	107	109	108	108	107	106	105	**97**	**96**	**95**	**95**	**95**	**94**	**94**	**94**
optimistic HC AC performance with best-case AAF performance and degrowth			108	107	109	108	108	107	106	105	**95**	**95**	**95**	**94**	**94**	**94**	**94**	**93**
breakthrough HC AC performance with worst-case AAF performance and degrowth	127	125	107	106	106	105	105	104	104	103	**99**	**98**	**96**	**95**	**96**	**95**	**95**	**95**
breakthrough HC AC performance with base-case AAF performance and degrowth			105	104	106	104	105	103	103	102	**95**	**95**	**94**	**93**	**94**	**93**	**93**	**93**
breakthrough HC AC performance with best-case AAF performance and degrowth			105	104	106	104	105	103	103	102	**94**	**93**	**93**	**93**	**93**	**92**	**93**	**92**

Figure C.6: Heat map depicting the results for warming neutrality of CO_2 emissions only, when considering the additional scenario dimensions of operational improvements (opp. impr.) and technological performance of AAF production. Values for scenarios which meet the requirement (i.e., values ≤100) are shown in bold. AC: aircraft.



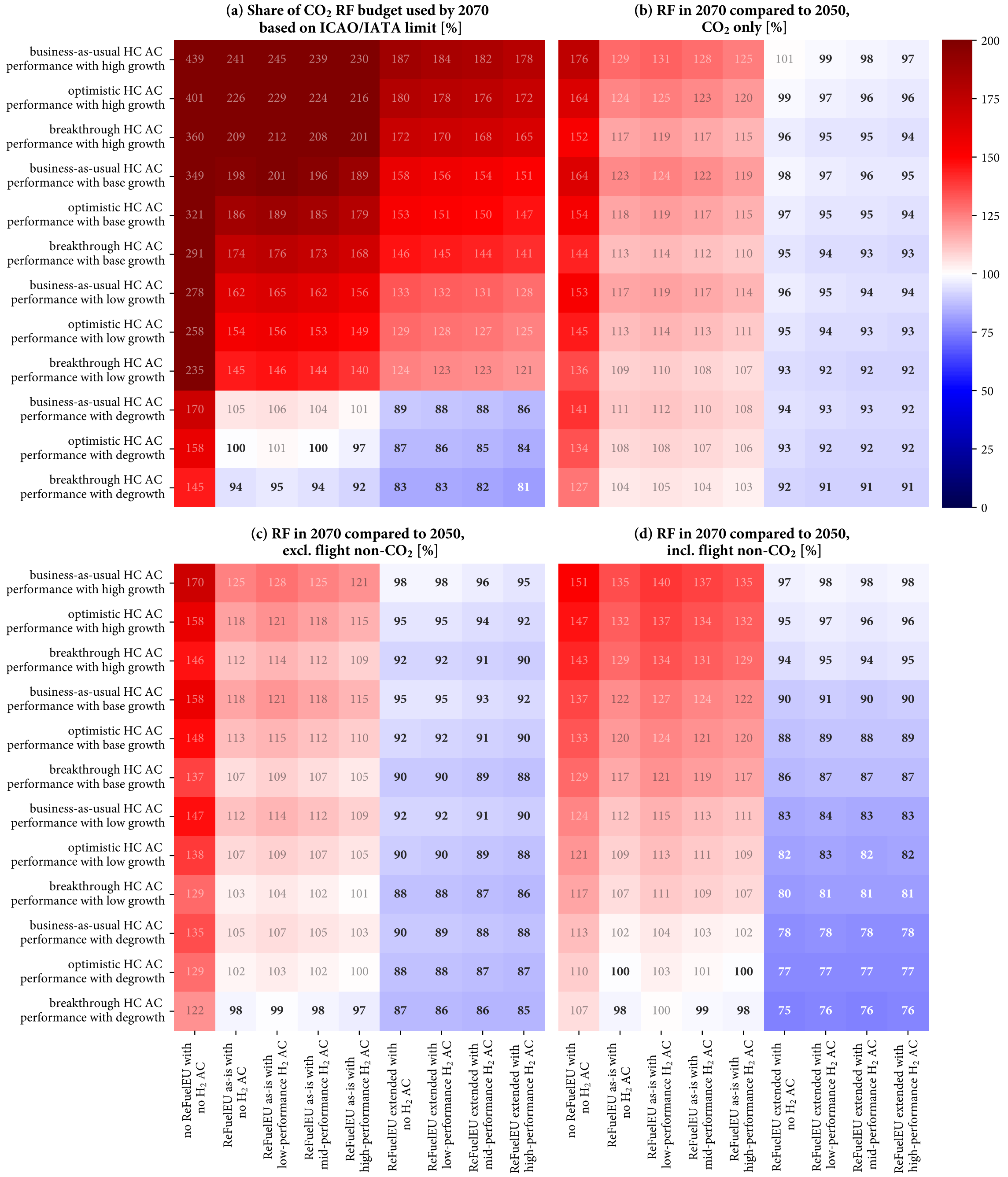
	no ReFuelEU with no opp. impr. and no H_2 AC	no ReFuelEU with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and no H_2 AC	ReFuelEU as-is with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and low-performance H_2 AC	ReFuelEU as-is with opp. impr. and low-performance H_2 AC	ReFuelEU as-is with no opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with no opp. impr. and high-performance H_2 AC	ReFuelEU as-is with opp. impr. and high-performance H_2 AC	ReFuelEU extended with no opp. impr. and no H_2 AC	ReFuelEU extended with opp. impr. and no H_2 AC	ReFuelEU extended with no opp. impr. and low-performance H_2 AC	ReFuelEU extended with opp. impr. and low-performance H_2 AC	ReFuelEU extended with no opp. impr. and mid-performance H_2 AC	ReFuelEU extended with opp. impr. and mid-performance H_2 AC	ReFuelEU extended with no opp. impr. and high-performance H_2 AC	ReFuelEU extended with opp. impr. and high-performance H_2 AC
business-as-usual HC AC performance with worst-case AAF performance and high growth	170	165	131	128	127	125	124	122	121	119	114	112	108	106	106	105	104	103
business-as-usual HC AC performance with base-case AAF performance and high growth			127	124	129	126	125	123	122	120	104	103	103	102	102	100	**100**	**99**
business-as-usual HC AC performance with best-case AAF performance and high growth			126	123	130	127	126	124	123	120	101	**100**	102	101	100	**99**	**99**	**98**
optimistic HC AC performance with worst-case AAF performance and high growth	158	154	124	121	121	118	118	116	116	114	109	108	104	102	102	101	101	**100**
optimistic HC AC performance with base-case AAF performance and high growth			120	118	122	120	119	117	116	114	101	**100**	**100**	**99**	**98**	**97**	**97**	**96**
optimistic HC AC performance with best-case AAF performance and high growth			119	117	123	120	120	117	117	115	**98**	**97**	**99**	**98**	**97**	**96**	**96**	**95**
breakthrough HC AC performance with worst-case AAF performance and high growth	146	143	116	114	114	112	112	110	109	108	104	103	**99**	**98**	**98**	**97**	**97**	**96**
breakthrough HC AC performance with base-case AAF performance and high growth			113	112	115	113	112	111	110	108	**97**	**96**	**96**	**95**	**95**	**94**	**94**	**93**
breakthrough HC AC performance with best-case AAF performance and high growth			113	111	115	113	113	111	110	109	**94**	**94**	**95**	**94**	**94**	**93**	**93**	**92**
business-as-usual HC AC performance with worst-case AAF performance and base growth	158	154	123	121	120	118	118	116	115	113	109	107	103	102	102	101	100	**99**
business-as-usual HC AC performance with base-case AAF performance and base growth			120	118	121	119	119	116	116	114	101	**99**	**99**	**98**	**98**	**97**	**97**	**96**
business-as-usual HC AC performance with best-case AAF performance and base growth			119	116	122	120	119	117	116	114	**98**	**97**	**98**	**97**	**97**	**96**	**96**	**95**
optimistic HC AC performance with worst-case AAF performance and base growth	148	144	117	115	115	113	112	111	110	108	105	103	**100**	**99**	**99**	**97**	**97**	**96**
optimistic HC AC performance with base-case AAF performance and base growth			114	112	115	113	113	111	111	109	**97**	**96**	**96**	**95**	**95**	**94**	**94**	**93**
optimistic HC AC performance with best-case AAF performance and base growth			113	111	116	114	114	112	111	109	**95**	**94**	**96**	**95**	**94**	**93**	**93**	**92**
breakthrough HC AC performance with worst-case AAF performance and base growth	137	134	111	109	109	107	107	105	105	103	100	**99**	**96**	**95**	**95**	**94**	**94**	**93**
breakthrough HC AC performance with base-case AAF performance and base growth			108	107	109	108	107	106	105	104	**94**	**93**	**93**	**92**	**92**	**91**	**91**	**91**
breakthrough HC AC performance with best-case AAF performance and base growth			108	106	110	108	108	106	106	104	**92**	**91**	**92**	**92**	**91**	**91**	**90**	**90**
business-as-usual HC AC performance with worst-case AAF performance and low growth	147	144	117	115	114	112	112	110	110	108	104	103	**99**	**98**	**98**	**97**	**97**	**96**
business-as-usual HC AC performance with base-case AAF performance and low growth			114	112	115	113	113	111	110	108	**97**	**96**	**96**	**95**	**95**	**94**	**94**	**93**
business-as-usual HC AC performance with best-case AAF performance and low growth			113	111	116	113	113	111	110	109	**95**	**94**	**95**	**94**	**94**	**93**	**93**	**92**
optimistic HC AC performance with worst-case AAF performance and low growth	139	135	112	110	109	107	107	106	105	104	101	**99**	**96**	**95**	**95**	**95**	**94**	**94**
optimistic HC AC performance with base-case AAF performance and low growth			109	107	110	108	108	106	106	104	**94**	**94**	**94**	**93**	**93**	**92**	**92**	**91**
optimistic HC AC performance with best-case AAF performance and low growth			108	106	110	109	108	107	106	105	**92**	**92**	**93**	**92**	**92**	**91**	**91**	**90**
breakthrough HC AC performance with worst-case AAF performance and low growth	130	127	106	105	104	103	103	101	101	**100**	**97**	**96**	**93**	**92**	**92**	**92**	**92**	**91**
breakthrough HC AC performance with base-case AAF performance and low growth			104	103	105	103	103	102	101	**100**	**92**	**91**	**91**	**90**	**90**	**89**	**89**	**89**
breakthrough HC AC performance with best-case AAF performance and low growth			103	102	105	104	104	102	102	100	**90**	**89**	**90**	**90**	**89**	**89**	**89**	**88**
business-as-usual HC AC performance with worst-case AAF performance and degrowth	135	132	110	108	107	106	106	104	104	103	**99**	**98**	**96**	**95**	**95**	**94**	**94**	**93**
business-as-usual HC AC performance with base-case AAF performance and degrowth			107	105	108	106	106	104	104	103	**94**	**93**	**93**	**92**	**92**	**91**	**91**	**90**
business-as-usual HC AC performance with best-case AAF performance and degrowth			106	105	108	106	106	105	104	103	**92**	**91**	**92**	**91**	**91**	**90**	**90**	**90**
optimistic HC AC performance with worst-case AAF performance and degrowth	129	126	106	104	104	102	102	101	101	**100**	**97**	**96**	**93**	**93**	**93**	**92**	**92**	**91**
optimistic HC AC performance with base-case AAF performance and degrowth			103	102	104	103	103	101	101	**100**	**92**	**91**	**91**	**90**	**90**	**89**	**89**	**89**
optimistic HC AC performance with best-case AAF performance and degrowth			103	101	104	103	103	101	101	**100**	**90**	**89**	**90**	**90**	**89**	**89**	**89**	**88**
breakthrough HC AC performance with worst-case AAF performance and degrowth	122	119	102	100	**100**	**99**	**99**	**98**	**97**	**96**	**94**	**93**	**91**	**90**	**90**	**90**	**90**	**89**
breakthrough HC AC performance with base-case AAF performance and degrowth			**100**	**98**	100	**99**	**99**	**98**	**97**	**96**	**90**	**89**	**89**	**88**	**88**	**88**	**88**	**87**
breakthrough HC AC performance with best-case AAF performance and degrowth			**99**	**98**	100	**99**	**99**	**98**	**98**	**97**	**88**	**88**	**88**	**88**	**88**	**87**	**87**	**87**

Figure C.7: Heat map depicting the results for warming neutrality of all surface-level GHG emissions, when considering the additional scenario dimensions of operational improvements (opp. impr.) and technological performance of AAF production. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft.



	no ReFuelEU with no opp. impr. and no H_2 AC	no ReFuelEU with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and no H_2 AC	ReFuelEU as-is with opp. impr. and no H_2 AC	ReFuelEU as-is with no opp. impr. and low-performance H_2 AC	ReFuelEU as-is with opp. impr. and low-performance H_2 AC	ReFuelEU as-is with no opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with opp. impr. and mid-performance H_2 AC	ReFuelEU as-is with no opp. impr. and high-performance H_2 AC	ReFuelEU as-is with opp. impr. and high-performance H_2 AC	ReFuelEU extended with no opp. impr. and no H_2 AC	ReFuelEU extended with opp. impr. and no H_2 AC	ReFuelEU extended with no opp. impr. and low-performance H_2 AC	ReFuelEU extended with opp. impr. and low-performance H_2 AC	ReFuelEU extended with no opp. impr. and mid-performance H_2 AC	ReFuelEU extended with opp. impr. and mid-performance H_2 AC	ReFuelEU extended with no opp. impr. and high-performance H_2 AC	ReFuelEU extended with opp. impr. and high-performance H_2 AC
business-as-usual HC AC performance with worst-case AAF performance and high growth	151	150	137	136	139	137	136	135	134	133	104	104	103	102	102	101	102	101
business-as-usual HC AC performance with base-case AAF performance and high growth			135	134	140	138	137	135	134	133	100	**100**	101	100	**100**	**99**	**100**	**99**
business-as-usual HC AC performance with best-case AAF performance and high growth			135	134	140	139	137	136	135	134	**99**	**98**	100	**100**	**99**	**99**	**99**	**99**
optimistic HC AC performance with worst-case AAF performance and high growth	147	146	133	132	136	134	133	132	131	130	101	101	100	**100**	**99**	**99**	**100**	**99**
optimistic HC AC performance with base-case AAF performance and high growth			132	131	137	135	134	132	132	130	**98**	**97**	**99**	**98**	**98**	**97**	**98**	**97**
optimistic HC AC performance with best-case AAF performance and high growth			132	131	137	136	134	133	132	131	**97**	**96**	**98**	**98**	**97**	**97**	**98**	**97**
breakthrough HC AC performance with worst-case AAF performance and high growth	143	142	130	129	133	131	130	129	128	127	**98**	**98**	**98**	**97**	**97**	**97**	**97**	**97**
breakthrough HC AC performance with base-case AAF performance and high growth			129	128	134	132	131	130	129	128	**95**	**95**	**96**	**96**	**96**	**95**	**96**	**96**
breakthrough HC AC performance with best-case AAF performance and high growth			129	128	134	133	131	130	130	128	**94**	**94**	**96**	**96**	**95**	**95**	**96**	**95**
business-as-usual HC AC performance with worst-case AAF performance and base growth	137	136	125	123	126	125	124	123	122	121	**96**	**96**	**95**	**94**	**94**	**93**	**94**	**93**
business-as-usual HC AC performance with base-case AAF performance and base growth			123	122	127	126	124	123	122	121	**92**	**92**	**93**	**92**	**92**	**92**	**92**	**92**
business-as-usual HC AC performance with best-case AAF performance and base growth			123	122	127	126	124	123	122	121	**91**	**91**	**92**	**92**	**91**	**91**	**91**	**91**
optimistic HC AC performance with worst-case AAF performance and base growth	133	132	121	120	123	122	121	120	119	118	**94**	**93**	**93**	**92**	**92**	**91**	**92**	**92**
optimistic HC AC performance with base-case AAF performance and base growth			120	119	124	123	121	120	120	119	**90**	**90**	**91**	**91**	**90**	**90**	**90**	**90**
optimistic HC AC performance with best-case AAF performance and base growth			120	119	124	123	122	121	120	119	**89**	**89**	**90**	**90**	**90**	**90**	**90**	**90**
breakthrough HC AC performance with worst-case AAF performance and base growth	129	128	118	117	121	119	118	117	117	116	**91**	**91**	**90**	**90**	**90**	**89**	**90**	**90**
breakthrough HC AC performance with base-case AAF performance and base growth			117	116	121	120	119	118	117	116	**88**	**88**	**89**	**89**	**88**	**88**	**89**	**88**
breakthrough HC AC performance with best-case AAF performance and base growth			117	116	122	121	119	118	118	117	**87**	**87**	**89**	**88**	**88**	**88**	**88**	**88**
business-as-usual HC AC performance with worst-case AAF performance and low growth	124	123	114	113	115	114	113	112	111	110	**89**	**89**	**88**	**88**	**87**	**87**	**87**	**87**
business-as-usual HC AC performance with base-case AAF performance and low growth			112	112	116	115	113	112	112	111	**86**	**85**	**86**	**86**	**85**	**85**	**85**	**85**
business-as-usual HC AC performance with best-case AAF performance and low growth			112	111	116	115	114	113	112	111	**84**	**84**	**86**	**85**	**85**	**85**	**85**	**85**
optimistic HC AC performance with worst-case AAF performance and low growth	121	120	111	110	113	112	111	110	109	108	**87**	**87**	**86**	**86**	**85**	**85**	**85**	**85**
optimistic HC AC performance with base-case AAF performance and low growth			110	109	113	112	111	110	109	108	**84**	**84**	**84**	**84**	**84**	**84**	**84**	**84**
optimistic HC AC performance with best-case AAF performance and low growth			109	109	113	112	111	110	109	109	**83**	**83**	**84**	**84**	**83**	**83**	**83**	**83**
breakthrough HC AC performance with worst-case AAF performance and low growth	117	117	108	107	110	109	108	108	107	106	**85**	**84**	**84**	**84**	**83**	**83**	**84**	**83**
breakthrough HC AC performance with base-case AAF performance and low growth			107	107	111	110	109	108	107	106	**82**	**82**	**83**	**82**	**82**	**82**	**82**	**82**
breakthrough HC AC performance with best-case AAF performance and low growth			107	106	111	110	109	108	107	107	**81**	**81**	**82**	**82**	**82**	**82**	**82**	**82**
business-as-usual HC AC performance with worst-case AAF performance and degrowth	113	112	104	104	105	104	103	103	102	101	**84**	**84**	**82**	**82**	**82**	**81**	**82**	**82**
business-as-usual HC AC performance with base-case AAF performance and degrowth			103	102	105	104	103	103	102	101	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**
business-as-usual HC AC performance with best-case AAF performance and degrowth			102	102	105	104	103	103	102	101	**79**	**79**	**80**	**80**	**79**	**79**	**79**	**79**
optimistic HC AC performance with worst-case AAF performance and degrowth	110	109	102	101	103	102	101	101	100	**100**	**82**	**82**	**81**	**81**	**80**	**80**	**80**	**80**
optimistic HC AC performance with base-case AAF performance and degrowth			101	100	103	102	101	101	100	**100**	**79**	**79**	**79**	**79**	**79**	**79**	**79**	**79**
optimistic HC AC performance with best-case AAF performance and degrowth			100	**100**	103	102	101	101	100	**100**	**78**	**78**	**79**	**79**	**78**	**78**	**78**	**78**
breakthrough HC AC performance with worst-case AAF performance and degrowth	107	106	**100**	**99**	101	**100**	**99**	**99**	**98**	**98**	**80**	**80**	**79**	**79**	**78**	**78**	**79**	**79**
breakthrough HC AC performance with base-case AAF performance and degrowth			**99**	**98**	101	**100**	**99**	**99**	**98**	**98**	**77**	**77**	**77**	**78**	**77**	**77**	**77**	**78**
breakthrough HC AC performance with best-case AAF performance and degrowth			**98**	**98**	101	100	**100**	**99**	**99**	**98**	**76**	**77**	**77**	**77**	**77**	**77**	**77**	**77**

Figure C.8: Heat map depicting the results for warming neutrality of all emissions, when considering the additional scenario dimensions of operational improvements (opp. impr.) and technological performance of AAF production. Values for scenarios which meet the requirement (i.e., values ≤100) are shown in bold. AC: aircraft.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	439	241	245	239	230	187	184	182	178
optimistic HC AC performance with high growth	401	226	229	224	216	180	178	176	172
breakthrough HC AC performance with high growth	360	209	212	208	201	172	170	168	165
business-as-usual HC AC performance with base growth	349	198	201	196	189	158	156	154	151
optimistic HC AC performance with base growth	321	186	189	185	179	153	151	150	147
breakthrough HC AC performance with base growth	291	174	176	173	168	146	145	144	141
business-as-usual HC AC performance with low growth	278	162	165	162	156	133	132	131	128
optimistic HC AC performance with low growth	258	154	156	153	149	129	128	127	125
breakthrough HC AC performance with low growth	235	145	146	144	140	124	123	123	121
business-as-usual HC AC performance with degrowth	170	105	106	104	101	**89**	**88**	**88**	**86**
optimistic HC AC performance with degrowth	158	**100**	101	**100**	**97**	**87**	**86**	**85**	**84**
breakthrough HC AC performance with degrowth	145	**94**	**95**	**94**	**92**	**83**	**83**	**82**	**81**

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	129	131	128	125	101	**99**	**98**	**97**
optimistic HC AC performance with high growth	164	124	125	123	120	**99**	**97**	**96**	**96**
breakthrough HC AC performance with high growth	152	117	119	117	115	**96**	**95**	**95**	**94**
business-as-usual HC AC performance with base growth	164	123	124	122	119	**98**	**97**	**96**	**95**
optimistic HC AC performance with base growth	154	118	119	117	115	**97**	**95**	**95**	**94**
breakthrough HC AC performance with base growth	144	113	114	112	110	**95**	**94**	**93**	**93**
business-as-usual HC AC performance with low growth	153	117	119	117	114	**96**	**95**	**94**	**94**
optimistic HC AC performance with low growth	145	113	114	113	111	**95**	**94**	**93**	**93**
breakthrough HC AC performance with low growth	136	109	110	108	107	**93**	**92**	**92**	**92**
business-as-usual HC AC performance with degrowth	141	111	112	110	108	**94**	**93**	**93**	**92**
optimistic HC AC performance with degrowth	134	108	108	107	106	**93**	**92**	**92**	**92**
breakthrough HC AC performance with degrowth	127	104	105	104	103	**92**	**91**	**91**	**91**

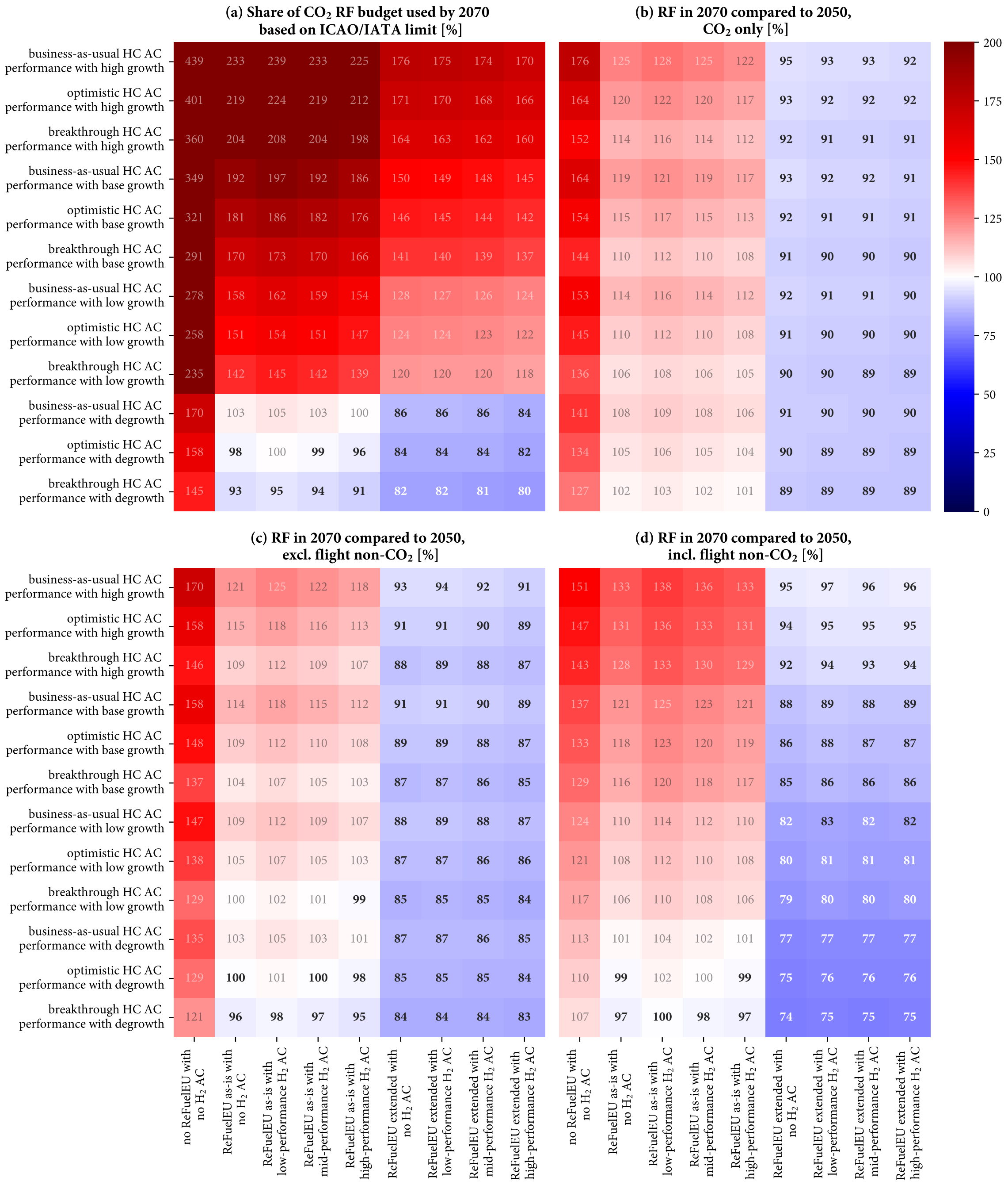
(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	125	128	125	121	**98**	**98**	**96**	**95**
optimistic HC AC performance with high growth	158	118	121	118	115	**95**	**95**	**94**	**92**
breakthrough HC AC performance with high growth	146	112	114	112	109	**92**	**92**	**91**	**90**
business-as-usual HC AC performance with base growth	158	118	121	118	115	**95**	**95**	**93**	**92**
optimistic HC AC performance with base growth	148	113	115	112	110	**92**	**92**	**91**	**90**
breakthrough HC AC performance with base growth	137	107	109	107	105	**90**	**90**	**89**	**88**
business-as-usual HC AC performance with low growth	147	112	114	112	109	**92**	**92**	**91**	**90**
optimistic HC AC performance with low growth	138	107	109	107	105	**90**	**90**	**89**	**88**
breakthrough HC AC performance with low growth	129	103	104	102	101	**88**	**88**	**87**	**86**
business-as-usual HC AC performance with degrowth	135	105	107	105	103	**90**	**89**	**88**	**88**
optimistic HC AC performance with degrowth	129	102	103	102	100	**88**	**88**	**87**	**87**
breakthrough HC AC performance with degrowth	122	**98**	**99**	**98**	**97**	**87**	**86**	**86**	**85**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	135	140	137	135	**97**	**98**	**98**	**98**
optimistic HC AC performance with high growth	147	132	137	134	132	**95**	**97**	**96**	**96**
breakthrough HC AC performance with high growth	143	129	134	131	129	**94**	**95**	**94**	**95**
business-as-usual HC AC performance with base growth	137	122	127	124	122	**90**	**91**	**90**	**90**
optimistic HC AC performance with base growth	133	120	124	121	120	**88**	**89**	**88**	**89**
breakthrough HC AC performance with base growth	129	117	121	119	117	**86**	**87**	**87**	**87**
business-as-usual HC AC performance with low growth	124	112	115	113	111	**83**	**84**	**83**	**83**
optimistic HC AC performance with low growth	121	109	113	111	109	**82**	**83**	**82**	**82**
breakthrough HC AC performance with low growth	117	107	111	109	107	**80**	**81**	**81**	**81**
business-as-usual HC AC performance with degrowth	113	102	104	103	102	**78**	**78**	**78**	**78**
optimistic HC AC performance with degrowth	110	**100**	103	101	**100**	**77**	**77**	**77**	**77**
breakthrough HC AC performance with degrowth	107	**98**	100	**99**	**98**	**75**	**76**	**76**	**76**

Figure C.9: Heat map depicting the results of the **SSP1-PkBudg500** scenario with hydrogen produced through **water electrolysis from wind**, for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values ≤ 100) are shown in bold. AC: aircraft, RF: radiative forcing.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	439	233	239	233	225	176	175	174	170
optimistic HC AC performance with high growth	401	219	224	219	212	171	170	168	166
breakthrough HC AC performance with high growth	360	204	208	204	198	164	163	162	160
business-as-usual HC AC performance with base growth	349	192	197	192	186	150	149	148	145
optimistic HC AC performance with base growth	321	181	186	182	176	146	145	144	142
breakthrough HC AC performance with base growth	291	170	173	170	166	141	140	139	137
business-as-usual HC AC performance with low growth	278	158	162	159	154	128	127	126	124
optimistic HC AC performance with low growth	258	151	154	151	147	124	124	123	122
breakthrough HC AC performance with low growth	235	142	145	142	139	120	120	120	118
business-as-usual HC AC performance with degrowth	170	103	105	103	100	**86**	**86**	**86**	**84**
optimistic HC AC performance with degrowth	158	**98**	100	**99**	**96**	**84**	**84**	**84**	**82**
breakthrough HC AC performance with degrowth	145	**93**	**95**	**94**	**91**	**82**	**82**	**81**	**80**

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	125	128	125	122	**95**	**93**	**93**	**92**
optimistic HC AC performance with high growth	164	120	122	120	117	**93**	**92**	**92**	**92**
breakthrough HC AC performance with high growth	152	114	116	114	112	**92**	**91**	**91**	**91**
business-as-usual HC AC performance with base growth	164	119	121	119	117	**93**	**92**	**92**	**91**
optimistic HC AC performance with base growth	154	115	117	115	113	**92**	**91**	**91**	**91**
breakthrough HC AC performance with base growth	144	110	112	110	108	**91**	**90**	**90**	**90**
business-as-usual HC AC performance with low growth	153	114	116	114	112	**92**	**91**	**91**	**90**
optimistic HC AC performance with low growth	145	110	112	110	108	**91**	**90**	**90**	**90**
breakthrough HC AC performance with low growth	136	106	108	106	105	**90**	**90**	**89**	**89**
business-as-usual HC AC performance with degrowth	141	108	109	108	106	**91**	**90**	**90**	**90**
optimistic HC AC performance with degrowth	134	105	106	105	104	**90**	**89**	**89**	**89**
breakthrough HC AC performance with degrowth	127	102	103	102	101	**89**	**89**	**89**	**89**

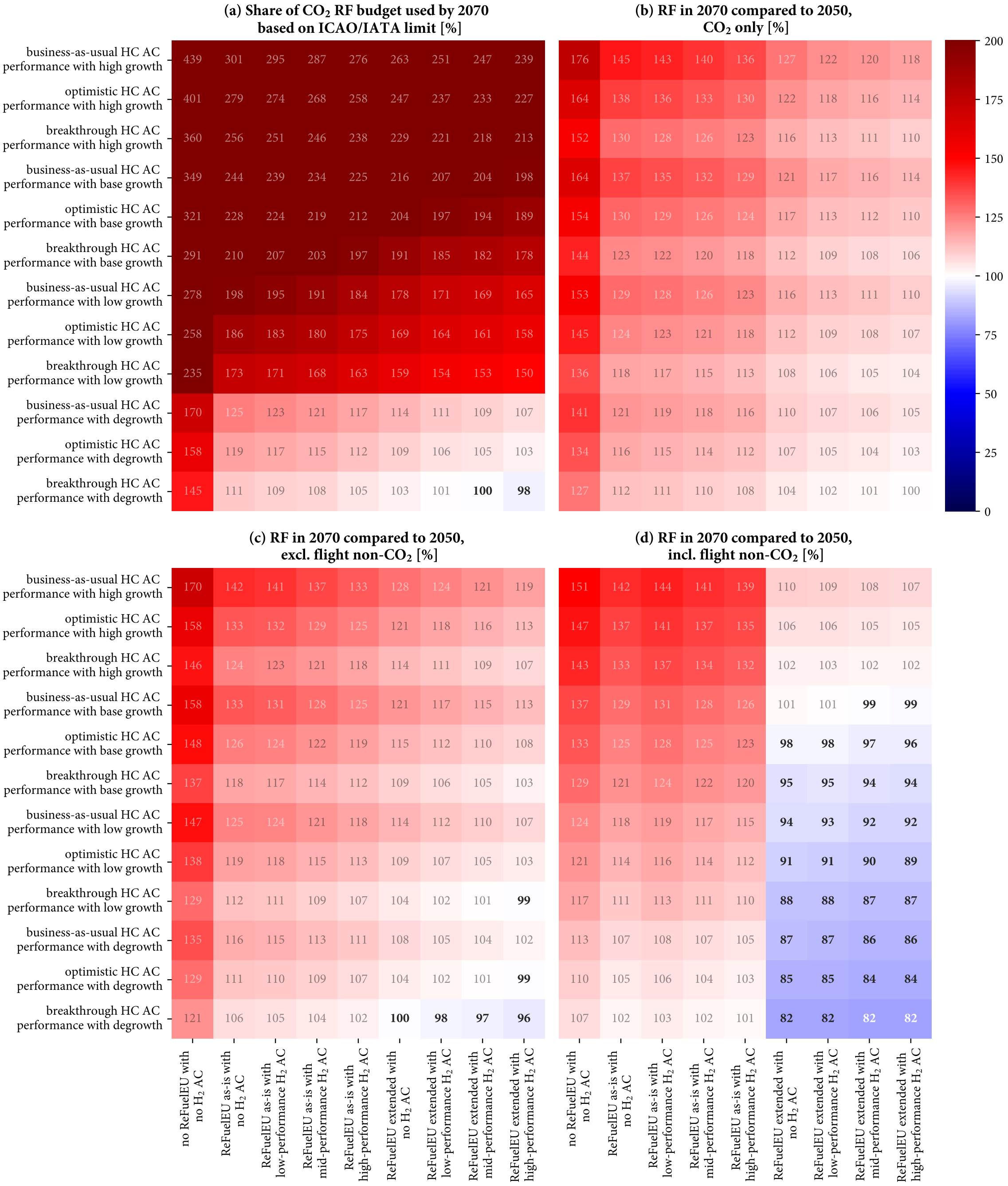
(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	121	125	122	118	**93**	**94**	**92**	**91**
optimistic HC AC performance with high growth	158	115	118	116	113	**91**	**91**	**90**	**89**
breakthrough HC AC performance with high growth	146	109	112	109	107	**88**	**89**	**88**	**87**
business-as-usual HC AC performance with base growth	158	114	118	115	112	**91**	**91**	**90**	**89**
optimistic HC AC performance with base growth	148	109	112	110	108	**89**	**89**	**88**	**87**
breakthrough HC AC performance with base growth	137	104	107	105	103	**87**	**87**	**86**	**85**
business-as-usual HC AC performance with low growth	147	109	112	109	107	**88**	**89**	**88**	**87**
optimistic HC AC performance with low growth	138	105	107	105	103	**87**	**87**	**86**	**86**
breakthrough HC AC performance with low growth	129	100	102	101	**99**	**85**	**85**	**85**	**84**
business-as-usual HC AC performance with degrowth	135	103	105	103	101	**87**	**87**	**86**	**85**
optimistic HC AC performance with degrowth	129	**100**	101	**100**	**98**	**85**	**85**	**85**	**84**
breakthrough HC AC performance with degrowth	121	**96**	**98**	**97**	**95**	**84**	**84**	**84**	**83**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	133	138	136	133	**95**	**97**	**96**	**96**
optimistic HC AC performance with high growth	147	131	136	133	131	**94**	**95**	**95**	**95**
breakthrough HC AC performance with high growth	143	128	133	130	129	**92**	**94**	**93**	**94**
business-as-usual HC AC performance with base growth	137	121	125	123	121	**88**	**89**	**88**	**89**
optimistic HC AC performance with base growth	133	118	123	120	119	**86**	**88**	**87**	**87**
breakthrough HC AC performance with base growth	129	116	120	118	117	**85**	**86**	**86**	**86**
business-as-usual HC AC performance with low growth	124	110	114	112	110	**82**	**83**	**82**	**82**
optimistic HC AC performance with low growth	121	108	112	110	108	**80**	**81**	**81**	**81**
breakthrough HC AC performance with low growth	117	106	110	108	106	**79**	**80**	**80**	**80**
business-as-usual HC AC performance with degrowth	113	101	104	102	101	**77**	**77**	**77**	**77**
optimistic HC AC performance with degrowth	110	**99**	102	100	**99**	**75**	**76**	**76**	**76**
breakthrough HC AC performance with degrowth	107	**97**	**100**	**98**	**97**	**74**	**75**	**75**	**75**

Figure C.10: Heat map depicting the results of the **SSP1-PkBudg500** scenario with hydrogen produced through **water electrolysis from the grid mix**, for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft, RF: radiative forcing.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	439	301	295	287	276	263	251	247	239
optimistic HC AC performance with high growth	401	279	274	268	258	247	237	233	227
breakthrough HC AC performance with high growth	360	256	251	246	238	229	221	218	213
business-as-usual HC AC performance with base growth	349	244	239	234	225	216	207	204	198
optimistic HC AC performance with base growth	321	228	224	219	212	204	197	194	189
breakthrough HC AC performance with base growth	291	210	207	203	197	191	185	182	178
business-as-usual HC AC performance with low growth	278	198	195	191	184	178	171	169	165
optimistic HC AC performance with low growth	258	186	183	180	175	169	164	161	158
breakthrough HC AC performance with low growth	235	173	171	168	163	159	154	153	150
business-as-usual HC AC performance with degrowth	170	125	123	121	117	114	111	109	107
optimistic HC AC performance with degrowth	158	119	117	115	112	109	106	105	103
breakthrough HC AC performance with degrowth	145	111	109	108	105	103	101	**100**	**98**

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	145	143	140	136	127	122	120	118
optimistic HC AC performance with high growth	164	138	136	133	130	122	118	116	114
breakthrough HC AC performance with high growth	152	130	128	126	123	116	113	111	110
business-as-usual HC AC performance with base growth	164	137	135	132	129	121	117	116	114
optimistic HC AC performance with base growth	154	130	129	126	124	117	113	112	110
breakthrough HC AC performance with base growth	144	123	122	120	118	112	109	108	106
business-as-usual HC AC performance with low growth	153	129	128	126	123	116	113	111	110
optimistic HC AC performance with low growth	145	124	123	121	118	112	109	108	107
breakthrough HC AC performance with low growth	136	118	117	115	113	108	106	105	104
business-as-usual HC AC performance with degrowth	141	121	119	118	116	110	107	106	105
optimistic HC AC performance with degrowth	134	116	115	114	112	107	105	104	103
breakthrough HC AC performance with degrowth	127	112	111	110	108	104	102	101	100

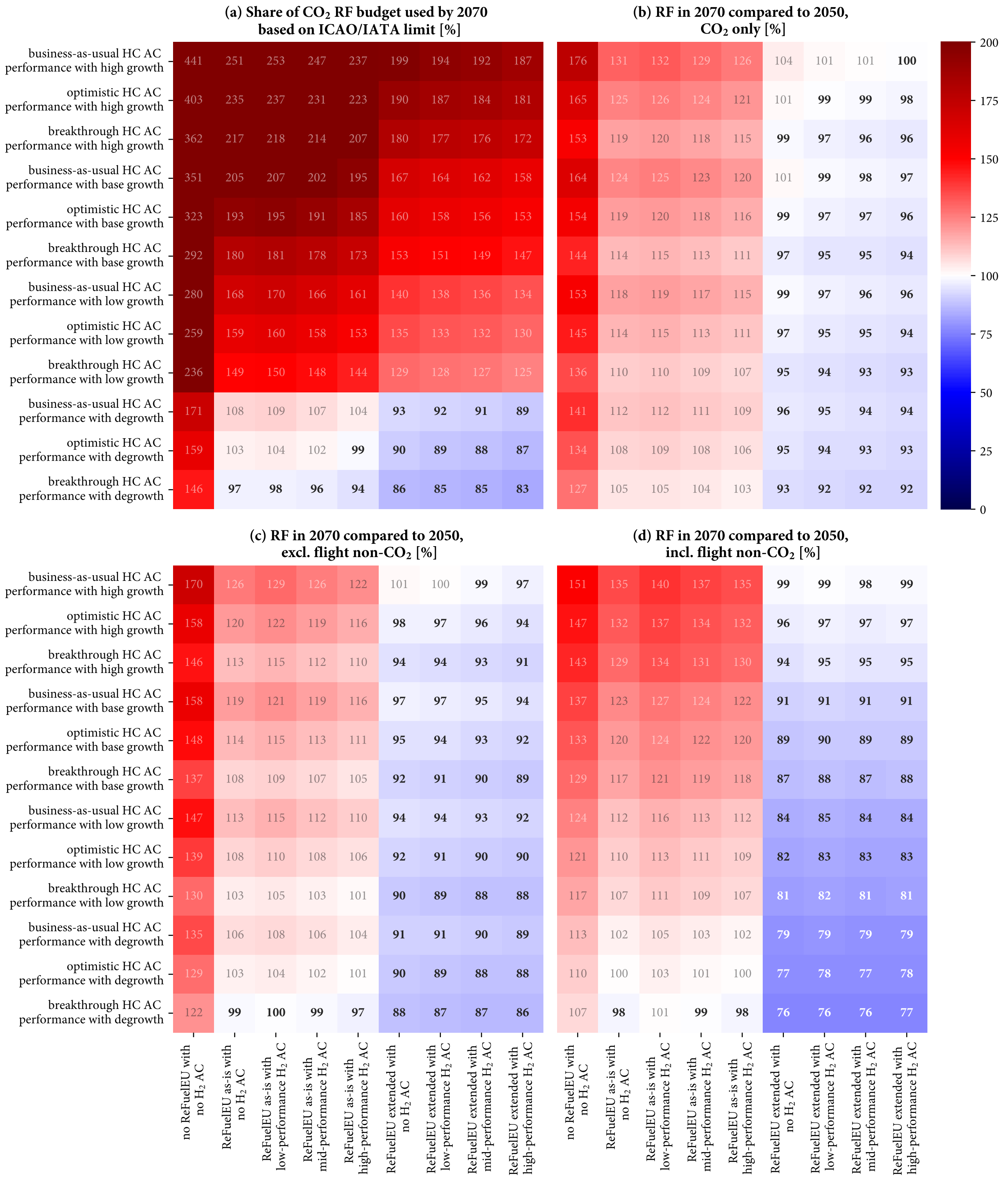
(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	142	141	137	133	128	124	121	119
optimistic HC AC performance with high growth	158	133	132	129	125	121	118	116	113
breakthrough HC AC performance with high growth	146	124	123	121	118	114	111	109	107
business-as-usual HC AC performance with base growth	158	133	131	128	125	121	117	115	113
optimistic HC AC performance with base growth	148	126	124	122	119	115	112	110	108
breakthrough HC AC performance with base growth	137	118	117	114	112	109	106	105	103
business-as-usual HC AC performance with low growth	147	125	124	121	118	114	112	110	107
optimistic HC AC performance with low growth	138	119	118	115	113	109	107	105	103
breakthrough HC AC performance with low growth	129	112	111	109	107	104	102	101	**99**
business-as-usual HC AC performance with degrowth	135	116	115	113	111	108	105	104	102
optimistic HC AC performance with degrowth	129	111	110	109	107	104	102	101	**99**
breakthrough HC AC performance with degrowth	121	106	105	104	102	**100**	**98**	**97**	**96**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	142	144	141	139	110	109	108	107
optimistic HC AC performance with high growth	147	137	141	137	135	106	106	105	105
breakthrough HC AC performance with high growth	143	133	137	134	132	102	103	102	102
business-as-usual HC AC performance with base growth	137	129	131	128	126	101	101	**99**	**99**
optimistic HC AC performance with base growth	133	125	128	125	123	**98**	**98**	**97**	**96**
breakthrough HC AC performance with base growth	129	121	124	122	120	**95**	**95**	**94**	**94**
business-as-usual HC AC performance with low growth	124	118	119	117	115	**94**	**93**	**92**	**92**
optimistic HC AC performance with low growth	121	114	116	114	112	**91**	**91**	**90**	**89**
breakthrough HC AC performance with low growth	117	111	113	111	110	**88**	**88**	**87**	**87**
business-as-usual HC AC performance with degrowth	113	107	108	107	105	**87**	**87**	**86**	**86**
optimistic HC AC performance with degrowth	110	105	106	104	103	**85**	**85**	**84**	**84**
breakthrough HC AC performance with degrowth	107	102	103	102	101	**82**	**82**	**82**	**82**

Figure C.11: Heat map depicting the results of the **SSP1-PkBudg500** scenario with the **prospective hydrogen mix** from Wei et al. (in preparation), for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft, RF: radiative forcing.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	441	251	253	247	237	199	194	192	187
optimistic HC AC performance with high growth	403	235	237	231	223	190	187	184	181
breakthrough HC AC performance with high growth	362	217	218	214	207	180	177	176	172
business-as-usual HC AC performance with base growth	351	205	207	202	195	167	164	162	158
optimistic HC AC performance with base growth	323	193	195	191	185	160	158	156	153
breakthrough HC AC performance with base growth	292	180	181	178	173	153	151	149	147
business-as-usual HC AC performance with low growth	280	168	170	166	161	140	138	136	134
optimistic HC AC performance with low growth	259	159	160	158	153	135	133	132	130
breakthrough HC AC performance with low growth	236	149	150	148	144	129	128	127	125
business-as-usual HC AC performance with degrowth	171	108	109	107	104	**93**	**92**	**91**	**89**
optimistic HC AC performance with degrowth	159	103	104	102	**99**	**90**	**89**	**88**	**87**
breakthrough HC AC performance with degrowth	146	**97**	**98**	**96**	**94**	**86**	**85**	**85**	**83**

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	131	132	129	126	104	101	101	**100**
optimistic HC AC performance with high growth	165	125	126	124	121	101	**99**	**99**	**98**
breakthrough HC AC performance with high growth	153	119	120	118	115	**99**	**97**	**96**	**96**
business-as-usual HC AC performance with base growth	164	124	125	123	120	101	**99**	**98**	**97**
optimistic HC AC performance with base growth	154	119	120	118	116	**99**	**97**	**97**	**96**
breakthrough HC AC performance with base growth	144	114	115	113	111	**97**	**95**	**95**	**94**
business-as-usual HC AC performance with low growth	153	118	119	117	115	**99**	**97**	**96**	**96**
optimistic HC AC performance with low growth	145	114	115	113	111	**97**	**95**	**95**	**94**
breakthrough HC AC performance with low growth	136	110	110	109	107	**95**	**94**	**93**	**93**
business-as-usual HC AC performance with degrowth	141	112	112	111	109	**96**	**95**	**94**	**94**
optimistic HC AC performance with degrowth	134	108	109	108	106	**95**	**94**	**93**	**93**
breakthrough HC AC performance with degrowth	127	105	105	104	103	**93**	**92**	**92**	**92**

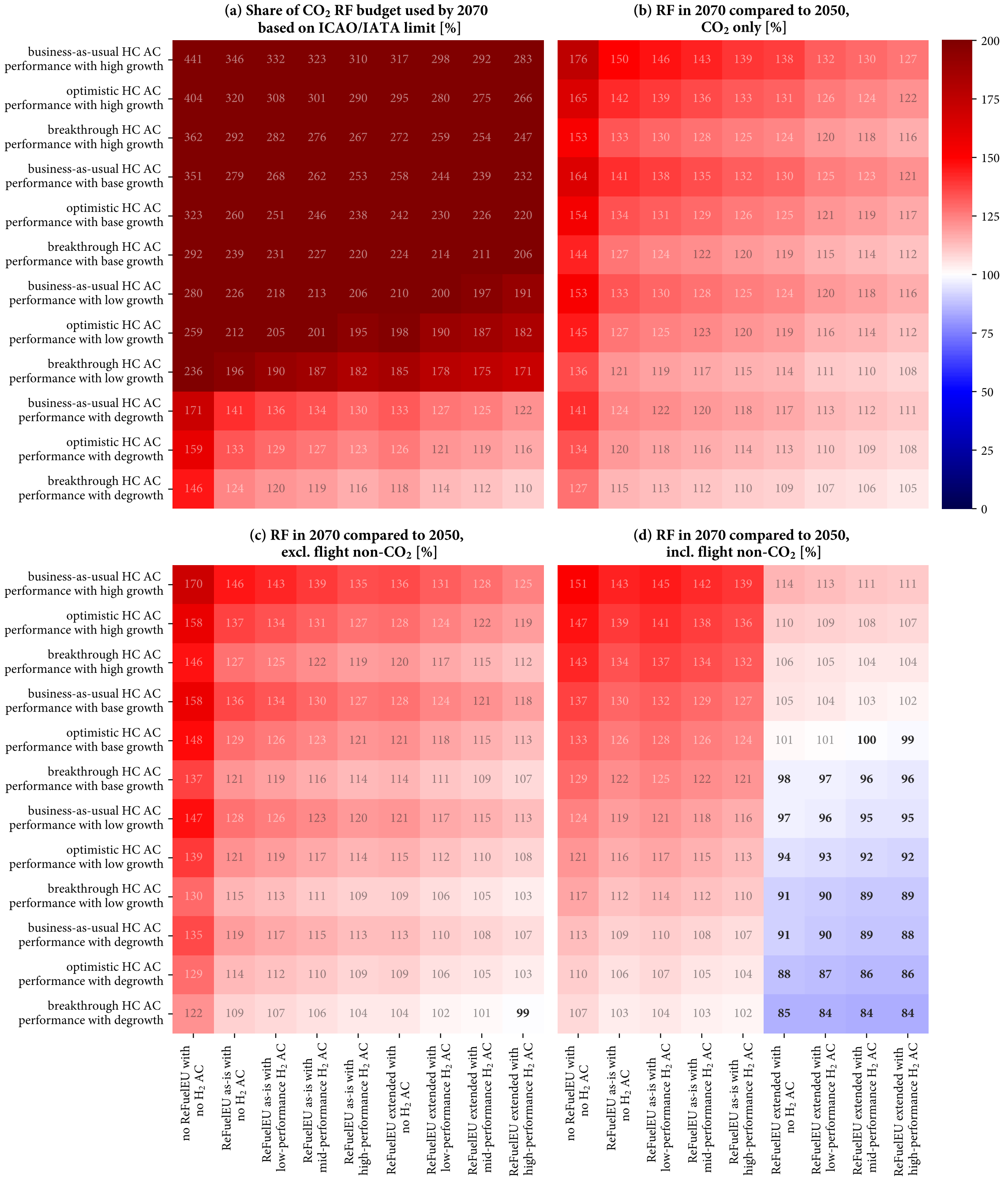
(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	126	129	126	122	101	100	**99**	**97**
optimistic HC AC performance with high growth	158	120	122	119	116	**98**	**97**	**96**	**94**
breakthrough HC AC performance with high growth	146	113	115	112	110	**94**	**94**	**93**	**91**
business-as-usual HC AC performance with base growth	158	119	121	119	116	**97**	**97**	**95**	**94**
optimistic HC AC performance with base growth	148	114	115	113	111	**95**	**94**	**93**	**92**
breakthrough HC AC performance with base growth	137	108	109	107	105	**92**	**91**	**90**	**89**
business-as-usual HC AC performance with low growth	147	113	115	112	110	**94**	**94**	**93**	**92**
optimistic HC AC performance with low growth	139	108	110	108	106	**92**	**91**	**90**	**90**
breakthrough HC AC performance with low growth	130	103	105	103	101	**90**	**89**	**88**	**88**
business-as-usual HC AC performance with degrowth	135	106	108	106	104	**91**	**91**	**90**	**89**
optimistic HC AC performance with degrowth	129	103	104	102	101	**90**	**89**	**88**	**88**
breakthrough HC AC performance with degrowth	122	**99**	**100**	**99**	**97**	**88**	**87**	**87**	**86**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	135	140	137	135	**99**	**99**	**98**	**99**
optimistic HC AC performance with high growth	147	132	137	134	132	**96**	**97**	**97**	**97**
breakthrough HC AC performance with high growth	143	129	134	131	130	**94**	**95**	**95**	**95**
business-as-usual HC AC performance with base growth	137	123	127	124	122	**91**	**91**	**91**	**91**
optimistic HC AC performance with base growth	133	120	124	122	120	**89**	**90**	**89**	**89**
breakthrough HC AC performance with base growth	129	117	121	119	118	**87**	**88**	**87**	**88**
business-as-usual HC AC performance with low growth	124	112	116	113	112	**84**	**85**	**84**	**84**
optimistic HC AC performance with low growth	121	110	113	111	109	**82**	**83**	**83**	**83**
breakthrough HC AC performance with low growth	117	107	111	109	107	**81**	**82**	**81**	**81**
business-as-usual HC AC performance with degrowth	113	102	105	103	102	**79**	**79**	**79**	**79**
optimistic HC AC performance with degrowth	110	100	103	101	100	**77**	**78**	**77**	**78**
breakthrough HC AC performance with degrowth	107	**98**	101	**99**	**98**	**76**	**76**	**76**	**77**

Figure C.12: Heat map depicting the results of the **SSP2-PkBudg1550** scenario with hydrogen produced through **water electrolysis from wind**, for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values ≤100) are shown in bold. AC: aircraft, RF: radiative forcing.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	441	346	332	323	310	317	298	292	283
optimistic HC AC performance with high growth	404	320	308	301	290	295	280	275	266
breakthrough HC AC performance with high growth	362	292	282	276	267	272	259	254	247
business-as-usual HC AC performance with base growth	351	279	268	262	253	258	244	239	232
optimistic HC AC performance with base growth	323	260	251	246	238	242	230	226	220
breakthrough HC AC performance with base growth	292	239	231	227	220	224	214	211	206
business-as-usual HC AC performance with low growth	280	226	218	213	206	210	200	197	191
optimistic HC AC performance with low growth	259	212	205	201	195	198	190	187	182
breakthrough HC AC performance with low growth	236	196	190	187	182	185	178	175	171
business-as-usual HC AC performance with degrowth	171	141	136	134	130	133	127	125	122
optimistic HC AC performance with degrowth	159	133	129	127	123	126	121	119	116
breakthrough HC AC performance with degrowth	146	124	120	119	116	118	114	112	110

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	150	146	143	139	138	132	130	127
optimistic HC AC performance with high growth	165	142	139	136	133	131	126	124	122
breakthrough HC AC performance with high growth	153	133	130	128	125	124	120	118	116
business-as-usual HC AC performance with base growth	164	141	138	135	132	130	125	123	121
optimistic HC AC performance with base growth	154	134	131	129	126	125	121	119	117
breakthrough HC AC performance with base growth	144	127	124	122	120	119	115	114	112
business-as-usual HC AC performance with low growth	153	133	130	128	125	124	120	118	116
optimistic HC AC performance with low growth	145	127	125	123	120	119	116	114	112
breakthrough HC AC performance with low growth	136	121	119	117	115	114	111	110	108
business-as-usual HC AC performance with degrowth	141	124	122	120	118	117	113	112	111
optimistic HC AC performance with degrowth	134	120	118	116	114	113	110	109	108
breakthrough HC AC performance with degrowth	127	115	113	112	110	109	107	106	105

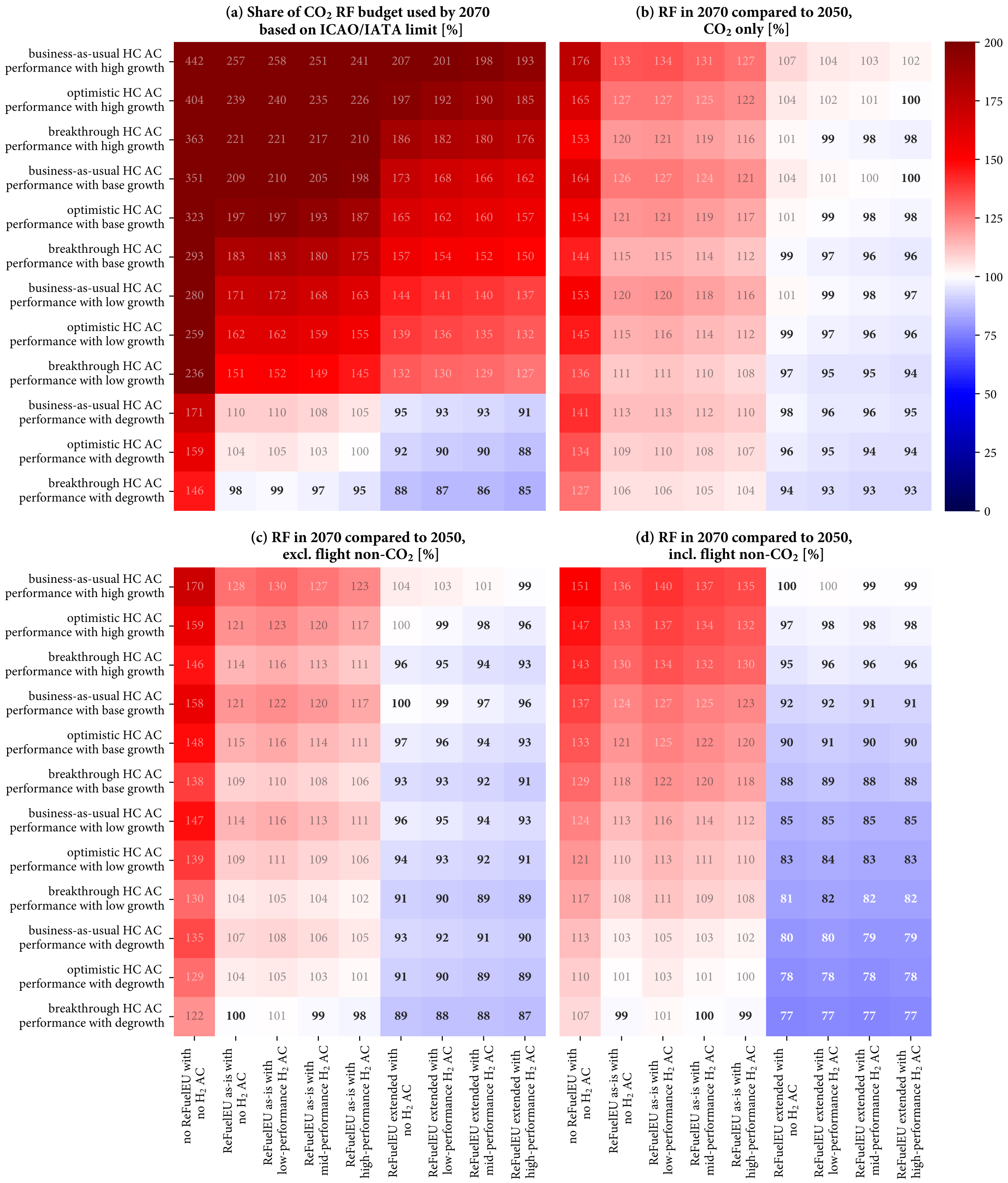
(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	146	143	139	135	136	131	128	125
optimistic HC AC performance with high growth	158	137	134	131	127	128	124	122	119
breakthrough HC AC performance with high growth	146	127	125	122	119	120	117	115	112
business-as-usual HC AC performance with base growth	158	136	134	130	127	128	124	121	118
optimistic HC AC performance with base growth	148	129	126	123	121	121	118	115	113
breakthrough HC AC performance with base growth	137	121	119	116	114	114	111	109	107
business-as-usual HC AC performance with low growth	147	128	126	123	120	121	117	115	113
optimistic HC AC performance with low growth	139	121	119	117	114	115	112	110	108
breakthrough HC AC performance with low growth	130	115	113	111	109	109	106	105	103
business-as-usual HC AC performance with degrowth	135	119	117	115	113	113	110	108	107
optimistic HC AC performance with degrowth	129	114	112	110	109	109	106	105	103
breakthrough HC AC performance with degrowth	122	109	107	106	104	104	102	101	**99**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	143	145	142	139	114	113	111	111
optimistic HC AC performance with high growth	147	139	141	138	136	110	109	108	107
breakthrough HC AC performance with high growth	143	134	137	134	132	106	105	104	104
business-as-usual HC AC performance with base growth	137	130	132	129	127	105	104	103	102
optimistic HC AC performance with base growth	133	126	128	126	124	101	101	**100**	**99**
breakthrough HC AC performance with base growth	129	122	125	122	121	**98**	**97**	**96**	**96**
business-as-usual HC AC performance with low growth	124	119	121	118	116	**97**	**96**	**95**	**95**
optimistic HC AC performance with low growth	121	116	117	115	113	**94**	**93**	**92**	**92**
breakthrough HC AC performance with low growth	117	112	114	112	110	**91**	**90**	**89**	**89**
business-as-usual HC AC performance with degrowth	113	109	110	108	107	**91**	**90**	**89**	**88**
optimistic HC AC performance with degrowth	110	106	107	105	104	**88**	**87**	**86**	**86**
breakthrough HC AC performance with degrowth	107	103	104	103	102	**85**	**84**	**84**	**84**

Figure C.13: Heat map depicting the results of the **SSP2-PkBudg1550** scenario with the **prospective hydrogen mix** from Wei et al. (in preparation), for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft, RF: radiative forcing.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	442	257	258	251	241	207	201	198	193
optimistic HC AC performance with high growth	404	239	240	235	226	197	192	190	185
breakthrough HC AC performance with high growth	363	221	221	217	210	186	182	180	176
business-as-usual HC AC performance with base growth	351	209	210	205	198	173	168	166	162
optimistic HC AC performance with base growth	323	197	197	193	187	165	162	160	157
breakthrough HC AC performance with base growth	293	183	183	180	175	157	154	152	150
business-as-usual HC AC performance with low growth	280	171	172	168	163	144	141	140	137
optimistic HC AC performance with low growth	259	162	162	159	155	139	136	135	132
breakthrough HC AC performance with low growth	236	151	152	149	145	132	130	129	127
business-as-usual HC AC performance with degrowth	171	110	110	108	105	**95**	**93**	**93**	**91**
optimistic HC AC performance with degrowth	159	104	105	103	100	**92**	**90**	**90**	**88**
breakthrough HC AC performance with degrowth	146	**98**	**99**	**97**	**95**	**88**	**87**	**86**	**85**

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	133	134	131	127	107	104	103	102
optimistic HC AC performance with high growth	165	127	127	125	122	104	102	101	**100**
breakthrough HC AC performance with high growth	153	120	121	119	116	101	**99**	**98**	**98**
business-as-usual HC AC performance with base growth	164	126	127	124	121	104	101	100	**100**
optimistic HC AC performance with base growth	154	121	121	119	117	101	**99**	**98**	**98**
breakthrough HC AC performance with base growth	144	115	115	114	112	**99**	**97**	**96**	**96**
business-as-usual HC AC performance with low growth	153	120	120	118	116	101	**99**	**98**	**97**
optimistic HC AC performance with low growth	145	115	116	114	112	**99**	**97**	**96**	**96**
breakthrough HC AC performance with low growth	136	111	111	110	108	**97**	**95**	**95**	**94**
business-as-usual HC AC performance with degrowth	141	113	113	112	110	**98**	**96**	**96**	**95**
optimistic HC AC performance with degrowth	134	109	110	108	107	**96**	**95**	**94**	**94**
breakthrough HC AC performance with degrowth	127	106	106	105	104	**94**	**93**	**93**	**93**

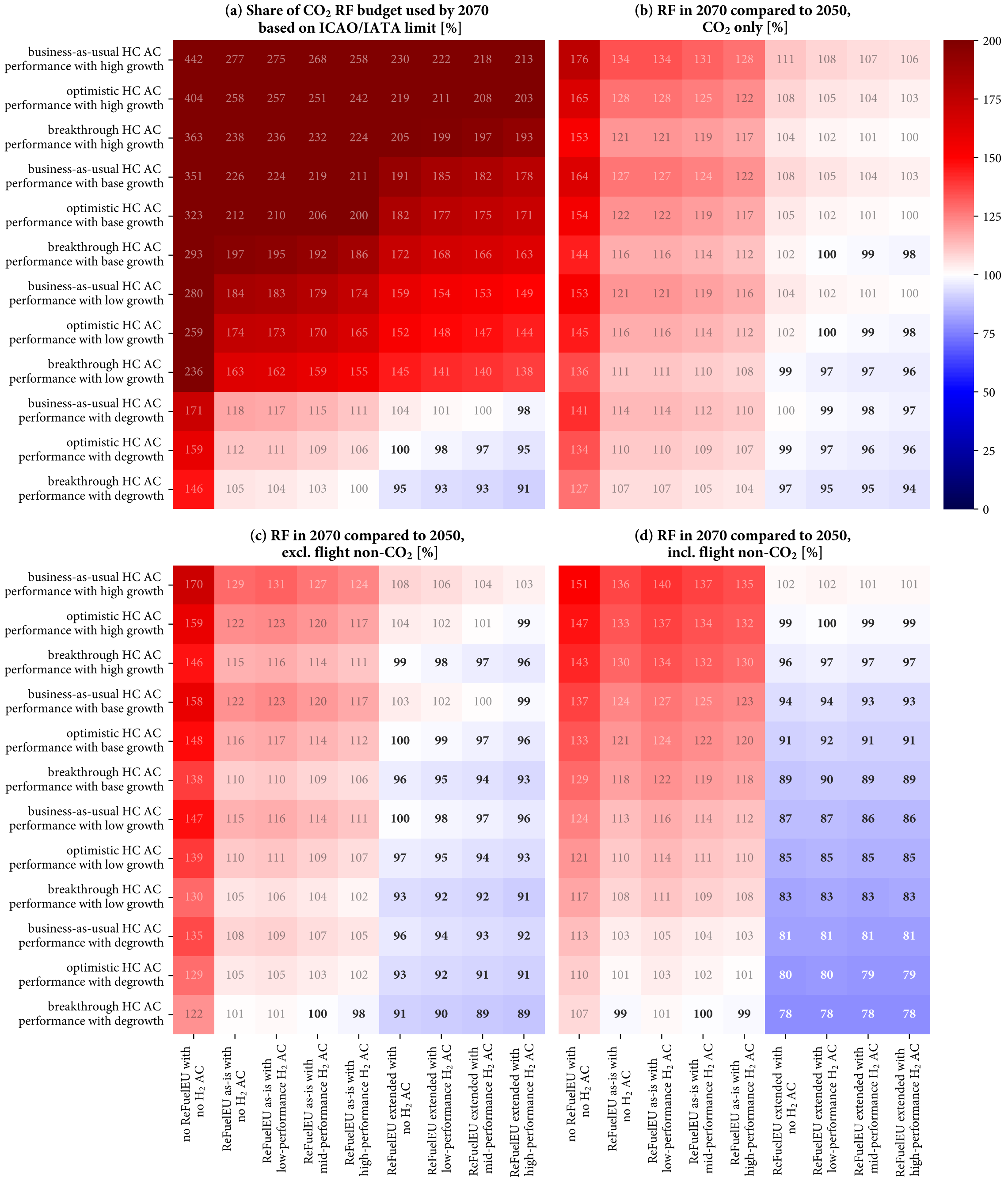
(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	128	130	127	123	104	103	101	**99**
optimistic HC AC performance with high growth	159	121	123	120	117	100	**99**	**98**	**96**
breakthrough HC AC performance with high growth	146	114	116	113	111	**96**	**95**	**94**	**93**
business-as-usual HC AC performance with base growth	158	121	122	120	117	**100**	**99**	**97**	**96**
optimistic HC AC performance with base growth	148	115	116	114	111	**97**	**96**	**94**	**93**
breakthrough HC AC performance with base growth	138	109	110	108	106	**93**	**93**	**92**	**91**
business-as-usual HC AC performance with low growth	147	114	116	113	111	**96**	**95**	**94**	**93**
optimistic HC AC performance with low growth	139	109	111	109	106	**94**	**93**	**92**	**91**
breakthrough HC AC performance with low growth	130	104	105	104	102	**91**	**90**	**89**	**89**
business-as-usual HC AC performance with degrowth	135	107	108	106	105	**93**	**92**	**91**	**90**
optimistic HC AC performance with degrowth	129	104	105	103	101	**91**	**90**	**89**	**89**
breakthrough HC AC performance with degrowth	122	**100**	101	**99**	**98**	**89**	**88**	**88**	**87**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	136	140	137	135	**100**	100	**99**	**99**
optimistic HC AC performance with high growth	147	133	137	134	132	**97**	**98**	**98**	**98**
breakthrough HC AC performance with high growth	143	130	134	132	130	**95**	**96**	**96**	**96**
business-as-usual HC AC performance with base growth	137	124	127	125	123	**92**	**92**	**91**	**91**
optimistic HC AC performance with base growth	133	121	125	122	120	**90**	**91**	**90**	**90**
breakthrough HC AC performance with base growth	129	118	122	120	118	**88**	**89**	**88**	**88**
business-as-usual HC AC performance with low growth	124	113	116	114	112	**85**	**85**	**85**	**85**
optimistic HC AC performance with low growth	121	110	113	111	110	**83**	**84**	**83**	**83**
breakthrough HC AC performance with low growth	117	108	111	109	108	**81**	**82**	**82**	**82**
business-as-usual HC AC performance with degrowth	113	103	105	103	102	**80**	**80**	**79**	**79**
optimistic HC AC performance with degrowth	110	101	103	101	100	**78**	**78**	**78**	**78**
breakthrough HC AC performance with degrowth	107	**99**	101	**100**	**99**	**77**	**77**	**77**	**77**

Figure C.14: Heat map depicting the results of the **SSP2-NDC** scenario with hydrogen produced through **water electrolysis from wind**, for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft, RF: radiative forcing.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	442	277	275	268	258	230	222	218	213
optimistic HC AC performance with high growth	404	258	257	251	242	219	211	208	203
breakthrough HC AC performance with high growth	363	238	236	232	224	205	199	197	193
business-as-usual HC AC performance with base growth	351	226	224	219	211	191	185	182	178
optimistic HC AC performance with base growth	323	212	210	206	200	182	177	175	171
breakthrough HC AC performance with base growth	293	197	195	192	186	172	168	166	163
business-as-usual HC AC performance with low growth	280	184	183	179	174	159	154	153	149
optimistic HC AC performance with low growth	259	174	173	170	165	152	148	147	144
breakthrough HC AC performance with low growth	236	163	162	159	155	145	141	140	138
business-as-usual HC AC performance with degrowth	171	118	117	115	111	104	101	100	**98**
optimistic HC AC performance with degrowth	159	112	111	109	106	**100**	**98**	**97**	**95**
breakthrough HC AC performance with degrowth	146	105	104	103	100	**95**	**93**	**93**	**91**

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	134	134	131	128	111	108	107	106
optimistic HC AC performance with high growth	165	128	128	125	122	108	105	104	103
breakthrough HC AC performance with high growth	153	121	121	119	117	104	102	101	100
business-as-usual HC AC performance with base growth	164	127	127	124	122	108	105	104	103
optimistic HC AC performance with base growth	154	122	122	119	117	105	102	101	100
breakthrough HC AC performance with base growth	144	116	116	114	112	102	**100**	**99**	**98**
business-as-usual HC AC performance with low growth	153	121	121	119	116	104	102	101	100
optimistic HC AC performance with low growth	145	116	116	114	112	102	**100**	**99**	**98**
breakthrough HC AC performance with low growth	136	111	111	110	108	**99**	**97**	**97**	**96**
business-as-usual HC AC performance with degrowth	141	114	114	112	110	100	**99**	**98**	**97**
optimistic HC AC performance with degrowth	134	110	110	109	107	**99**	**97**	**96**	**96**
breakthrough HC AC performance with degrowth	127	107	107	105	104	**97**	**95**	**95**	**94**

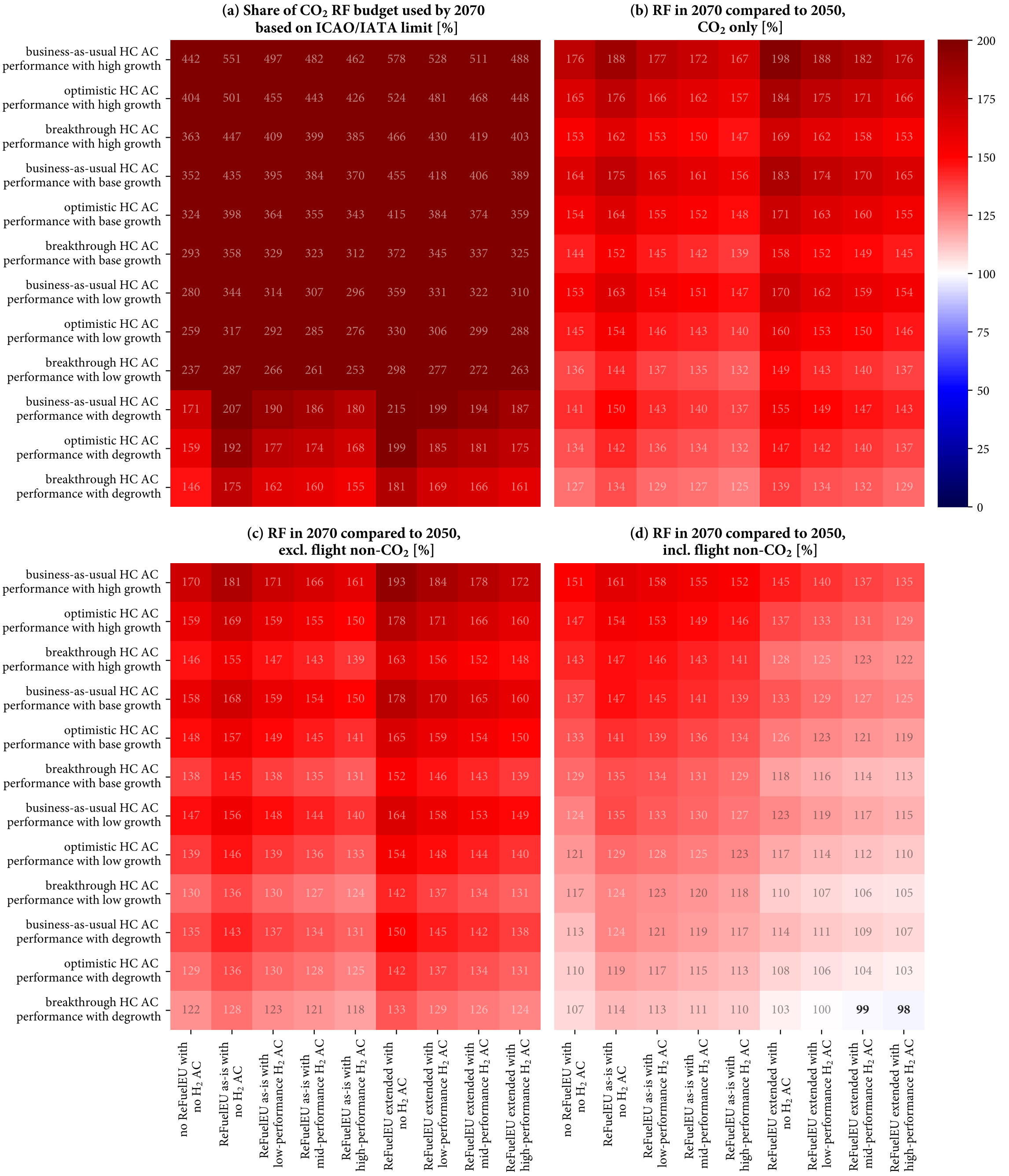
(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	129	131	127	124	108	106	104	103
optimistic HC AC performance with high growth	159	122	123	120	117	104	102	101	**99**
breakthrough HC AC performance with high growth	146	115	116	114	111	**99**	**98**	**97**	**96**
business-as-usual HC AC performance with base growth	158	122	123	120	117	103	102	100	**99**
optimistic HC AC performance with base growth	148	116	117	114	112	**100**	**99**	**97**	**96**
breakthrough HC AC performance with base growth	138	110	110	109	106	**96**	**95**	**94**	**93**
business-as-usual HC AC performance with low growth	147	115	116	114	111	**100**	**98**	**97**	**96**
optimistic HC AC performance with low growth	139	110	111	109	107	**97**	**95**	**94**	**93**
breakthrough HC AC performance with low growth	130	105	106	104	102	**93**	**92**	**92**	**91**
business-as-usual HC AC performance with degrowth	135	108	109	107	105	**96**	**94**	**93**	**92**
optimistic HC AC performance with degrowth	129	105	105	103	102	**93**	**92**	**91**	**91**
breakthrough HC AC performance with degrowth	122	101	101	**100**	**98**	**91**	**90**	**89**	**89**

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	136	140	137	135	102	102	101	101
optimistic HC AC performance with high growth	147	133	137	134	132	**99**	**100**	**99**	**99**
breakthrough HC AC performance with high growth	143	130	134	132	130	**96**	**97**	**97**	**97**
business-as-usual HC AC performance with base growth	137	124	127	125	123	**94**	**94**	**93**	**93**
optimistic HC AC performance with base growth	133	121	124	122	120	**91**	**92**	**91**	**91**
breakthrough HC AC performance with base growth	129	118	122	119	118	**89**	**90**	**89**	**89**
business-as-usual HC AC performance with low growth	124	113	116	114	112	**87**	**87**	**86**	**86**
optimistic HC AC performance with low growth	121	110	114	111	110	**85**	**85**	**85**	**85**
breakthrough HC AC performance with low growth	117	108	111	109	108	**83**	**83**	**83**	**83**
business-as-usual HC AC performance with degrowth	113	103	105	104	103	**81**	**81**	**81**	**81**
optimistic HC AC performance with degrowth	110	101	103	102	101	**80**	**80**	**79**	**79**
breakthrough HC AC performance with degrowth	107	**99**	101	**100**	**99**	**78**	**78**	**78**	**78**

Figure C.15: Heat map depicting the results of the **SSP2-NDC** scenario with hydrogen produced through **water electrolysis from the grid mix**, for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft, RF: radiative forcing.



(a) Share of CO_2 RF budget used by 2070 based on ICAO/IATA limit [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	442	551	497	482	462	578	528	511	488
optimistic HC AC performance with high growth	404	501	455	443	426	524	481	468	448
breakthrough HC AC performance with high growth	363	447	409	399	385	466	430	419	403
business-as-usual HC AC performance with base growth	352	435	395	384	370	455	418	406	389
optimistic HC AC performance with base growth	324	398	364	355	343	415	384	374	359
breakthrough HC AC performance with base growth	293	358	329	323	312	372	345	337	325
business-as-usual HC AC performance with low growth	280	344	314	307	296	359	331	322	310
optimistic HC AC performance with low growth	259	317	292	285	276	330	306	299	288
breakthrough HC AC performance with low growth	237	287	266	261	253	298	277	272	263
business-as-usual HC AC performance with degrowth	171	207	190	186	180	215	199	194	187
optimistic HC AC performance with degrowth	159	192	177	174	168	199	185	181	175
breakthrough HC AC performance with degrowth	146	175	162	160	155	181	169	166	161

(b) RF in 2070 compared to 2050, CO_2 only [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	176	188	177	172	167	198	188	182	176
optimistic HC AC performance with high growth	165	176	166	162	157	184	175	171	166
breakthrough HC AC performance with high growth	153	162	153	150	147	169	162	158	153
business-as-usual HC AC performance with base growth	164	175	165	161	156	183	174	170	165
optimistic HC AC performance with base growth	154	164	155	152	148	171	163	160	155
breakthrough HC AC performance with base growth	144	152	145	142	139	158	152	149	145
business-as-usual HC AC performance with low growth	153	163	154	151	147	170	162	159	154
optimistic HC AC performance with low growth	145	154	146	143	140	160	153	150	146
breakthrough HC AC performance with low growth	136	144	137	135	132	149	143	140	137
business-as-usual HC AC performance with degrowth	141	150	143	140	137	155	149	147	143
optimistic HC AC performance with degrowth	134	142	136	134	132	147	142	140	137
breakthrough HC AC performance with degrowth	127	134	129	127	125	139	134	132	129

(c) RF in 2070 compared to 2050, excl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	170	181	171	166	161	193	184	178	172
optimistic HC AC performance with high growth	159	169	159	155	150	178	171	166	160
breakthrough HC AC performance with high growth	146	155	147	143	139	163	156	152	148
business-as-usual HC AC performance with base growth	158	168	159	154	150	178	170	165	160
optimistic HC AC performance with base growth	148	157	149	145	141	165	159	154	150
breakthrough HC AC performance with base growth	138	145	138	135	131	152	146	143	139
business-as-usual HC AC performance with low growth	147	156	148	144	140	164	158	153	149
optimistic HC AC performance with low growth	139	146	139	136	133	154	148	144	140
breakthrough HC AC performance with low growth	130	136	130	127	124	142	137	134	131
business-as-usual HC AC performance with degrowth	135	143	137	134	131	150	145	142	138
optimistic HC AC performance with degrowth	129	136	130	128	125	142	137	134	131
breakthrough HC AC performance with degrowth	122	128	123	121	118	133	129	126	124

(d) RF in 2070 compared to 2050, incl. flight non-CO_2 [%]

	no ReFuelEU with no H_2 AC	ReFuelEU as-is with no H_2 AC	ReFuelEU as-is with low-performance H_2 AC	ReFuelEU as-is with mid-performance H_2 AC	ReFuelEU as-is with high-performance H_2 AC	ReFuelEU extended with no H_2 AC	ReFuelEU extended with low-performance H_2 AC	ReFuelEU extended with mid-performance H_2 AC	ReFuelEU extended with high-performance H_2 AC
business-as-usual HC AC performance with high growth	151	161	158	155	152	145	140	137	135
optimistic HC AC performance with high growth	147	154	153	149	146	137	133	131	129
breakthrough HC AC performance with high growth	143	147	146	143	141	128	125	123	122
business-as-usual HC AC performance with base growth	137	147	145	141	139	133	129	127	125
optimistic HC AC performance with base growth	133	141	139	136	134	126	123	121	119
breakthrough HC AC performance with base growth	129	135	134	131	129	118	116	114	113
business-as-usual HC AC performance with low growth	124	135	133	130	127	123	119	117	115
optimistic HC AC performance with low growth	121	129	128	125	123	117	114	112	110
breakthrough HC AC performance with low growth	117	124	123	120	118	110	107	106	105
business-as-usual HC AC performance with degrowth	113	124	121	119	117	114	111	109	107
optimistic HC AC performance with degrowth	110	119	117	115	113	108	106	104	103
breakthrough HC AC performance with degrowth	107	114	113	111	110	103	100	**99**	**98**

Figure C.16: Heat map depicting the results of the **SSP2-NDC** scenario with the **prospective hydrogen mix** from Wei et al. (in preparation), for **(a)** cumulative CO_2 emissions and **(b)** warming neutrality when considering only CO_2 emissions, **(c)** when considering all surface-level GHGs, and **(d)** when considering all climate forcers, including flight non-CO_2 effects. Each sub-plot depicts the same scenarios. Values for scenarios which meet the requirement (i.e., values $\leq$100) are shown in bold. AC: aircraft, RF: radiative forcing.