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Posted Date: 23 April 2024

doi: 10.20944/preprints202404.1533.v1

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Consolidating and Stepping up Aviation's Climate Ambition: A Comprehensive Definition of a Climate Neutral Air Transport System

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Abstract: In 2011, commercial aviation contributed approximately 3.5% of global anthropogenic climate change through the emission of greenhouse gases during flight and operational non-CO_2 climate effects. Over the last few years, numerous aviation-related organisations have set goals to reduce aviation's climate impact. These goals, however, lack alignment, are poorly or ambiguously defined, or are internally inconsistent. This increases uncertainty about what aviation should work towards, how various stakeholders can contribute, and introduces problems with respect to accountability. In order to address this issue, this paper presents a comprehensive definition of a climate neutral air transport system as an "air transport system of which the climate effects of all its greenhouse gases and non-carbon dioxide effects throughout the entire life-cycle of each element of the system is balanced". The proposed definition spans relevant system and encompasses all life cycle phases. To achieve a climate neutral air transport system by 2050, all life-cycle greenhouse gas emissions and non-CO_2 climate effects remaining after in-sector reduction should be neutralised, as should all remaining non-CO_2 climate forcing from emissions prior to 2050. Clarity on governance is furthermore needed, as the goal and associated targets proposed should be adopted globally.

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1. Introduction

Commercial aviation contributes to global anthropogenic climate change through the emissions of greenhouse gases and non-CO_2 climate effects. Especially the non-CO_2 effects are caused by various gaseous and particulate emissions, resulting in changes of the chemical and physical composition of the atmosphere at higher altitudes. Understanding and (policy) awareness of non-CO_2 climate effects of aviation has grown notably over the last few years [1,2], allowing to estimate the total contribution of in-flight CO_2 emissions and non-CO_2 climate effects to man-made climate change at 3.5% [1] for the year 2011. Despite this seemingly limited contribution, the percentage is foreseen to grow, as a combination of the future growth of aviation activity and of the difficulty to decarbonise aviation operations, unless substantial action is taken [3–5]. Regardless of the exact current share, aviation has to make its contribution towards solving global warming from a fundamental fairness perspective, as part of all human activities.

In this context, at the 2022 ILA Berlin Air Show, the Advisory Council for Aviation Research and Innovation in Europe (ACARE) presented its new vision for the future European aviation, titled 'Fly the Green Deal' [6]. Among the goals for 2050 is to achieve climate neutral aviation, thereby adding onto the list of environmental sustainability goals and ambitions set by the aviation industry [7–11]. Among those, the agreement of a Long-Term Aspirational Goal (LTAG) reached by the International Civil Aviation Organisation (ICAO) Assembly in October 2022, aiming at net-zero international aviation from 2050 [12], can be seen as a global landmark, at least for the aviation sector specifically.

However, there are significant differences across all those visions and targets, especially when reading beyond the titles and headlines. Moreover, differences exist between aviation-specific goals and targets and the visions (and expectations) of society at large. This is a problem. Aviation is a

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global sector and the difference in ambitions across various stakeholders' groups and at European and world-wide levels increase uncertainty on where we should be headed. This uncertainty allows for individual actors in the sector to set-up their own strategies that might seem to align, but at times are actually in conflict with national and international sustainability strategies and targets.

This paper is split into three parts. First, these different goals are further investigated and detailed, from both aviation (Section 2) and societal and governmental perspectives (Section 3), finding that a clear definition of climate neutral aviation is lacking. Next, such a definition is proposed (Section 4). Last, recommendations are made towards targets which would fit the new definition, next to a governance model which could enable the aviation sector to actually achieve the goal of a climate neutral aviation by 2050 (Section 5).

2. Climate Goals of the Aviation Sector

ACARE's 'Fly the Green Deal' (FTGD) replaces the 2011 publication 'FlightPath 2050' (FP2050). FP2050 has guided European aviation research for the past decade, and FTGD has been conceived to do the same for the next decades. As first overarching goal of the vision, FTGD aims to "by 2050, achieve climate neutral aviation" [6]. For a definition of climate neutrality, the document points to the European Climate Law adopted in 2021, in which the European Parliament sets "a binding objective to climate neutrality in the Union by 2050" [13].

Prior to the release of FTGD, five key European aviation associations – ACI EUROPE (airports), Airlines for Europe (A4E; airlines), Europe's Regional Airlines Association (ERA; regional airlines), Civil Air Navigation Services Organization (CANSO; air navigation service providers) and the European Aeronautics, Space, Defence and Security Industries Association (ASD; manufacturers) – launched the 'Destination 2050' initiative in February 2021 [14]. Whereas FTGD is research focused, Destination 2050 can be seen to represent the aviation industry perspective. Destination 2050 sets a goal of net-zero CO_2 emissions by 2050 for flights in and departing from the European Union, the United Kingdom and the European Free Trade Association (Iceland, Liechtenstein, Norway and Switzerland). The International Air Transport Association (IATA; airlines) adopted the same net-zero-CO_2-by-2050 goal at global level at their 77th IATA Annual General Meeting in October 2021 [9] and the Air Transport Action Group (ATAG; entire aviation industry) followed suit one day later [10]. In February 2022, some 40 (mainly European) countries and almost 150 industry stakeholder groups – including the Destination 2050 associations – signed the 'Toulouse Declaration', reaffirming their commitment to the decarbonisation of aviation by 2050 [11]. Meanwhile, Airlines for America (A4A) as well as ACI World also adopted net-zero goals for 2050 [15,16].

The Toulouse Declaration also explicitly called upon partners to agree to a net-zero CO_2 Long Term Aspirational Goal (LTAG) at the next International Civil Aviation Organization (ICAO) assembly, in October 2022 [12]. This goal was indeed adopted but, per the scope of the ICAO, only applies to international aviation. In the nature of ICAO's deliberations, it does not attribute specific obligations or commitments in the form of emissions reduction targets to individual States. Instead, it recognizes that each State's special circumstances and respective capabilities (e.g., the level of development, maturity of individual aviation markets, sustainable growth of its international aviation, fair transition, and national priorities of air transport development) will inform the ability of each State to contribute to the LTAG within its own national timeframe. Each State will contribute to achieving the goal in a socially, economically and environmentally sustainable manner and in accordance with its national circumstances.

Back in Europe, in addition to the various groups and organisations just listed, there are numerous other associations, alliances and joint undertakings. Almost all individual companies, research organisations and universities are member of multiple of those associations and alliances. In general, all claim to coherently connect to EU Green Deal and in large measure to the ACARE's vision. In addition to this, many also have set their own vision regarding climate impact and how that can best be reduced. Unfortunately, those visions and claims are not always aligned.

The vision of the Clean Aviation Joint Undertaking (CAJU), a public-private partnership between the European Commission and the European aeronautics industry, is towards climate

 doi:10.20944/preprints202404.1533.v1

neutrality in 2050. Though its mission targets a reduction in greenhouse gas (GHG) emissions, its strategic research and innovation agenda (SRIA) only sets quantified targets in terms of net carbon emissions reduction and in relation to aircraft operation. This is in line with the fact that of (direct) greenhouse gas emissions by aviation, CO_2 is most dominant – something also reflected in the EU ETS for aviation (detailed in section B). However, although reducing carbon emissions indeed is a contribution "towards" climate neutrality, it does not span the entire climate impact. The importance of including non-CO_2 effects is publicly acknowledged by CAJU as well, but no quantitative targets are set.

Then there is the recently launched Alliance for Zero Emission Aviation (AZEA), which has as objective to prepare the entry into commercial service of hydrogen-powered and electric aircraft. Whereas battery-electric aircraft indeed have zero in-flight emissions, lifecycle impacts seem unaccounted for. Similarly, hydrogen-powered aircraft are indeed without (in-flight) carbon emission, but definitely do emit water vapour and, depending on the propulsion technology, oxides of nitrogen (NO_X).

Specifically, regarding the research establishments, the Association of European Research Establishments in Aeronautics (EREA) has no formal goal related to climate impact of aviation in its vision study, released in 2021 [17]. Nonetheless, as member of ACARE, EREA endorsed ACARE's FTGD goal of climate neutrality, also in the strategy of the EREA's Future Sky initiative. Beyond Europe, a spin-off of thirteen research organisations members of the International Forum for Aviation Research (IFAR), agreed in 2020 on the Zero Emission Aviation (ZEMA) declaration that stated "the overall goal is to achieve the least possible impact of aviation. That means close to zero emission aviation for the entire product life cycle" [18]. Despite the declaration, no roadmap nor strategy is available on how the signatories of the ZEMA declaration intend to contribute to – let alone fully achieve – this goal.

How individual European research establishments relate back to those overarching goals varies, mainly in line with the climate leadership of individual governments. For example, the vision of the German Aerospace Centre (DLR) seems to be clear from its title "Towards zero emission aviation", but the content of the document explains the vision as "research at DLR is paving the way for the air transport system of tomorrow and shaping its transformation to climate-neutral flight" [19]. "Zero emission aviation" and "climate-neutral flight", however, are not the same. As another example, the Royal Netherlands Aerospace Centre (NLR) has "sustainable aviation" as one of three strategic themes [20], and lists the ambition to make aviation climate neutral by 2050. Emphasis is on CO_2 emissions and non-CO_2 effects from a full lifecycle perspective, but quantitative targets are not set. At the same time, NLR is also part of the Dutch Roundtable on Sustainable Aviation in which the Dutch aerospace sector in 2020 agreed to reach zero-carbon emission (but not climate-neutral) aviation, in this case only by 2070. Moreover, targets differ in the extent to which they allow for (some or all forms of) out-of-sector offsetting (most targets) or do not (e.g. [21]). Lastly, besides the differences and inconsistencies in terms of content, there are differences with respect to the (perceived) priority and commitment: some of the targets set by the various research establishments are closely connected to standing (supra)national policy; others seem to be defined hastily and do not always seem to be a coherent part of an organisation's strategy.

3. Societal and Governmental Climate Goals

Next to the aviation-specific goals discussed in the previous section, there are the broader societal and governmental targets on reducing environmental impact – global warming especially – that encompass a broader range of industries and (economic) activities. Following the Paris Agreement in 2015, the European Commission in 2019 launched its Green Deal, which was approved in 2020. Key parts of it are the European Climate Law, adopted in 2021, which sets a legally binding goal to a climate neutral continent by 2050 [13]. In the context of this paper, the Sustainable and Smart Mobility Strategy of December 2020 is also of relevance [22]. It stipulates the "European Green Deal calls for a 90% reduction in greenhouse gas emissions from transport, in order for the EU to become a climate-neutral economy by 2050".

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This raises two ambiguities. The first relates to the (possible) discrepancy between the European Climate Law and the Mobility Strategy. If transport greenhouse gases have to be reduced by 90% by 2050 while Europe should be a climate neutral continent by that same year, 10% of transport emissions remain unaccounted for. The second is of a more fundamental nature and relates to the definition of climate neutrality. Article 2 of the European Climate Law defines the climate neutrality objective as "Union-wide greenhouse gas emissions and removals regulated in Union law shall be balanced within the Union at the latest by 2050, thus reducing emission to net zero by that date"[1]. Article 1 explicates that the emissions and removals covered by the Climate Law are the ones defined in Regulation (EU) 2018/1999 [23] (Annex V, Part 2): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF6), nitrogen trifluoride (NF_3), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)[2]. This list is consistent with the amended Kyoto Protocol [24,25], but it is more restrictive than the definition set by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on 1.5°C Global Warming: "Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds"[3] [26].

Setting aside this difference, in this context the more relevant problem is that the EU definition of climate neutrality does not capture all relevant (currently known) non-CO_2 climate effects from aviation. Neither the emission of NO_X at cruise altitude, which interacts with ozone (O_3; warming effect) and methane (CH_4; cooling effect) to have a net-warming effect [1], nor the emission of water vapour (H_2O) is included, although both could be argued to be part of the 'catch-all' part of the IPCC-definition. Contrail cirrus, sometimes referred to as aviation-induced cloudiness (AIC), also is not unambiguously covered by IPCC-definition, because, even though contrail cirrus starts from water vapour, this water in contrails is in a solid phase – ice – which directly contrasts the definition's explicit reference to "gaseous constituents". More importantly, soot and other (non-gaseous) particulate emissions are excluded from the definition, but, as catalyst for the development of and influence on the climatological effect of contrails [27,28], definitely contribute to the climate impact of aviation.

To summarise, Table 1 provides an overview of all the goals mentioned, both from society in general, as well as from the aviation sector specifically.

Table 1. Overview of national, regional (mainly European) and worldwide visions related to reducing the climate impact of society in general and aviation specifically by various organisations and entities.

Organisation	Vision and year	Scope (geographical and life-cycle)	Publication
		National visions	
DLR	Zero emission aviation	Entire aircraft life-cycle	2021
NLR	Climate neutral aviation by 2050	Full life-cycle (although not quantified)	2022
Dutch Roundtable on	Zero-carbon aviation by 2070	Flights departing from the Netherlands, in-flight emissions	11/2020

[1] This, including the use of the world 'balanced' (as opposed to, for example, 'neutralised') aligns well with the IPCC definition on climate neutrality, which reads "Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface albedo or local climate." [27].

[2] Per the current consolidated version of Directive 2003/87/EC, the EU Emissions Trading Scheme as it applies to aviation only covers carbon dioxide emission [45].

[3] Other parts of Union legislation are more similar to the IPCC definition. By Directive 2009/29/EC (Art. 1.2(a)) [46], Article 3(c) of Directive 2003/87/EC was for example updated to include in the definition of greenhouse gas emissions "other gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation" [45].

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Sustainable Aviation			
	Regional (European) visions		
Sustainable and Smart Mobility Strategy	90% reduction in transport greenhouse gas emissions by 2050	Transport sector	12/2020
Destination 2050: ACI EUROPE, A4E, ERA, ASD, ERA	Net zero CO_2 by 2050	Flights within and departing EU+ (= EU + UK + EFTA), in-flight only	02/2021
A4A	Net zero CO_2 by 2050	United States, in-flight only	03/2021
European Union	Climate neutrality by 2050	Europe, full life cycle	06/2021
Clean Aviation JU	Towards climate neutral aviation by 2050	Worldwide, but focus on Europe. In-flight only	12/2021
AZEA	Zero emission aviation	Europe, in-flight emissions, noting need for supporting infrastructure	06/2022
ACARE	Climate neutrality by 2050	Europe, in-flight emissions	06/2022
	Worldwide visions		
ZEMA	Zero emission aviation	Entire product life-cycle	2020
ACI World	Net zero CO_2 by 2050	-	06/2021
IATA	Net zero CO_2 by 2050	Worldwide, in-flight emissions	10/2021
ATAG	Net zero CO_2 by 2050	Worldwide, in-flight emissions	10/2021
ICAO	Net zero CO_2 by 2050 for international aviation	Worldwide, international aviation only, in-flight emissions	10/2022

4. Achieve Climate Neutral Aviation without Agreeing on What Climate Neutrality Is?

The overview provided in the previous two sections yields a number of conclusions. First of all, it makes clear that the aviation sector is facing multiple goals and targets in different geographical regions and across different stakeholders' groups. This is particularly confusing given that many times an individual company or organisation is part of different groups with different goals. It also raises the question on how one organisation could seriously commit to any one goal, when subscribing to multiple (and at times conflicting) goals and related targets. Related to that, there is the topic of accountability: vagueness about goals and commitments stands in the way of society being able to hold organisations to these goals and commitments.

Second, the review of European policy and legislation highlights inconsistencies and shows a lack of clarity. The combination of these two problems culminates in the situation in which ACARE:

1. on one hand, refers to and aligns its vision with the European objective of climate neutrality as defined in the European Climate Law, which was shown not to include non-CO_2 climate effects; and
2. on the other, sets quantitative targets that do cover (a share of) such non-CO_2 effects.

It hence appears that the future visions and interests of the European society at large (represented by, in this case, the European Climate Law) on the one hand, and the future visions and interests of the (European) aviation sector (collectively united under the ACARE mission) on the other, are not aligned.

A clearer definition is thus needed. In the recent white paper by Delft University of Technology and NLR [29], the IPCC definition of climate neutrality was used: "Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local bio-geophysical effects of human activities that, for example, affect surface albedo or local climate" [26]. This is a rather generic definition.

 doi:10.20944/preprints202404.1533.v1

Focused on aviation, NLR defines climate neutrality as "net zero temperature rise from all aviation greenhouse gases (CO_2 and non-CO_2)[4]" [20]. DLR puts forward the following, explicitly including non-CO_2 effects: "climate-neutral aviation balances the climate impact of all carbon dioxide and non-carbon dioxide effects so that aviation no longer makes a net contribution to global warming" [19]. As the latter is rather a *description* of climate neutral aviation rather than a *definition* of climate neutral aviation, and as the explanatory second part of the definition is not fully consistent with the first (the second part is limited to warming effects, whereas the first is not), the following alternative definition is proposed instead:

Climate neutral aviation: "Type of aviation of which the climate impact of all carbon dioxide and non-carbon dioxide effects is balanced"

This definition is consistent with the generic climate neutrality definition by the IPCC. Explicit inclusion of "non-carbon dioxide effects" addresses the "regional and local bio-geophysical effects […] that […] affect surface albedo or local climate". Furthermore, if climate neutral aviation is achieved, aviation activities (part of the larger group of "human activities" referred to be the IPCC) will "result in no net effect on the climate system".

This alternative definition proposed addresses part of the previously presented critique. Still, the definition could be considered unclear – on two crucially important aspects, in particular: the 'breadth' and the 'depth' of the definition. First, regarding 'breadth', there is unclarity about scope and system boundaries, as the term 'aviation' tends to be used ambiguously. Second, on 'depth', the proposed definition is not explicit about the temporal scale of climate neutrality.

3.1. Breadth: Scope and System Boundaries

The definition of the term 'aviation' can be taken from several sources. Wikipedia cites: "Aviation is the activities surrounding mechanical flight and the aircraft industry. Aircraft includes fixed-wing and rotary-wing types, morphable wings, wing-less lifting bodies, as well as lighter-than-air craft such as hot air balloons and airships." The Cambridge dictionary quotes: "The activity of flying aircraft, or of designing, producing, and keeping them in good condition". In the authors' view, and in line with dictionary definition of 'aviation', the system boundaries should encompass the entire lifecycle of the aviation system, each element within it, from cradle to grave.

However, a closer look at the aviation-sector goals mentioned previously shows this definition is not universally accepted. FTGD, for example, has as goal to achieve "climate neutral aviation" [6] (p. 23), but only sets quantified targets related to in-flight emissions – a narrow perspective limited to part of the life cycle, and even limited with the operational life cycle phase. Contrastingly, the explanatory text to ACARE's first overarching goal, which talks about a "fully climate neutral air mobility system", seems to take an even wider view than the overarching goal itself. Whichever perspective is the one actually meant, remains unclear. The Toulouse Declaration also speaks of "aviation" but, in line with Destination 2050, seems limited to in-flight emissions, too. The target set in Destination 2050 specifically mentions "flights" and is hence clear. Besides that, only ZEMA is really explicit, targeting the full lifecycle of aviation[5]. AZEA does not go quite as far – it presents itself as "the European aeronautics industry's commitment to net zero" and refers to Destination 2050 [30].

Research has shown how the majority of the climate impact of aviation comes from in-flight emissions [31]. Although the outcome of such research is solid and undeniable, thus requiring R&D efforts for addressing the aviation's contribution to global warming, these studies seldomly look beyond in-flight impacts, and hence might not be suitable for concluding that other impacts are not (or less) relevant. Indeed, a more comprehensive and complimentary perspective seems necessary when aiming at climate neutrality over the entire life cycle of aviation.

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[4] This incorrectly refers to non-CO_2 climate effects as a (set of) greenhouse gas(es).

[5] ZEMA targets "zero emission aviation", but explains that as meaning "close to zero emission aviation for the entire product life cycle", noting that "in the long run, a single parameter target, such as being CO_2 neutral, is insufficient and misleading" [18].

First of all, the approach by which those emissions are calculated (life cycle assessment or LCA) is a method open to significant variability and uncertainty [32]. Though codified in ISO standards (ISO 14040 and 14044), a number of decisions and assumptions necessary for performing an LCA are left to the researcher, and are not currently harmonised across different studies or at times properly indicated. This is particularly relevant for the boundaries of the analysis. Current aviation LCAs exclude parts of the life cycle of aircraft and other elements of the aviation system. In addition to this, the availability of relevant and reliable data has been identified as a challenge. As such, it is questionable whether existing assessments of other life cycle phases (could) have been thorough enough to draw conclusions on the (low) contribution of such phases to the total climate impact of aviation. Indeed, the extraction and production of aerospace and infrastructure materials are proven to have high GHG emissions (global steel production accounts for 8% of manmade CO_2 emissions and aluminium for 3% CO_2 [48]; carbon fibre production CO_2 emissions are estimated to be at least an order of magnitude higher than those related to steel production [49]). Also, the impact of aviation infrastructures, in terms of embodied carbon, has so far not been accounted for in aviation or air transport system LCA studies. Similarly, the impact of disposal of aviation assets varies substantially, but is not accounted for in current estimates of aviation impact on climate or society. It must be noted that this paper mainly addresses climate neutrality from a global warming point of view, focused on emissions and greenhouse gas effects. Material use and reuse, however, is another important part of the impact of aviation on the environment. The European research project PAMELA found that up to 90% of aircraft parts could be recycled [33], meaning the materials recovered from aircraft find application in other sectors – and are downcycled. Commercial scalability of those results has unfortunately never materialised, differently than in the cases of end-of-life road vehicles and e-waste. Also, recyclability is not a solution for a climate neutrality aviation. Only a limited amount of the recovered or recycled materials derived from aircraft find their way back in aviation products. Generating a one-directional resource stream is incompatible with any climate neutrality goal.

Second, the fact that climate effects of these activities (which could be considered as supporting and/or ground activities) are most likely covered under Nationally Determined Contributions agreed in the Paris Agreement, as they take place in specific countries, or in agreements regarding other sectors, could be a reason they are seldomly – if ever – considered in aviation LCAs. That does, however, not make these activities any less part of the aviation sector. Third, the relevance of other life cycle phases is only set to increase if the sector manages to successfully reduce or eliminate in-flight emissions. Last, knowledge of the emissions of each life cycle of the aircraft or of other aviation assets is necessary in order to enable decisions makers to evaluate which developments substantially contribute to climate neutrality. In conclusion, all those emissions need to be accounted for when aiming at climate neutral aviation.

To resolve the ambiguity related to the term 'aviation' and more explicitly address life cycle emissions from the aircraft as well as supporting and related infrastructure, the term 'climate neutral air transport system' is proposed. Aiming at a climate neutral air transport system is considered clearer and understood to encompass the entire breadth described in this section. This includes all relevant system elements (such as the aircraft, the airport, air traffic management and fuel or energy supply) and the various life cycle phases (ranging from materials extraction to end-of-life).

3.2. Depth: Temporal Scale of Climate-Neutrality

Besides the 'breadth' of the system just discussed, there is the 'depth' of time. One of the complexities of limiting climate change, is the fact that the effects of different greenhouse gases (or more in general: climate agents or climate forcers) differ in terms of timescale. Contrail cirrus, for example, disappears after a day at most. During this period, it contributes to climate change, but when it is gone, it no longer has an impact. For CO_2, on the other hand, 15 to 40% of an instantaneous emission will remain in the atmosphere for more than a thousand years [34], 10 to 25% will remain there for about ten thousand years, and the rest will only be (naturally) removed over a period of multiple hundreds of thousands of years. As long as CO_2 molecules are in the atmosphere, they

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contribute to global warming. Given, thus, the fact that aviation emissions continue to contribute to global warming decades after they were produced, stopping to emit does not clean up past emissions.

This timescale-discussion might seem one of semantics, but as a recently published article shows, these semantics matter [35]. In it, the authors propose three possible definitions of climate neutral aviation (p. 763), evaluate aviation's contribution to temperature change in 2100 [6] and subsequently assess the compatibility of these definitions with the 1.5°C Paris-target [7]. In all cases, 2050 is used as the onset date of climate neutral aviation.

1. Bronze: aviation is climate neutral "compared with its contribution" to global warming in 2050. Realises net zero CO_2 emissions from 2050 and stabilizes non-CO_2 aviation forcing at 2050 levels [8]. Depending on activity growth (expressed through the Shared Socioeconomic Pathway, SSP), this results in 0.07 (SSP1-2.6) to 0.2°C (SSP5-8.5) warming by 2100 – not compatible with the Paris agreement.
2 Silver: aviation is climate neutral "relative to a world on a 1.5°C trajectory". Offsets all emissions above a 1.5°C-pathway and therefore is, by definition, compatible with the Paris Agreement. It however does not necessarily achieve net zero CO_2 and/or net zero non-CO_2.
3. Gold: aviation is climate neutral "compared with a world without aviation emissions". Achieves net zero CO_2 and non-CO_2 by 2050, neutralizes historic non-CO_2 effects remaining in 2050 [9] and leads to a Paris-compatible warming contribution of 0.02 to 0.03°C by 2100.

In all definitions, non-CO_2 emissions are – to the extent required by the definition – neutralised by deploying (additional) CO_2 removal. Furthermore, CO_2 emitted prior to 2050 is left unmitigated. Following that, the authors want to propose an even more ambitious definition:

4. Platinum: aviation is climate neutral "compared with a world in which aviation emissions never existed". Achieves net zero CO_2 and non-CO_2 by 2050 and neutralizes all historic CO_2 emissions and non-CO_2 effects remaining in 2050 [9]. Although not numerically evaluated, aviation's contribution to temperature change in this case should be 0°C, making it compatible with the Paris Agreement.

The table shows how future and historic CO_2 and non-CO_2 emissions and effects are dealt with under each of the definition. An additional 'net zero CO_2' scenario is added for reference.

Table 2. Comparison between net zero CO_2 and various definitions of climate neutrality (based on [35]).

	Net emissions from 2050		**Remaining effects of emissions prior to 2050**		**Contribution to warming / compatibility with Paris agreement**
	CO_2	**Non-CO_2**	**CO_2**	**Non-CO_2**	
Net zero CO_2	0				0.09 – 0.35°C
Bronze	0	Stable at 2050 levels			0.07 – 0.2°C
Silver	Compatible with Paris Agreement / 1.5° C warming				0.04°C
Gold	0	0		Neutralised	0.02 – 0.03°C
Platinum	0	0	Neutralised	Neutralised	~ 0°C

Requiring compatibility with the Paris Agreement makes the net zero CO_2 and Bronze targets irrelevant. Silver, even though Paris-compatible, could mean going back on (net zero CO_2)

[6] The researchers have modelled "absolute temperature changes using empirical sensitivity parameters, the GWP* metric and a reduced-complexity climate model" [35].
[7] An aviation contribution to global warming of 0.04°C is considered compatible with the 1.5°C-scenario.
[8] As it stabilizes non-CO_2 forcing, this definition is already more ambitious than current industry net zero CO_2 targets.
[9] The point in time at which historic effects should be neutralised is not specified. Some time should be allowed for this, although a longer period could be argued to delay achieving 'true' climate neutrality.

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commitments already made and is therefore set aside as well. Platinum, which would substantially go beyond the Paris Agreement goals, could be considered a hypothetical climate ideal, but might not get broad political support. As such, Gold is identified as most realistically achievable. That pathway stipulates that past emissions indeed have to be dealt with. Even though Gold's complete neutralisation of non-CO_2 effects that originated prior to 2050 (mainly NO_X, as contrails are short-lived) in that respect might be argued to do more than what is required by the Paris Agreement, complete neglect of these effects is likely to not meet the Paris goals. On the other hand, by not explicitly neutralising remaining effects of CO_2 emissions prior to 2050, it does not guarantee cumulative CO_2 emissions are limited to a socially accepted share of the global carbon budget [50–53].

3.1. Refining the Definition

Following the further exploration of scope and system boundaries on one hand, and the temporal dimension of climate change on the other, the previously proposed draft definition can be updated. To explicate that 'climate neutral aviation', in the view of the authors, requires a 'climate neutral air transport system', the definition is adapted to apply to the latter term as follows:

Climate neutral air transport system: "Air transport system of which the climate impact of all its greenhouse gases and other non-carbon dioxide effects throughout the entire life-cycle of each element of the system is balanced"

Besides the broadening to 'air transport system', 'greenhouse gas effects' replaces 'carbon dioxide effects', as other greenhouse gases also play a role during especially non-flight phases. Non-carbon dioxide effects are maintained as a separate element, as these effects do not fit the definition of a greenhouse gas.

Figure 1 presents a graphical version of this definition: all individual boxes are part of the climate impact of the air transport system (across system elements, across life cycle phases, and spanning activities across a given period of time), which should be climate neutral in order to get to a climate neutral air transport system: the climate impact of aviation operations today (darker blue) and the remaining climate impact of aviation operations 15 years ago (lighter blue), but also the climate impact of maintenance activities to airports today (orange), climate impact of production of ATM infrastructure today (green) and climate impact of aircraft assembly activities 5 years ago (yellow) should be considered.

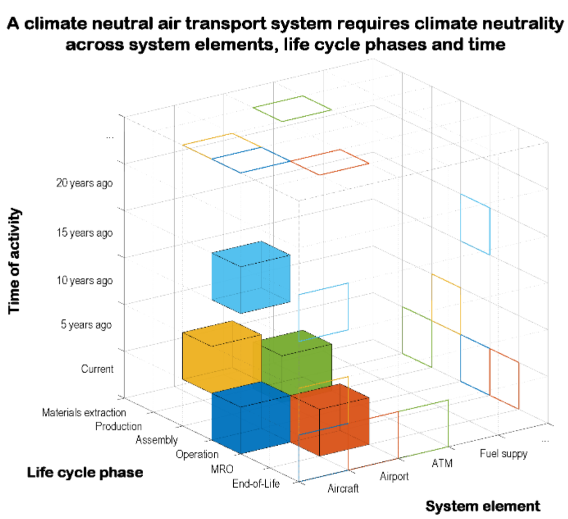

Figure 1. Illustration of air transport system elements addressed in the proposed definition of climate neutral aviation.

 doi:10.20944/preprints202404.1533.v1

It is important to stress that the proposal made by the authors is a definition, and nothing more. The definition itself does not hold any additional information, regarding whether a climate neutral air transport system should even be targeted, or when that should be achieved. Similarly, it also does not specify, for example, what (type of) solutions should be acceptable – or desirable, or preferred – means of balancing climate impact. All those considerations are left open to multiple opinions. The opinions of the authors regarding these aspects are discussed in the next section, which applies the definition to outline a path towards a climate neutral air transport system, and derives corresponding targets.

5. Towards a Climate Neutral Air Transport System

Achieving a climate neutral air transport system as just defined is not straightforward. This section provides perspectives on three necessary steps: first on governance, second on timelines and geographical scope, and third on (quantitative) targets.

3.1. Governance

Individual initiatives cannot solely achieve the climate neutrality target defined: no single actor or stakeholder can. Nevertheless, the overarching vision must be coherent and consistent across all sector partners, such that all can make their contribution towards that vision. Finally, it should be ensured that all these individual contributions indeed add up to jointly realise the overall goal.

As the goal of climate neutrality is already defined, there is the need for a monitoring and steering role – which entity or organisation can indeed take that role is not readily clear. Industrial partners are typically focused on shareholder interests, profitability and shorter-term results. Governments, on the other hand, are at times not involved closely enough with specific topics to set a long-term strategy and develop an associated implementation plan for any sector. Academia is focussed on education and research establishments are also not always sufficiently connected to specific parts of the sector (depending on their specific research focus) and can be heavily influenced by local and national governments. Overall, independent, non-governmental organisations with a research-oriented culture might be most suitable. From the ones discussed in this paper, organisations like ICAO and ACARE[10] come to mind as possible candidates for such a role.

An organisation like ICAO has a substantially larger – global – 'sphere of influence', compared to an organisation corresponding to ACARE, with a more limited (in this case: European) focus. Given the global nature of the air transport system, setting goals at a comparable – global – level should be preferred. On the other hand, local initiatives tend to show more ambition and have been able to push technology development (for example, ACARE by informing Clean Sky and Clean Sky 2 programme targets), whereas a large organisation as ICAO has been adopting a more coordinating role (so in a sense "following" the opinions of the members, rather the setting the direction). Of course, this is also due to the specific mandate and participants of ICAO (a UN entity), compared to ACARE. Furthermore, although a target monitoring role could fit ICAO, setting ambitious climate targets for aviation might be complicated by the fact that one of the aims of ICAO is to "insure the safe and orderly growth of international civil aviation" [40]– two objectives that might not be (always) compatible.

At the global level, the United Nations Framework Convention on Climate Change (UNFCCC) might therefore be better suited for this task. The UNFCCCs Subsidiary Body for Scientific and Technological Advice (SBSTA), for example, is already concerned with emissions from fuel used for international aviation and maintains a working relationship with ICAO [36]. However, as discussions on that topic have been deferred in at least the last eight SBSTA sessions [37–40], as the SBSTA stipulates that emissions from fuels used for international aviation "are not subject to the limitation and reduction commitments of Annex I Parties under the Convention and the Kyoto Protocol" [36],

[10] The European Union Aviation Safety Agency (EASA) or the European Environmental Agency (EEA) could be alternatives, especially for the monitoring role. As this paper mostly aims to start the search for a suitable organisation, EASA and EEA are not further discussed.

 doi:10.20944/preprints202404.1533.v1

and as a more refined understanding of the air transport system seems beneficial, ACARE overall seems the most suitable organisation to set such a more ambitious goal and perform the necessary monitoring role – at least until the time such ambitions can be adopted at global level.

3.2. Timelines and Geographical Scope

Defining what a climate neutral air transport system is helps in target setting, but the latter also requires agreement on timelines and geographical scope. For the former, this paper aligns to the many publications that focus on 2050, in line with the IPCC Special Report on 1.5 °C [26]. Given the international nature of the air transport system, the geographical scope of an associated climate neutrality goal should be global as well. Indeed, this prevents potential waterbed effects (in which climate effects are not reduced, but shifted to other regions) and competitive distortion (e.g. [41]). Given the previously discussed varying ambition levels around the globe, the authors would feel worldwide agreement on such a goal is unlikely to be reached in a short term. As such, again aligning to ACARE, the remainder of this paper considers an initially feasible scope of a climate neutrality goal to be the European air transport system, meaning flights within and departing from European airports, as well as all ground activities related to the operational and all other life cycle phases. Nevertheless, the scope should be increased to a worldwide one as soon as possible.

3.3. From Goal to Targets

In order to measure progress towards achieving a specific goal, more detailed targets are necessary. Furthering the previous section, these targets are developed starting from the year 2050. As a starting point, the quantitative targets from Annex A of FTGD can be used and, for this paper, summarised as follows:

- By 2050, net-zero CO_2 emissions has been achieved for all intra-EU flights and those departing the EU;
- By 2050, new technologies, fuels and operational procedures in service result in:
  - 90% reduction in NO_X emissions and non-volatile particulate matter (nvPM) emissions from all intra-EU flights and those departing the EU relative to the year 2000;
  - 90% reduction in warming contrail cirrus relative to the 2000 baseline[11].

A comparison with Table 2 shows achieving the above does not meet the Gold target, as NO_X and nvPM emissions and warming contrail cirrus are reduced by 90% (rather than neutralised completely), and because non-CO_2 effects from emissions prior to 2050 are not addressed. On the other hand, the Gold definition of climate neutrality talks about 'net' emissions and effects, whereas for these non-CO_2 effects, FTGD targets gross (in-sector) reductions[12]. Recognising that heavy reliance on out-of-sector measures is riskier, potentially more expensive [42] and could be perceived as unfair (e.g. [54]), but also noting that aviation is considered harder (or at least, more costly) to abate [43] and that some out-of-sector (e.g. carbon removal) action is likely unavoidable[13] (e.g. [8]), the following targets are proposed:

1. By 2050, in-sector measures (e.g. new technologies, energy carriers and operational measures) result in a 90% (or larger) reduction in life-cycle greenhouse gas emissions and non-CO_2 climate effects (due to, but not limited to, NO_X and non-volatile particulate matter (nvPM) emissions and contrail cirrus) across the European air transport system, relative to the baseline.

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[11] Annex A does not specify a geographical scope on which target applies.

[12] This example again stresses the need for detailed targets. Requiring neutralisation 'only', applying the Gold pathway described by [35], essentially only specifies that the aviation sector is to pay for neutralisation of its emissions, but fails to address who is responsible for realising the emissions reductions and/or negative emissions required to achieve emissions neutrality.

[13] As far as the authors know, no pathway or roadmap has been published that allows aviation to meet net-zero CO_2 emission by 2050 (let alone more general Paris compatibility) without at least some out-of-sector measures.

 doi:10.20944/preprints202404.1533.v1

2. By 2050, the climate impact of any remaining climate forcing (including life-cycle greenhouse gas emissions (GHG), NO_X and nvPM emissions, and contrail cirrus) from emissions from 2050 onwards is neutralised.
3. By 2050, the remaining climate impact of non-GHG climate forcing (including NO_X and nvPM emissions and contrail cirrus, excluding CO_2 emissions) from emissions prior to 2050 is neutralised.

Compared to FTGD, these targets have been clarified and made consistent by changes in a number of areas:

1. Related to the first target:
    - "Fuels" has been clarified to "energy carriers", to more clearly put battery-electric alternatives in scope, besides drop-in hydrocarbon alternatives (bio-based or synthetic sustainable aviation fuel, compatible with current aircraft, engines and infrastructure) and non-drop-in gaseous or liquid fuels (mainly: zero-aromatic sustainable aviation fuels and green hydrogen).
    - "Operational procedures" has been widened to "operational measures", to prevent misinterpretation that only changes in flight procedures (and not in, for example, weight reduction) are considered to contribute to the target.
    - "New technologies, energy carriers and operational measures" has been maintained as an example, but is replaced by the more generic term "in-sector measures", as there could be other measures within the aviation sector that could contribute to these targets.
    - "Warming contrail cirrus" has been replaced by "contrail cirrus", as the definition of a climate neutral air transport system requires balanced climate impact (different from: no net warming).
    - A "90% reduction" has been changed to a "90% (or larger) reduction" to stimulate further in-sector action.
    - "CO_2" has been broadened to life-cycle greenhouse gas emissions, in line with the definition of a climate neutral air transport system.
    - In-sector reduction targets for GHG, NO_X and nvPM emissions and contrail cirrus have been aligned to 90% (or larger) compared to the baseline in order to ensure in-sector action also in terms of CO_2 reduction.
    - The baseline year 2000 has been removed, as it could be considered to change that to 1990, to better align with Fit for 55 and other targets.
    - "For all intra-EU flights and those departing the EU" has been expanded to "across the European air transport system", consistent with the definition of a climate neutral air transport system (which spans beyond flights) and the (initial) European focus. The European air transport system encompasses all intra-EU flights and those departing the EU.

2. Related to the second target:
    - A target has been added to neutralise any remaining climate effects from aviation activities in or after the target year. If the first targets are just met, meaning that in-sector measure result in 90% lower climate impact, the second target requires neutralisation of the remaining 10%.

3. Related to the third target:
    - A target has been added to neutralise any remaining climate effects from aviation activities prior to the target year, per the Gold definition. Given atmospheric lifetimes of NO_X (some 20 years) and contrails (hours to days), current understanding implies that this target comes down to neutralising the climate impact from NO_X emissions between 2030 and 2050.

From these targets for 2050, intermediate targets can be derived. Based on the 2030 and 2035 targets set in FTGD, these are shown in Table 3. Appendix A elaborates on differences to the FTGD targets.

Table 3. Intermediate targets towards realising a climate neutral air transport system by 2050.

Year	Target

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2025	• Confirm one of the current FTGD baseline years (e.g. 2020), or agree to update it in order to better align with e.g. Fit for 55 (using a 1990 baseline). • Quantify baseline levels for all greenhouse gases, NO_X and nvPM emissions and contrail cirrus, and other non-CO_2 effects across full life cycle for each part of the ATS. • Agree on criteria related to acceptable means of 'neutralising' remaining climate effects. • Explicate the boundaries of "full life cycle".
2028	• Have ready for implementation (i.e., TRL9) mitigation solutions to reduce non-CO_2 climate effects.
2030	• Reduce and neutralise remaining full life-cycle CO_2 emissions of intra-European flights by 55% compared to 1990 levels. • Reduce life-cycle greenhouse gas emissions and non-CO_2 climate effects by 30% across the air transport system, relative to the baseline. • Confirm reduction and neutralisation targets for non-CO_2 climate effects, based on the latest scientific understanding and available mitigation solutions.
2035	• Reduce life-cycle greenhouse gas emissions and non-CO_2 climate effects by 40% across the air transport system, relative to the baseline.
2040	• Reduce and neutralise remaining full life-cycle CO_2 emissions of intra-European flights by 90% compared to 1990 levels. • Reduce life-cycle greenhouse gas emissions and non-CO_2 climate effects by 60% across the air transport system, relative to the baseline.

6. Next Steps

The aforementioned improvements towards clarity of definition and scope, and the proposed quantitative targets should help reach a climate neutral air transport by 2050 and, through that, make sure the aviation ecosystem contributes to limit and mitigate dangerous climate change. Besides implementing these targets, two aspects have to be addressed:

- Global scale up. As recalled earlier in this article, European research, collaboration, and advocacy and policy work have previously played an undeniable role in increased global ambition when it comes to aviation CO_2 emissions targets, also at global level. As an increasing body of research shows [1,35], ambition should expand beyond CO_2 emissions. For example, through ACARE, but also through its separate members (industry parties, institutions and States), a further push should be made to align global targets with the state of the science. This effort should pay attention to distribute global efforts in a fair manner, recognising some regions are responsible for a larger part of historical emissions and associated climate effects than others.
- Stimulate and keep track of progress towards the goals, for example through ACARE or – following global adoption of these targets – ICAO.

7. Conclusions

Achieving climate neutrality in all sectors is the only long-term, viable solution to mitigate global warming and associated dangerous climate change. Aviation should embrace such ambition as well, aiming to achieve a fully climate neutral air transport system. In such a system, all greenhouse gas and non-carbon dioxide effects throughout the entire life-cycle of each element of that system should be balanced. To be compatible with a pathway to 1.5 °C global warming, this should be achieved by 2050. Greenhouse gas and non-CO_2 effects from aviation activities by 2050 should be neutralised from that date, as well as remaining non-CO_2 climate effects from activity prior to 2050. Through increased understanding (of especially non-CO_2 climate effects, by 2028), the development and implementation of mitigation strategies to tackle climate effects (by 2030) and increasing in-sector action to reduce climate effects, a climate neutral air transport system in 2050 could be within reach.

It is recognised that no individual stakeholder can bear responsibility for achieving such a goal, or has the individual influence to realise it. As such, there is a clear need for an organisation to keep track of – and ideally stimulate – progress towards such a goal. Progress should happen 'bottom-up', i.e., reasoning from the (quantified) targets, but also 'top-down', identifying how various initiatives (e.g. Destination 2050, Clean Aviation, AZEA, ZEMA, and others) contribute to the overarching goal and, more importantly, whether leave key topics unaddressed. Given the European policy focus on achieving climate neutrality, that region is considered most likely to adopt the targets proposed here, in which ACARE seems well-positioned to pick up the aforementioned supervising role. Nevertheless, fitting with the global nature of the air transport industry, this goal and associated targets should be adopted globally.

The need for a clearly defined vision with equally clear targets aligned with national strategies and especially with research evidence, is of absolute importance if the aviation sector wants to succeed at eliminating the harmful impact of its activities on the climate and society, without losing its beneficial impacts on society and economies. Only then, stakeholders can truly collaborate in realising what is necessary.

Author Contributions: Conceptualization, Bram Peerlings and Ligeia Paletti; Data curation, Bram Peerlings and Ligeia Paletti; Formal analysis, Bram Peerlings and Ligeia Paletti; Investigation, Bram Peerlings and Ligeia Paletti; Methodology, Bram Peerlings and Ligeia Paletti; Resources, Bram Peerlings and Ligeia Paletti; Validation, Bram Peerlings and Ligeia Paletti; Visualization, Bram Peerlings; Writing – original draft, Bram Peerlings and Ligeia Paletti; Writing – review & editing, Bram Peerlings and Ligeia Paletti. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: While the core of the research presented in this publication had been carried out by Ligeia Paletti while still at NLR Netherlands Aerospace Centre, the author wants to thank its current organisation, DLR German Aerospace Center, and in particular the Institute of Maintenance, Repair and Overhaul, for the support during the finalisation of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The intermediate targets related to "achieving climate neutral air mobility" shown in FTGD (Annex A) are the following:

1. Short-term (< 2030):
    a. By 2030, net CO_2 emissions from all intra-EU flights and those departing the EU are reduced by 55% compared to the 1990 baseline (aligned with Fit for 55).
    b. By 2030, non-CO_2 climate effects are fully understood, managed, monitored and reduction targets are set in line with the latest scientific understanding and available mitigation solutions.
2. Medium-term (< 2035):
    a. By 2035 new technologies, fuels and operational procedures in service result in a 30% reduction in non-CO_2 climate effects of all intra-EU flights and those departing the EU relative to the 1990 baseline.

The intermediate targets proposed in this paper deviate in a number of areas, and for the following reasons:

- The FTGD-target of reducing net emissions from all intra-EU flights and those departing the EU by 55% compared to 1990 by 2030 (1.a) is considered unrealistic, given for example the analysis by [8] and current (especially global) net emissions reduction targets. In [8] it is shown, however, that the target could be realistic for intra-European flights. The intermediate target proposed here is set in line with that.
- The FTGD-target on understanding on non-CO_2 effects (1.b) is replaced by a target in which mitigation strategies should be ready for implementation, as scientific understanding and the development of mitigation strategies occurs in parallel. The FTGD-target in which "reduction targets are set in line with the latest scientific understanding and available mitigation solutions"

is changed to the confirmation of such targets, as these are already proposed (both in FTGD and in this present work).

- The medium-term FTGD-target (2.a) is set to 2030 (rather than "before 2035"), aligning with research on carbon budgets for aviation stipulating the need to act quickly [50], and brought in line with the 2050-targets proposed here. Related, a medium-term reduction target of 40% is set for 2035.
- A 2025 target is added to quantify the relevant baseline values. For nvPM, for example, it is noted that nvPM mass standards were only introduced in 2020 [44], with nvPM mass and number standards following in 2023 [44], such that it might be difficult to establish such a historic baseline. Similarly, NO_x (and also nvPM and previously smoke number) standards, only apply to these emissions during the landing and take-off cycle (LTO-cycle), whereas the baselines should span the entire flight. Given the strong dependency of these emissions on the engine thrust setting, it is uncertain to what extent LTO-values (at or near ground level, per definition) are applicable to cruise flight. Whereas EASA notes [2] (p. 11 and Section 3.4.3) that "cruise NO_x and LTO emissions are generally considered to be related to LTO emission trends", these emissions are not measured at cruise thrust settings. nvPM emissions at cruise conditions are "not well characterized" and work on estimating nvPM emissions during cruise based on LTO-data is still ongoing [2] (Section 3.5.3).
- A 2040 reduction target has been added to span the period between 2035 and 2050, based on the recently announced 2040 climate target [55]. In line with the first item in this list, it is set to apply to intra-European flights only.

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