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Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Gössling, S, Humpe, A and Sun, Y-Y (2024) Are emissions from global air transport significantly underestimated? Current Issues in Tourism, 28 (5). pp. 695-708. ISSN 1368-3500

Current Issues in Tourism

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rcit20

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To cite this article: Stefan Gössling, Andreas Humpe & Ya-Yen Sun (2025) Are emissions from global air transport significantly underestimated?, Current Issues in Tourism, 28:5, 695-708, DOI: 10.1080/13683500.2024.2337281

To link to this article: https://doi.org/10.1080/13683500.2024.2337281

Published online: 08 Apr 2024.

CURRENT ISSUES IN TOURISM
2025, VOL. 28, NO. 5, 695–708
https://doi.org/10.1080/13683500.2024.2337281

Routledge
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Are emissions from global air transport significantly underestimated?

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ABSTRACT

Air transport is energy-intense, and considerable attention has been paid to the sector's use of fuel and emissions of greenhouse gases. Commercial aviation is believed to currently emit about 1 Gt CO_2 per year, if considering global bunker fuel use (scope 1 in the Greenhouse Gas Protocol). A growing database is becoming available on scope 1–3 emissions; this is, including up- and downstream emissions, and it is now possible to assess the aviation system's carbon intensity more comprehensively. This paper investigates the annual reports of 26 of the largest airlines in the world by market capitalisation, finding that reporting on emissions for scopes 1–3 is still inconsistent and characterised by reporting gaps. Yet, available data suggests that scope 3 emissions are significant (about 30% of scope 1 emissions). These findings have repercussions for the sector's net-zero ambitions, climate governance, consumer choices and air transport finance, as the overall contribution from air travel to climate change remains underestimated. Results suggest that it is in the sector's interest to present robust, transparent, consistent and accurate emission inventories – and to engage with the implications.

ARTICLE HISTORY
Received 30 November 2023
Accepted 25 March 2024

KEYWORDS
Aviation; climate change; ESG reporting; EU ETS; scopes 1–3; UN global compact

1. Introduction

Aviation is an energy-intense form of transport that is about to rebound to pre-pandemic levels, with industry expectations of continued growth (Airbus, 2022). Aviation is generally believed to contribute to about 2.5% of emissions of CO_2 (Lee et al., 2021) and to have contributed to an estimated 4% of global warming, including the effects of short-lived non-CO_2 emissions at flight altitude (Klöwer et al., 2021). Emissions will likely continue to grow under business-as-usual scenarios, as revenue passenger kilometre (RPK) growth exceeds decarbonisation rates (Gössling & Humpe, 2024). Yet, some authors have posited that under radical propulsion technology change scenarios, it may be possible to significantly reduce emissions (Dray & Schäfer, 2022). Most assessments remain sceptical, however, that such technology-solution scenarios are plausible (Åkerman et al., 2021; Bergero et al., 2023; Brazzola et al., 2022; Sharmina et al., 2021), as political, societal, technological and economic barriers persist (Gössling & Humpe, 2024).

The challenge for aviation can be illustrated on the basis of remaining carbon budgets, i.e. the amounts of greenhouse gases that can be emitted before critical temperature thresholds are

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exceeded. According to the IPCC, remaining carbon budgets for limiting global warming to 1.5°C, 1.7°C and 2.0°C are approximately 400 Gt CO_2, 700 Gt CO_2 and 1150 Gt CO_2 (67% chance; IPCC et al., 2021, p. 29). Under the assumption that all economic sectors have to reduce emissions to net-zero by mid-century, and that the remaining carbon budget is distributed equally between sectors, a share can be allocated to aviation. On the basis of current contributions to CO_2 emissions of 2.5%, this would be 10 Gt CO_2 for a 1.5°C warming objective, and 28.75 Gt CO_2 for a 2.0°C scenario.

Assessments of global aviation fuel use and emissions are somewhat inconsistent. The International Energy Agency (IEA, 2019) quantified total aviation fuel demand at 310.56 Mt in 2017, about 60.4% of this for international aviation and 39.6% for domestic aviation Lee et al. (2021). Total aviation emissions have been estimated to be 1034 Mt CO_2 in 2018 (IEA, 2023). This suggests that in 2018, global aviation burned approximately 320 Mt of fuel and emitting one Gt CO_2, of which 88% are related to commercial aviation, 8% on military and 4% private; with further distinction of commercial aviation, where emissions can be divided into passenger (81%) and freight (19%) shares (Gössling & Humpe, 2020). Should emissions continue to grow at observed rates, with evidence that the sector is not on track to net-zero (IEA, 2023), it is likely that aviation will deplete its remaining carbon budget before mid-century. The IEA (2023) also highlights that efficiency improvements show signs of slowing down. Growth, on the other hand, is expected to continue. For example, IATA (2021) projects that emissions will double between 2020 and 2050. Offsets are considered a solution (ICAO, 2016), with IATA (2021) expecting to 'abate' 21.2 Gt CO_2 between 2020 and 2050. The scale of compensation needed according to industry's expectations is thus considerable and can be discussed against growing evidence of failure (Pan et al., 2022; see also The New Yorker, 2023).

This challenge is the starting point for this paper, also because scenario studies have concluded that aviation can significantly reduce *lifecycle* CO_2 emissions (Dray & Schäfer, 2022). Yet, so far, there exist no assessments of lifecycle emissions, as often-cited assessments of air transport emissions (Lee et al., 2021) refer to scope 1 emissions, i.e. the direct energy use by airlines. For example, IEA (2023) suggests that in 2019, the sector emitted 619 Mt CO_2 (international aviation) and 417 Mt CO_2 (domestic aviation) in *direct* CO_2 emissions from fossil jet kerosene combustion. This excludes emissions related to scopes 2 and 3 of the greenhouse gas protocol. The purpose of this paper is to provide a preliminary assessment of the 'gap' between scope 1 and scopes 2 and 3 that is currently absent from the discussions of aviation's contribution to global warming.

2. Method

The international reporting standard for firms is the GHG Protocol Corporate Standard (GHG Protocol, 2023), which consists of three scopes. As outlined by the GHG Protocol (2023), 'Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions'.

Scope 3 emissions consequently differ from product lifecycle emissions in that scope 3 assessments have been developed for companies, here airlines. The GHG Protocol underscores that most large companies currently report emissions on direct emissions from operations (scopes 1 and 2), i.e. excluding the value chain that often is responsible for the largest contributions to climate change. While the inclusion of scope 3 emission in company GHG assessments is voluntary – and not considered a responsibility of the company – these emissions have relevance for the carbon-intensity of consumption.

Scope 3 emissions comprise 15 categories (Table 1). As highlighted by Bloomberg (2023: no page), a provider of business and financial information, scope 3 emissions may account for 70% of 'the average corporate value chain's total emissions', but only 20% of 15,000 companies tracked by Bloomberg reported scope 3 emissions for the 2020 fiscal year. As underscored by

Table 1. Scope 3 categories.

1. Purchased goods and services
2. Capital goods
3. Fuel- and energy-related activities
4. Upstream transportation and distribution
5. Waste generated in operations
6. Business travel
7. Employee commuting
8. Upstream leased assets
9. Downstream transportation and distribution
10. Processing of sold products
11. Use of sold products
12. End-of-life treatment of sold products
13. Downstream leased assets
14. Franchises
15. Investments

Bloomberg, this is a considerable data gap, and 'a problem for financial market participants who require scope 3 emissions data to allocate capital in line with decarbonisation targets'.

Given the significance of emission data for firm value assessments, as well as potential implications for climate change governance, this paper seeks to advance the issue by evaluating the data provided by the world's 26 largest airlines included in the Bloomberg World Airline Index (by market capitalisation). Data in this paper is sourced directly from airlines' annual reports, as far as these provide information: out of 26 airlines, 23 have published scope 1 and 2 emissions data, and 18 scope 3 data (at least once in the period 2019–2022; Table 2). Only ten have reported scope 3 consistently over the entire period, however. This means that scope 3 data is available for 69% of the largest airlines in the world by market capitalisation, for at least 1 year in the years 2019–2022. Globally, the share of airlines not reporting scope 1, 2 or 3 is likely larger, as stock exchange listing should be a motivator for data accounting. The analysis includes 23 airlines

Table 2. Largest airlines* reporting on scopes 1, 2 or 3 in the period 2019–2022.

		Scope 1	Scope 2	Scope 3
1	Air Canada	x	x	x
2	Air China Ltd	x	x	
3	Air France-KLM	x	x	x
4	Alaska Air Group Inc.	x	x	x
5	American Airlines Group Inc.	x	x	x
6	ANA Holdings Inc.	x	x	x
7	Cathay Pacific Airways Ltd	x	x	x
8	China Eastern Airlines Corp Ltd	x	x	
9	China Southern Airlines Co Ltd	x	x	
10	Delta Air Lines Inc.	x	x	x
11	Deutsche Lufthansa AG	x	x	x
12	easyJet PLC	x	x	x
13	Eva Airways Corp	x	x	x
14	Hainan Airlines Holding Co Ltd			
15	InterGlobe Aviation Ltd	x	x	
16	International Consolidated Airlines Group SA	x	x	x
17	Japan Airlines Co Ltd	x	x	x
18	Juneyao Airlines Co Ltd			
19	Korean Air Lines Co Ltd	x	x	x
20	Latam Airlines Group SA	x	x	x
21	Qantas Airways Ltd	x	x	x
22	Ryanair Holdings PLC	x	x	x
23	Singapore Airlines Ltd	x	x	
24	Southwest Airlines Co	x	x	x
25	Spring Airlines Co Ltd			
26	United Airlines Holdings Inc.	x	x	x

* According to Bloomberg World Airline Index, reporting for at least one year in the period.

publishing data on scopes 1 and 2, as well as further evaluation of 18 airlines providing scope 3 data *for at least one year*. It is noted that Bloomberg provides emissions data for Hainan Airlines Holding Co Ltd and Juneyao Airlines Co Ltd. These reports are only available in Chinese, however, and could not be evaluated. It also needs to be noted that the accuracy of the data provided by airlines could not be independently assessed.

3. Results

Data for the 26 airlines shows that reporting is inconsistent on different levels: Not all airlines provide data on scope 1 and 2, and fewer on scope 3. No data is published by Spring Airlines. Only ten airlines provide data throughout 2019–2022, and for all three scopes, including Air France-KLM (Netherlands), Delta Air Lines (USA), Deutsche Lufthansa (Germany), easyJet (UK), International Consolidated Airlines, Korean Airlines (South Korea), Latam Airlines Group, Quantas (Australia), Southwest Airlines (USA) and United Airlines Holdings (USA). Data confirms that reporting is most common in the USA, which is also the home of three of the world's largest airlines. There is also evidence that reporting has become more common over time, specifically as data for 2022 may not as yet have been published by several airlines.

For the 21 airlines reporting for 2019, i.e. the last 'normal' year before the COVID pandemic, emission data shows that scope 1 emissions were in the order of 418 Mt CO_2, corresponding to 40.3% of the total of 1036 Mt CO_2 emitted by airlines globally in direct emissions (national and international flights) according to IEA (2023). This confirms the leading role of the 21 airlines in global operations. In total, the International Air Transport Association counts some 300 airline members (IATA, 2023). Scope 2 emissions, reported by 20 airlines for 2019, add a comparably small amount to scope 1, just 1.8 Mt CO_2 or 0.4% of scope 1 of these airlines. This suggests that scope 2 emissions – from the generation of purchased energy – are very small in comparison to direct energy use.

Scope 3 emissions are available for 15 airlines in 2019. These amounted to 79.7 Mt CO_2, which can be compared to 314.2 Mt CO_2 in scope 1 and 1.4 Mt CO_2 in scope 2 emissions caused by the 15 airlines. This suggests that for the sample of airlines, scope 2 is small, but scope 3 emissions amount to 25.3% of scope 1 and 2 emissions (Table 3). It also implies that according to GHG Protocol accountability principles, the 15 airlines are responsible for 315.6 Mt CO_2 (scopes 1, 2), while the system-wide emissions caused by their activities amount to 395.3 Mt CO_2 (scope 1–3).

However, further analysis indicates that this likely represents an underestimate of 'true' scope 3 emissions (Table 3, see highlighted data). Data for the 15 airlines providing data for 2019 shows that scope 3 emissions are between 1.79% (Latam Airlines) and 38.55% (American Airlines Group) of scope 1 and 2 emissions. Such a large range is difficult to explain, as airlines would be expected to account for similar 'additional' emissions for specific scopes, such as the production of fuels. To explain the range, scope 3 emissions are evaluated in more detail.

Detailed scope 3 data is available for nine airlines (Table 4). The analysis confirms that none of the airlines reports data for all 15 categories, though improvements in reporting trends are evident. For example, Cathay Pacific and easyJet have started to report detailed scope 3 emissions in 2022, and other airlines, such as Delta, Southwest and United, have reported data for a greater number of categories in 2022. Data, however, also reveals that reporting is inconsistent, as for example employee commuting is not reported by Cathay Pacific or Delta. While it is possible that airlines do not cause emissions in some of the categories, it is evident that all of them have employees commuting to work; all of them are also likely to generate waste. This suggests that scope 3 emissions are currently underreported. Further inconsistencies arise out of the significant differences found in some categories. For example, American Airlines (AA) reports that upstream transportation and distribution is 29.2% of scope 3 emissions, but it is close to zero for ANA, IAG, Japan Airlines and Southwest. It is currently unclear how these discrepancies can be explained. American Airlines appears to consider passengers transported by contracted regional carriers as AA passengers, while emissions caused by contracted regional carriers are listed as scope 3 emissions. This has repercussions for double

Table 3. Scope 1–3 emissions in Mt CO2e for 2022.

	Scope 1				Scope 2				Scope 3				% Scope 3 of Scope 1 + 2			
Airlines	2019	2020	2021	2022	2019	2020	2021	2022	2019	2020	2021	2022	2019	2020	2021	2022
Air Canada	13.205	5.034	4.913		0.011	0.010	0.007		1.612	0.575	0.572		12.19%	11.40%	11.63%	
Air China Ltd		14.850	15.218	9.823		0.190	0.224	0.229								
Air France-KLM	28.289	14.048	16.339	22.620	0.008	0.007	0.018	0.018	5.907	3.034	4.146	5.746	20.88%	21.59%	25.35%	25.38%
Alaska Air Group Inc.	7.951	4.145	5.935		0.036	0.035	0.036		0.634	0.411	0.534		7.94%	9.83%	8.94%	
American Airlines Group Inc.	41.143	19.831	28.810		0.274	0.250	0.249		15.968	9.674	12.907		38.55%	48.17%	44.42%	
ANA Holdings Inc.	12.373	5.414	7.699		0.084	0.070	0.066		4.364	1.749	1.993		35.03%	31.89%	25.67%	
Cathay Pacific Airways Ltd	18.430	7.535	6.021	5.350	0.070	0.054	0.039	0.040				5.205				96.56%
China Eastern Airlines Corp Ltd	22.623	13.843	15.736	9.824	0.124	0.107	0.135	0.119								
China Southern Airlines Co Ltd	28.360	19.318	19.109	14.328	0.167	0.147	0.135	0.172								
Delta Air Lines Inc.	37.328	17.175	24.561	30.741	0.296	0.274	0.246	0.203	12.893	5.936	8.561	12.302	34.27%	34.02%	34.51%	39.76%
Deutsche Lufthansa AG	33.349	11.510	13.823	23.210	0.200	0.135	0.139	0.125	10.589	3.492	4.668	8.955	31.56%	29.99%	33.43%	38.38%
easyJet PLC	8.325	4.247	2.115	6.421	0.001	0.001	0.001	0.000	2.112	1.146	0.585	1.661	25.37%	26.97%	27.67%	25.86%
Eva Airways Corp	6.116	4.311	4.127	4.490	0.014	0.013	0.012	0.012		0.006	0.008	0.007		0.14%	0.18%	0.15%
Hainan Airlines Holding Co Ltd																
InterGlobe Aviation Ltd			2.940	3.114			0.003	0.003								
Intern. Consol. Airlines Group	30.740	11.020	10.920	21.150	0.020	0.009	0.008	0.012	8.270	3.660	3.320	5.480	26.89%	33.18%	30.38%	25.90%
Japan Airlines Co Ltd	9.121	4.421	6.214		0.057	0.051	0.053		1.403	1.046	1.535		15.28%	23.39%	24.49%	
Juneyao Airlines Co Ltd																
Korean Air Lines Co Ltd	13.336	7.627	7.504	8.631	0.065	0.049	0.041	0.043	2.844	1.623	1.700	1.975	21.22%	21.15%	22.53%	22.77%
Latam Airlines Group SA	12.150	5.614	6.498	9.780	0.018	0.016	0.015	0.007	0.218	0.025	0.002	3.198	1.79%	0.44%	0.04%	32.68%
Qantas Airways Ltd	12.373	9.341	3.237	4.734	0.121	0.084	0.065	0.065	1.212	0.882	0.218	0.460	9.70%	9.36%	6.61%	9.58%
Ryanair Holdings PLC	11.800	12.700	2.900	9.193				0.004				2.076				22.57%
Singapore Airlines Ltd	16.488	16.301	3.958	7.797	0.012	0.012	0.008	0.009								
Southwest Airlines Co	20.144	12.364	16.178	18.627	0.045	0.038	0.035	0.030	4.206	2.604	3.399	5.610	20.83%	21.00%	20.96%	30.07%
Spring Airlines Co Ltd																
United Airlines Holdings Inc.	34.414	15.490	21.370	30.401	0.190	0.175	0.161	0.139	7.471	4.280	5.562	13.108	21.59%	27.32%	25.83%	42.92%

Source: Airlines' annual reports.

Table 4. Scope 3 emissions in thousand metric tons CO2 for airlines, 2019.

	American Airlines				ANA				Cathay Pacific			
Scope 3 category	2019	2020	2021	2022	2019	2020	2021	2022	2019	2020	2021	2022
1. Purchased goods and services	2640.0	1905.0	2031.0		986.6	624.9	548.8					312.3
2. Capital goods	271.0	289.0	296.0		788.6	361.3	327.2					312.3
3. Fuel and energy related activities	12,348.0	6802.0	6074.0		1664.1	734.2	1038.1					1145.1
4. Upstream transp. & distribution			3771.0		1.7	0.6	0.7					156.2
5. Waste generated in operations	2.0	2.0	2.0		30.8	17.5	13.6					
6. Business travel	122.0	58.0	75.0		1.6	0.3	0.4					
7. Employee commuting	227.0	223.0	210.0		9.4	9.9	8.9					
8. Upstream leased assets	3.0	52.0	42.0									
9. Downstream transp. & distribut.	23.0	11.0	14.0									
10. Processing of sold products												
11. Use of sold products					881.7	0.0	0.0					
12. End-of-life treatm. of products												
13. Downstream leased assets							55.6					
14. Franchises												
15. Investments	332.0	332.0	392.0									3279.2
Total	15,968.0	9674.0	12,907.0		4364.5	1748.7	1993.3					5205.0
	Delta Airlines				**easyJet**				**IAG**			
	2019	**2020**	**2021**	**2022**	**2019**	**2020**	**2021**	**2022**	**2019**	**2020**	**2021**	**2022**
1. Purchased goods and services				1514.5				282.2	0.7	0.5	0.2	0.3
2. Capital goods				1395.4				47.6	568.0	912.0	424.0	232.0
3. Fuel and energy related activities	12,893.3	5936.0	8561.1	8453.7				1319.8	6371.6	2285.0	2266.6	4385.3
4. Upstream transp. & distribution				938.8				0.2				
5. Waste generated in operations								0.0	3.7	2.9	2.2	2.8
6. Business travel								0.7				
7. Employee commuting								5.7	17.5	5.7	5.5	7.3
8. Upstream leased assets												
9. Downstream transp. & distribut.									248.6	157.6	174.7	165.0
10. Processing of sold products												
11. Use of sold products								1.3	244.5	59.1	65.4	152.3
12. End-of-life treatm. of products								0.1				
13. Downstream leased assets									0.0	0.0	14.0	52.9
14. Franchises									810.3	235.2	369.7	475.6
15. Investments								2.9	0.0			
Total	12,893.3	5936.0	8561.1	12,302.2				1660.5	8264.9	3657.9	3322.4	5473.4
Others									0.3	2.6	1.8	7.3
	Japan Airlines				**Southwest Airlines**				**United Airlines**			
	2019	**2020**	**2021**	**2022**	**2019**	**2020**	**2021**	**2022**	**2019**	**2020**	**2021**	**2022**
1. Purchased goods and services	215.0	166.0	198.0					1,496.4				
2. Capital goods	721.0	264.0	481.0					198.0				

3. Fuel and energy related activities	455.0	603.0	842.0		4052.4	2484.6	3254.8	3751.3				7015.1
4. Upstream transp. & distribution									7050.5	4067.1	5310.2	5587.2
5. Waste generated in operations	1.0	0.8	1.3		2.2	1.5	1.6	1.6				
6. Business travel	4.6	4.7	4.6									
7. Employee commuting	6.1	7.7	7.7		151.4	118.3	142.2	162.8	176.2	81.0	52.3	111.1
8. Upstream leased assets												
9. Downstream transp. & distribut.												
10. Processing of sold products												
11. Use of sold products												
12. End-of-life treatm. of products												
13. Downstream leased assets												
14. Franchises												163.9
15. Investments									244.6	132.2	199.3	231.1
Total	1402.7	1046.2	1534.6		4206.0	2604.3	3398.6	5610.0	7471.3	4280.3	5561.7	13,108.4

counting (a share of AA scope 3 emissions represents scope 1 emissions of the contracted airlines), as well as performance indicators, as the efficiency of AA (per passenger or revenue passenger kilometre) improves. Findings such as these confirm that it is necessary to further investigate the implications of contracted carriers for scopes 1–3 reporting by major airlines.

Fuel and energy related activities are the only category for which data has been reported by all airlines for at least one of the years in 2019–2022. This is also the most relevant of the 15 categories, responsible for an average 68.2% of all emissions reported by airlines under scope 3. The share needs to be treated with caution, however, as it is affected by underreporting in other categories, and will decline when this data becomes available. The analysis of scope 3 data also suggests that for the nine airlines providing more detailed data, scope 3 emissions are one third (32.9%) of scopes 1 and 2. This supports a view that scope 3 is likely higher than the 25.3% determined for all airlines reporting scope 3 emissions (Table 3).

4. Discussion

The preliminary conclusion is that scope 1–3 emissions from air transport are one-third higher than scope 1 assessments suggest. These research findings need to be confirmed for the entire sector, which is currently impossible due to the lack of data and the inconsistencies in reporting. Bloomberg (2023: no page) critically remarks, for example, that:

> Bloomberg's data teams have observed many such inconsistencies due to changes in accounting methodology or reporting scope year to year. This could be due to a lack of mandatory reporting requirements which would otherwise clearly define how to measure and report Scope 3 emissions. To overcome these irregularities, many firms turn to estimates, though not all estimates are created equal.

As the quote reveals and this research confirms, only a few airlines currently report emissions consistently for all three scopes. For those reporting scope 3 emissions, there are considerable gaps in the data, as well as inconsistencies. For example, while Southwestern Airlines reports emissions from waste generated in operations, this data is not available for United Airlines and Delta Airlines, even though it can be assumed that all airlines generate waste. Both Delta and Southwestern report on emissions related to purchased goods and services as well as capital goods, but this data is missing for United Airlines. United reports on employee commuting, as does Southwestern, but this data is not provided by Delta. It is unclear how data gaps can be explained, though Bloomberg (2023) underlines that strategic underreporting appears to be common.

Bearing in mind these inconsistencies, data evaluated in this paper posits that the energy-intensity of aviation as well as the sector's overall contribution to climate change is not fully accounted for. Considering scope 3 emissions, the evidence is that the air transport system requires significantly more energy than current assessments focused on scope 1 suggest. Data provided by airlines included in the analysis is inconsistent, as not all scope 3 categories are reported upon, and up- and downstream emissions may even be higher. Even though further refinement in assessments is needed, various implications seem evident that are further discussed in subsequent sections:

1. The aviation system is responsible for a higher total contribution to climate change than currently assumed, with repercussions for net-zero goals.
2. Emissions associated with a flight are considerably higher than carbon calculators provided by airlines suggest. This might directly and indirectly affect air travellers.
3. Climate governance and aviation finance are confronted with a scenario where the sector's total impact on climate change, as well as its energy intensity per revenue passenger kilometre, prove to be substantially higher than presently assumed.

Net-zero goals. There is much evidence that the aviation sector will have difficulties to reach net-zero goals by mid-century through technology innovation and new fuels (Bergero et al., 2023).

Current assessments of the scale of the fuel transition consider about 350 Mt of fuel per year, though this research suggests that the *aviation system* requires considerably larger energy-inputs. Technically, the sector may not be responsible for the emissions associated with the energy use in the value-chain, such as the oil and gas extracting sectors; it is nevertheless clear that air transport depends on these value chain inputs. The challenge is thus to decarbonise the wider economy that caters to air transport.

Findings also need to be considered in light of the aviation sector's 'aspirational' net-zero goals. A recent press release from the International Civil Aviation Organization (ICAO, 2023, no page) states that: 'Culminating 2 weeks of intensive diplomacy by over 2500 delegates from 184 States and 57 organisations at the 41st ICAO Assembly, ICAO Member States adopted a collective long-term global aspirational goal (LTAG) of net-zero carbon emissions by 2050'. In light of the findings presented in this paper, how is this goal defined – does it include scope 2 and 3 emissions, i.e. the *system* of aviation? And, more importantly, given that there is no consistent, transparent reporting on scope 1 (as well as scopes 2 and 3) emissions, how will ICAO monitor progress on its ambitions?

In the context of net-zero, there are also notable implications for the adoption of sustainable aviation fuels (SAF). SAF can reduce emissions from air transport significantly, provided they are produced sustainably (Dray et al., 2022). Airlines will wish to account for the difference in 'net' emissions, with implications for reporting: SAF, including synthetic (e-)fuels emit as much CO_2 as fossil fuels; it is their production that has removed an equivalent amount of CO_2 from the atmosphere. As fuel burn may be counted as scope 1, while production is scope 3, the difference may not be accounted for by airlines. This also has implications for CORSIA, a scheme that seeks to measure 'avoided emissions' from forest projects against scope 1 emissions; a strategy that is potentially incompatible with the SBTi requirement of reducing scope 1 against the 1.5°C goal, and scope 3

Table 5. Airlines setting science-based targets*.

Airline	Near-term	Net-zero
Air France – KLM Group.	Well below 2°C	–
Air New Zealand.	Well below 2°C	–
American Airlines	Well below 2°C	–
ANA Holdings Inc.	Well below 2°C	–
Azul SA	Committed	Committed
Braathens Regional Airlines AB	Committed	Committed
Cargojet Zirways Ltd.	Committed	Committed
China Airlines	Committed	Committed
Delta Air Lines	Well below 2°C	Committed
easyJet plc	Well below 2°C	Committed
Eva Airways Corporation	Committed	Committed
Finnair plc	Committed	–
GOL S.A.	Committed	–
IBERIA S.A.	Committed	Committed
International Consolidated Airlines	Committed	Committed
Japan Airlines	Committed	Committed
JetBlue Airways	Well below 2°C	–
LATAM Airlines Group S.A.	Commitment removed	–
Lufthansa Group	Well below 2°C	Committed
Rytanair Holdings plc	Committed	–
Scandinavian Airlines System	Committed	Committed
TUI Group	Well below 2°C	–
United Airlines, Inc.	Well below 2°C	Committed
Wizz Air Holdings plc	Committed	–

Source: SBTi (2023).

*The Science-Based Targets Initiative states that: 'For all transport-related emissions across all sectors, companies shall report these emissions on a well-to-wheel (WTW) basis in their GHG inventory (well-to-wake for aviation)'. For aviation this is the sum of both scope 1 emissions from jet fuel combustion and scope 3 category 3 'fuel- and energy-related activities' emissions from upstream production and distribution of jet fuel (SBTi, 2023:52). Mitigation progress on scope 1&2 and scope 3 is also differentiated, as absolute reduction targets for scope 1 and 2 refer to the 1.5°C goal and for scope 3 to 2.0°C.

against the 2°C goal, and the notable implication that cross-compensation is not allowed under the SBTi (see note in connection to Table 5). These complexities deserve further consideration.

Climate governance. Reaching net-zero goals will likely require governance at the national level (Lyle, 2018). A growing number of countries – including Denmark, France, New Zealand, Norway, Sweden, the United Kingdom – have indicated that they will include emissions from international aviation in their NDCs (IPCC, 2022). The European Union has pledged to cut emissions by 55% by 2030, compared to 1990 levels, and for this reason implemented, for intra-European Union flights, a blending obligation for advanced biofuels and synthetic fuels at 5% by 2030 and 63% by 2050 (European Parliament, 2023). As has been outlined, it is unclear whether these regulatory policies can be translated into practice, given that synthetic fuels are not currently produced anywhere at scale, though ICAOs (2023) SAF tracker lists e-fuel production sites as 'in service' that are not (as an example, Werlte, Germany, is listed with a production capacity of 0.46 million litres per year, but the site is not operational as of January 2024). Even if a 5% biofuel quota was implemented in 2030, it would be inadequate to compensate expected fuel growth rates of about 4% per year, let alone lead to a decline in the sector's overall emissions (Gössling and Humpe, 2024).

This situation is further complicated by the findings presented in this paper. While up- and downstream emissions can be partially addressed through climate change policies such as carbon taxes, electrification and other measures, the challenge increases throughout the supply chain. As scope 3 emissions are insufficiently understood, it is premature to discuss adequate policy designs and industry action. A central insight is, however, that consistent scope 1–3 data is needed to understand air transport's emission intensities and total contributions to climate change, and to reduce the sector's contribution to climate change accordingly. ICAO, as the umbrella organisation for civil aviation, may act as a clearing house for collecting airline emission data.

Consumer choices and tourism. Tourists are increasingly aware of the carbon-intensity of air transport (Alcock et al., 2017; Higham et al., 2016; Kantenbacher et al., 2017). For others, the comparison of the carbon-intensity of air transport with other forms of consumption, other transport modes, as well as between airlines have gained importance, as travellers seek to make greener choices (Baumeister et al., 2022). As an example, Google Flights is a tool comparing airline emissions on specific routes, offering travellers an opportunity to choose the airline with the lowest carbon impact (www.google.com/travel/flights). Travellers may also use tools such as carbon calculators to compare air transport with other transport modes, potentially affecting choices in favour of slower but less carbon-intense forms of transport where this is feasible. The research presented in this paper has implications for these comparisons, as scope 3 data inclusion is likely to affect relationships significantly, with concomitant implications for travel decisions.

Even more relevant are implications of price hikes, for example because of carbon taxes. Under scenarios including scope 3 emissions in the taxation of air transport, fares would increase significantly if the cost of carbon is passed on to customers. This should affect air transport demand. For example, Falk and Hagsten (2019) found that the introduction of a departure tax in Germany and Austria led to a decline in passenger numbers by 9% in the year of introduction and 5% in the following year. Notably, the tax primarily affected airports served by low-cost airlines, indicating that much air transport demand is induced. It can thus be anticipated that the introduction of taxes internalising the cost of CO_2 for scopes 1–3 would cause a share of low-cost leisure travel to disappear. This will depend on the tax level, as current taxation is far below the cost of CO_2 (Tol, 2023), but adding scope 3 emissions – if costs are passed through fully to customers – may increase the tax-related cost of air transport and thus have concomitant consequences for demand.

Air transport finance. Disclosure of environmental, social and governance (ESG) information is valuable for investors seeking to understand a firm's weaknesses and strengths. Many firms regularly and voluntarily report on their contributions to climate change, with evidence that ESG disclosure increases the value of firms with ESG strengths (Fatemi et al., 2018), as well as their financial efficiency (Abdi et al., 2022). Climate change performance is measured in emissions, or, indirectly, in energy use, as well as on the basis of indicators such as emissions per unit of value generation.

Data is submitted on the basis of guidelines and frameworks, provided for example by the Global Reporting Initiative or the International Integrated Reporting Council, to ensure consistent assessments. While Fatemi et al. (2018: 46) critically note that reporting 'may be a mere façade' and that some firms might 'understate ESG activities for fear of alienating investors', it is evident that reporting has become increasingly more common. As highlighted by accountants such as PriceWaterhouseCoopers, sustainability reports or statements are expected by 'investors and other stakeholders calling on companies to disclose more about their sustainability', as they 'enable the company to be more transparent about the risks and opportunities it faces. It is a communication tool that plays an important role in convincing sceptical observers that the company's actions are sincere' (PWC, 2023, no page).

This reflect on reasons for voluntary reporting, but there is also growing regulatory pressure on companies to disclose emissions. For example, in the European Union, the Industrial Emissions Directive has forced 52,000 installations to obtain permits, which are based on assessments of emissions to air, water and land, generation of waste, use of raw materials, energy efficiency and noise since 2010 (EC, 2023a). The EU Emissions Trading Scheme (EU ETS) covers and limits emissions from more than 10,000 installations in the energy sector and manufacturing industry. The EU ETS also includes aircraft operating between EU countries plus Iceland, Liechtenstein and Norway, as well as departures to Switzerland and the United Kingdom (EC, 2023b). The system was established in 2003 through a Directive of the European Parliament and requires airlines to provide 'robust, transparent, consistent and accurate' emission inventories (EC, 2023b: no page). For this, airlines have to engage in an annual monitoring, reporting and verification process known as the ETS compliance cycle.

Under the EU ETS, emissions entail a cost, as emission allowances are reduced year-on-year and operators must surrender allowances for emissions exceeding permits. In the future, airlines will also have to purchase SAF quotas under the EU's ReFuel programme (European Parliament, 2023). Disclosure thus has direct relevance for the operational cost of airlines in the EU. In the USA, the Securities and Exchange Commission has the mission to protect investors and sets rules for climate-related disclosures (SEC, 2022). Even here, disclosure is a regulatory process forcing airlines to report on emissions. Reasons for disclosure are consequently diverse, including investments and capitalisation, as well as regulation that is also associated with cost; all of these affect firm value. Currently, this disclosure is focused on scope 1 emissions, though as findings in this paper suggest, the *aviation system's* emissions, based on inclusion of scope 3, are much larger. As air transport is depending on value chain inputs, scope 3 emissions should have indirect relevance for firm value, and for this reason be disclosed.

There is a general consensus that sustainability disclosure has positive implications for the financial performance and efficiency or airlines (Abdi et al., 2022), and many airlines voluntarily provide public data. For example, the UN Global Compact was launched in 2000 as a disclosure mechanism and is linked to the Science-based Targets Initiative, a platform for companies and financial institutions that have committed to ambitious emission reductions (SBTi). The Initiative includes 24 airlines, several of them discussed in this paper. Of interest is that of the 24 airlines, 13 are 'committed', 10 seek to reduce emissions to 'well below 2°C', while one airline as abandoned an earlier commitment (LATAM Airlines Group S.A.; see also Table 5). To 'commit' implies that a company has indicated that it 'will work to set a science-based emission reduction target aligned with the SBTi's target-setting criteria' (SBTi, 2022: 2), i.e. a 'commitment' is not per se an indicator of progress. Only 13 airlines have committed to net-zero goals. This, however, is likely to be financially meaningful, as Msiska et al. (2021) find that after joining the UN Global Compact, companies experience a more positive portfolio performance.

Overall, results show that while scope 1–3 assessments are not as yet a standard for airlines, there is a tendency for a growing number of airlines to develop data on a voluntarily basis or for regulatory reasons. This is meaningful for financial and efficiency reasons, as it increases the value of airlines. However, the analysis of scope 3 emissions reveals that the sector's emissions are significantly larger than currently believed. The implications for net-zero goals, climate governance, and consumers remain insufficiently understood, and require immediate attention, as the sector is on track to resume its pre-COVID growth. Specifically, there is a role for ICAO to streamline and widen scope 1–3 assessments to include a greater number of airlines, and to provide consistent data for the sector in transparent ways.

5. Conclusion

Decarbonising air transport is difficult under scenarios of continued growth (Gössling et al., 2024; Gössling and Humpe, 2024). The expectation is that global demand will double or triple between 2019 and 2050, with corresponding growth in the sector's energy requirements. To provide this energy in sustainable, carbon neutral ways, is a considerable challenge. Calculations of aviation's current and future fuel use have centered on bunker fuels (scope 1), though this research suggests that significant additional emissions characterise the supply chain, making the system of air transport far more emission intense than currently thought. Even though data availability is limited, the evidence is that aviation consumes significantly larger amounts of fossil fuels than evident from accounts of bunker fuel use. Data from a sample of large airlines analysed in this paper suggests that this share may be as high as one third of scope 1 emissions. This means that air transport is much more energy and emission-intense than currently understood. While airlines are only responsible for scope 1–2 emissions, findings nevertheless have relevance for decarbonisation, as they potentially influence air traveller decision-making, climate governance, as well as air transport finances.

To reliably measure emissions for the entire sector, it is necessary to find consistent approaches to reporting. Many airlines do not report emissions at all, while others report inconsistently (between years or for scopes). There is a small risk of double-counting for contracted services. A central conclusion is that a global initiative is needed, possibly by ICAO, to introduce a common reporting standard for all airlines. Without such a standard, it is unclear how ICAO intends to measure progress on its 'aspirational' net-zero goals. Further research is needed to analyse inconsistencies in the data, and to determine whether there are deliberate patterns of underreporting. Annual reports from a larger sample of airlines may be evaluated for this purpose. Irrespective of these weaknesses, policy makers and airlines should begin to immediately investigate the implications of these findings.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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