Transportation Research Part A 186 (2024) 104121

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Pathways toward sustainable aviation: Analyzing emissions from air operations in Europe to support policy initiatives

Nicolò Avogadro [*], Renato Redondi

Department of Management, Information and Production Engineering, University of Bergamo, Italy

ARTICLE INFO

Keywords:
Policy initiatives
GHG emissions
Sustainable aviation
Ground operations
Net-zero aviation

ABSTRACT

Reducing aviation emissions has become a global priority, leading policymakers and industry stakeholders to commit to the achievement of net-zero carbon emissions. Reaching this ambitious goal requires quickly devising and promoting effective policies and measures. Emission levels are heavily influenced by the technological and operational efficiency of airlines and airports. Accordingly, understanding the main patterns underlying aviation emissions is fundamental for evaluating aviation efficiency, ultimately informing the adoption of appropriate policy interventions. In this context, the present study assessed the fuel efficiency and emission patterns of intra-European and intercontinental flights to and from Europe. We estimated the fuel efficiency and carbon intensity of different mission lengths and flight stages using a tool developed by the European Environment Agency and leveraging an extensive flight-level dataset. Our results highlight several critical areas that require policy intervention. First, we found that a relatively high proportion of overall emissions is due to landing and take-off procedures as well as on-ground activities. These emissions tend to be concentrated at major airports due to layout complexities and congestion, necessitating improvements in surface operations at the individual airport and system-wide levels. Second, regional routes represent the most carbon-intense travel segment, emphasizing the need for efficiency improvements. Promoting innovative aircraft technologies can greatly contribute to increase transportation efficiency and potentially improve the economic sustainability of these routes. Third, the majority of emissions from intra-European aviation occur on cross-border routes, underlying the need for coordinated European-level initiatives, such as strengthening cross-border high-speed rail services and implementing infrastructure investments to mitigate emissions.

1. Introduction

The air transportation industry is one of the fastest growing industries worldwide, doubling in size about every 15 years (ATAG, 2019). This rapid growth does not come without drawbacks or side effects, such as a significant environmental burden. According to the latest data from the European Environment Agency (EEA, 2021), transportation was the only major European economic sector whose greenhouse gas (GHG) emissions steadily increased between 2013 and 2019, accounting for approximately one-quarter of the total EU emissions in 2019. Although ground transportation generates the largest share of overall emissions (i.e., 72%) in the transportation industry, aviation poses the greatest concern. The air transportation industry's emissions have more than doubled since 1990, reaching approximately 3.9% of EU GHG emissions in 2019 (EEA, 2019b). Furthermore, between 2013 and 2017, emissions from the sector increased at an average annual rate of 3% (EEA, 2019b). The COVID-19 pandemic reversed this trend,

---

[*] Corresponding author.
E-mail addresses: nicolo.avogadro@unibg.it (N. Avogadro), renato.redondi@unibg.it (R. Redondi).

https://doi.org/10.1016/j.tra.2024.104121

severely affecting aviation in Europe and around the world and leading to a 58% reduction in emissions from international aviation in 2020 compared to the previous year (EEA, 2021). Nonetheless, the pre-pandemic traffic levels (and, accordingly, emissions) almost completely recovered in 2023, and mid- and long-term industry growth is expected to resume shortly (Eurocontrol, 2023, 2022). Despite strong research efforts and technological advancements, this expected increase in traffic will likely result in an increase in emissions because the marginal fuel efficiency improvements of conventional aircraft are diminishing (D'Alfonso et al., 2016; Liu et al., 2017). This trend highlights key concerns about the sustainability of the air transportation industry as currently conceived.

In response to such concerns, policymakers at the European and global levels have endorsed ambitious decarbonization targets and pledged to reach net-zero aviation CO_2 emissions by 2050 (EC, 2019; IATA, 2021). To achieve these goals, although airlines are already implicitly considering environmental mitigation to some extent because of the correlation of costs with fuel consumption and therefore emissions — a tendency that is likely to intensify in the near future due to growing environmental concerns and the adoption of carbon offsetting and pricing mechanisms (e.g., EU ETS and CORSIA) — the development and implementation of a wide set of policies and measures to effectively curb aviation emissions is crucial (Sgouridis et al., 2011). Among others, the plethora of sustainability options available for aviation includes sustainable aviation fuels (SAFs), aircraft fuel efficiency improvements, new aircraft technologies (e.g., electric-powered aircraft), more efficient air traffic management and on-ground procedures, and modal shift initiatives (Avogadro and Redondi, 2023; Becken and Mackey, 2017; Scheelhaase et al., 2018; Schefer et al., 2020; Fukui and Miyoshi, 2017; Künnen et al., 2023; Kousoulidou and Lonza, 2016; Hamdan et al., 2022). All of these measures are focused on improving aviation's capability to serve demand while minimizing its negative externalities (Eskenazi et al., 2023). Emissions are indeed highly influenced by the technological and operational efficiency (from an environmental standpoint) of airlines and airports in accommodating a given demand. Technological efficiency primarily concerns (innovative) aircraft technologies and fuels, while operational efficiency involves many factors, such as the environmental implications of network structures and configurations, in-flight trajectory optimization, and airport surface congestion management. In such a context, understanding the main patterns of aviation emissions and evaluating the heterogeneity in fuel efficiency of different mission lengths and flight stages based on a high-resolution emission inventory can contribute to explorations of the technological and operational efficiency of airlines and airports, ultimately informing the adoption and prioritization of effective policy interventions (An et al., 2024).

This paper explores the heterogeneity in fuel efficiency and GHG emission patterns across different mission lengths and flight stages with the final aim of investigating the technological and operational efficiency of airlines and airports and supporting the evaluation of policy initiatives. We focus on Europe because it represents one of the world's largest aviation markets. Specifically, we consider scheduled commercial passenger services that in 2019 departed from or arrived in countries within the European border control-free travel area (Schengen area) plus the United Kingdom, Ireland, and Turkey. In 2019, connections from/to these 33 countries accounted for around 9 million flights and more than 1,530 million offered seats. Of these, there were 6.9 million intra-European flights (76.9%) with about 1,050 million seats. To estimate emissions, we rely on a methodology proposed in the European Environment Agency Emission Inventory Guidebook (EEA, 2019a). We estimate the emissions on a per-flight basis as well as for different flight subphases and then aggregate those values into airport- and country-level figures. Based on the estimated values, we quantify the relative weight of the emissions that occurred during the flight subphases (i.e., taxi-out, take-off, climb-out, climb, cruise, descend, approach, landing, and taxi-in) for different mission lengths (i.e., regional and short-, medium-, and long-haul flights). Building on these statistics, we investigate the expected reduction in emissions that could be obtained by sustainable measures such as the optimization of aircraft ground operations (taxi-in and taxi-out) as well as the potentialities of improving alternative transportation modes on cross-border connections or substituting conventional with electric-powered aircraft in regional routes. Focusing on local emissions (i.e., emissions from landing and take-off activities affecting air quality in the neighborhoods of airports), we evaluate the spatial distribution of emissions across the airports and investigate the heterogeneity in the emissions patterns of the different European countries, also considering the presence of major hubs. Furthermore, we compare the (per capita) emissions from intra-European flights with the values for other domestic markets reported by Liao et al. (2021) to obtain an international comparison. Overall, these analyses highlight critical areas that require policy interventions to increase transport efficiency, such as aircraft ground movements and airport operations, regional flights and internal connectivity, and cross-border flights.

Contributions

The contribution of this paper is threefold. First, it investigates the technological and operational efficiency of airlines and airports through the lens of GHG emissions by building a comprehensive inventory of GHG emissions generated from intra-European and intercontinental flights to and from Europe and quantifying the fuel efficiency and carbon intensity of different flight subphases and mission lengths. This includes emissions from single domestic markets and cross-border connections. Second, it evaluates the amount, incidence, and spatial distribution of fuel consumption and GHG emissions that occurred during on-ground operations, ultimately quantifying the incidence of fuel efficiency and the resulting pollutant emissions of longer taxiing times. Third, the study findings have key implications for European policymakers and actors in the aviation supply chain, ultimately assisting them in *ex-ante* prioritizing and evaluating measures and initiatives based on their potential to enhance transportation efficiency in order to reduce the industry's overall environmental footprint.

The rest of this paper is structured as follows. Section 2 introduces the research background and design, detailing the methodology used to estimate emissions and data sources. Section 3 presents the results and discusses them from different perspectives. Section 4 summarizes the findings from a policy perspective and propose avenues for future research.

2. Research background and design

In recent years, to support policymakers in evaluating and devising more efficient policies toward net-zero aviation, researchers have committed to quantifying the environmental impact of aviation (Liao et al., 2021). Emissions that occurr during the en-cruise phase of a flight (i.e., the climb, cruise, and descend (CCD) cycle) have long been the focus of research, likely because their larger amount compared to emissions generated at low altitudes for landing and take-off procedures (LTO cycle). Subsequent studies focused on emissions from LTO activities, which mainly affect air quality in airports' neighborhoods and have relevant implications for human health and local ecosystems (Wang et al., 2018; Yılmaz, 2017; Makridis and Lazaridis, 2019). Such studies typically analyzed LTO cycle emissions as a whole rather than investigating the LTO subphases responsible for those emissions (i.e., taxiing, take-off, climb out, approach, and landing). More recently, some studies have jointly considered emissions generated during the LTO and CCD cycles to more comprehensively assess the emissions generated from a flight (Kito et al., 2020; Liu et al., 2019; Lo et al., 2020).[1] In terms of geographical coverage, most previous studies have focused on emissions at the airport, regional, or country levels, ultimately lacking international comparisons. One of the few exceptions is the study by Liao et al. (2021) comparing the domestic aviation emissions of six major countries: the US, Canada, Australia, Mainland China, Brazil, and India. Meanwhile, Europe has thus far been deeply under investigated. Indeed, to the best of our knowledge, there have been no comprehensive assessments of fuel efficiency or GHG emissions at the European level or evaluations of the heterogeneity in emissions patterns across European countries and airports. At the same time, although, from an environmental standpoint, emissions are highly dependent on aviation's ability to effectively accommodate demand, no studies have analyzed the technological and operational efficiency of airlines and airports through the lens of GHG emissions.

To fill these gaps, in this study, we estimate GHG emissions from passenger flights departing from or arriving at European airports in order to investigate the efficiency of airlines and airports and inform the adoption of relevant policy interventions. We focus on Europe for three main reasons. First, although Europe is one of the world's largest aviation markets, it has received relatively less attention in prior literature. Second, Europe stands at the forefront of global efforts to combat global warming and has recently committed to becoming the first continent to achieve carbon neutrality by 2050. Third, Europe represents a unique case study as a group of sovereign countries governed through a coordinated and common set of policies, thus facilitating the adoption of policies on a continental scale.

To accurately estimate GHG emissions, we use a tool developed by the European Environment Agency (EEA, 2019a) and leverage an extensive flight-level dataset. Specifically, of the different emission inventory methodologies proposed by the EEA, we adopt the Tier 3A method, a bottom-up approach that aims to accurately estimate fuel consumption and emissions based on actual flight movement data.[2] Therefore, details on origin and destination airports and aircraft models are required to use this approach. By leveraging this methodology, we estimate fuel consumption and GHG emissions on a per-flight basis as well as for single-flight subphases. We then aggregated the single-flight emissions into airport- or country-level figures.

In Sections 2.1 and 2.2, we introduce the methodology for calculating fuel consumption and GHG emissions and the data sources.

2.1. Fuel and GHG emission estimation

Conventional flight operations consist of two main phases: LTO and CCD. The LTO cycle includes all flight operations conducted below 3,000 ft (i.e., about 914 m) during the departure and arrival phases of a flight. In turn, LTO can be divided into the following subphases: taxi-out, take-off, climb-out, approach, landing, and taxi-in. The CCD cycle covers the phases taking place above 3,000 ft, namely climb, cruise, and descend. Bad weather conditions, air traffic controller requirements, and specific airport regulations can induce deviations from this ideal flight profile (Murça et al., 2018). However, for the scope of the current research, we consider the conventional flight trajectory pattern. According to this classification, the fuel consumption of operating flight j using aircraft type a is the sum of the consumption that occurs during the LTO and CCD cycles:

$$F_{ja} = F_{ja,LTO} + F_{ja,CCD} \tag{1}$$

Following the EEA (2019a) guidelines, the fuel used during the LTO cycle can be estimated by considering engine-specific consumption factors and the time spent in each LTO subphase. Specifically, fuel consumption can be determined using the following formulation:

$$F_{ja,LTO} = \sum_{i \in LTO} T_{ji} \varphi_{ai} \tag{2}$$

where T_{ji} is the time required by flight j for each LTO subphase i, and φ_{ai} denotes the fuel consumption rate of aircraft type a during LTO subphase i. φ_{ai} takes into account the number of engines equipped in the specific aircraft model and their efficiency as well as the engine thrust setting that is typically used during each LTO subphase.

Fuel consumption during the CCD cycle can be estimated by considering the specific aircraft type — and thus the specific engine characteristics — and the flight distance between the departure and arrival airports. For each aircraft model, EEA (2019a) provides

---

[1] For a more comprehensive review of studies quantifying aviation emissions, please refer to Liao et al. (2021).

[2] Due to the lack of an extensive dataset of precise flight trajectories and altitude profiles, we could not estimate fuel consumption and associated GHG emissions using the more sophisticated Tier 3B methodology.

estimates of fuel consumption for different sector lengths from which the consumption for a specific CCD length can be inferred by linear interpolation.

Based on the fuel consumption, we estimate the GHG emissions for operating flight j using aircraft type a by considering the life cycle emissions of jet fuel. Specifically, we consider well-to-wake jet fuel emissions, including emissions from the extraction, generation, processing, transportation, and distribution of fuel as well as direct emissions from its combustion in an aircraft engine. We report GHG emissions in units of equivalent carbon dioxide (kg of CO_{2eq}) and consider the contributions of CO_2, CH_4, and N_2O. To account for the diverse impacts individual gases have on global warming, following IPCC's guidelines, gases other than CO_2 are converted to CO_{2eq} by multiplying their global warming potential (GWP) relative to CO_2 over a 100-year time horizon (IPCC, 2014). Specifically, we consider the baseline life cycle emission value for aviation fuel to be equal to 89 g of CO_{2eq}/MJ^{-1}, which was adopted by ICAO (2018) and used for calculating and reporting GHG emissions under the CORSIA initiative.[3]

2.2. Data sources

To estimate fuel consumption and associated emissions, a comprehensive dataset of commercial passenger flights departing from or arriving in countries in the European border control-free travel area (Schengen area) plus the United Kingdom, Ireland, and Turkey was collected from the Official Airline Guide (OAG) database. OAG provides flight-level information for scheduled flights, including the departure and arrival airports and the aircraft model used. Given the COVID-19 pandemic's huge impact on the aviation industry in 2020 and 2021 and the incomplete recovery of air traffic and networks in 2022, for our analysis we consider 2019 as a representative steady-state year of air operations. Furthermore, we exclude from the analysis a small proportion of flights (less than 0.5% of the overall sample) that are referred to as rotorcraft or ultra-short flights (less than 25 km). The dataset gathered according to these specifications includes approximately 9 million flights with more than 1,530 million offered seats. Of these, there are approximately 6.9 million intra-European flights (76.7%) with 1,055 million offered seats (68.9%).

To estimate fuel consumption and emissions during LTO, we use the fuel consumption rates for each aircraft type and LTO subphase provided by EEA (2019a), which relies on ICAO Aircraft Engine Emissions DataBank (AEED) information on fuel efficiency and the number and type of engine(s) of each aircraft. Concerning the engine thrust settings employed during each LTO subphase, we consider the standard ICAO (2021) values. Moreover, while we adhere to ICAO standard times for the duration of the LTO subphases other than taxi-out and taxi-in, the actual time spent in these last two subphases at each airport were considered. Specifically, the actual average taxi-out and taxi-in times for 2019 flights at each European airport were obtained from Eurocontrol's Central Office of Delay Analysis (CODA).

Fuel consumption and emissions generated during the CCD cycle are estimated based on the actual distance covered through interpolation, considering the EEA's aircraft-specific estimates for different mission lengths. Due to maneuvering, holding, the fragmentation of European airspace, and inefficiencies in air traffic management procedures, aircraft rarely fly direct great circle routes from the departure airport to the destination airport (EP, 2015). The IPCC (1999) estimated that these inefficiencies cause an increase in fuel consumption between 6% and 12%. Therefore, to account for route inefficiencies when computing fuel consumption during CCD and associated emissions, we estimate the actual flight path distance covered by flight j ($d_{j,fp}$) based on the following linear relationship:

$$d_{j,fp} = \alpha d_{j,gc} + \beta \tag{3}$$

where α and β are empirical coefficients, and $d_{j,gc}$ is the great circle distance between the departure and destination airports. In our analysis, we used Seymour et al.'s (2020) estimates for α and β (1.0387 and 40.5, respectively), which were empirically calibrated on historical aircraft flight track data from the Automatic Dependent Surveillance-Broadcast (ADS-B).

3. Results and discussion

3.1. Emissions by flight length

Based on route distance, flights can be categorized into four main groups: regional (less than 500 km), short-haul (between 500 and 1500 km), medium-haul (between 1500 and 4000 km), and long-haul (more than 4000 km) flights (Eurocontrol, 2011).[4] Table 1 reports the number of flights and the associated GHG emissions for flights from/to Europe by route distance.

Regional and short-haul flights — which primarily consist of domestic connections — cumulatively account for more than half of the flights arriving to or departing from European airports (66.6%). The medium-haul flights, which cover intra-European flights and flights to North Africa and Russia, generate approximately 22.8% of the movements. The long-haul flights represent only about 10.7% of the movements and mainly include air services to intercontinental destinations.

---

[3] Similar to Baumeister et al. (2020), we assumed a heating value of jet fuel equal to 43.15 MJ/kg.

[4] Although various classifications of flights by distance exist, we adopt Eurocontrol's classification for two main reasons. First, it effectively classifies routes in which air transportation competes with alternative transportation modes to varying degrees, thus presenting useful insights into the formulation of tailored policies aimed at reducing aviation emissions. Second, from a regulatory perspective, the adoption of a well-established and widely used classification allows for the proposal of policy initiatives that can be more easily understood by industry stakeholders and policymakers. Nevertheless, the key insights of this study are robust in terms of the modification of categories' boundaries.

Table 1
Number of flights and GHG emissions by mission length.

	Flights		GHG emissions				
			Total		Per flight	Per seat	Per ASK
		%	CO_{2eq} ('000 tons)	%	CO_{2eq} (tons)	CO_{2eq} (kg)	CO_{2eq} (g)
Regional	2,175,410	24.2%	13,087.7	3.9%	6.0	49.9	168.5
Short-haul	3,812,891	42.4%	54,641.3	16.2%	14.3	90.3	101.8
Medium-haul	2,049,983	22.8%	66,018.5	19.6%	32.2	172.3	78.4
Long-haul	964,253	10.7%	202,848.7	60.3%	210.4	701.1	99.1

When considering pollutant emissions, we estimate that the regional flights are responsible for 3.9% of total GHG emissions, followed by the short- and medium-haul flights (16.2% and 19.6%, respectively). Notably, the long-haul flights generate approximately 60.3% of total GHG emissions but only account for 11% of the flights. This could be traced back to the higher per-flight and per-seat emissions of this travel segment. Indeed, an average long-haul flight emits about 210.4 tons of CO_{2eq}, which results in an average of 700 kg of CO_{2eq} per available seat. Based on these values, a long-haul flight pollutes 6.5x (15x) more than an average medium-haul (short-haul) flight and 4x (8x) more on a per seat basis. Although the long-haul flights are the most impactful in absolute terms, the regional flights represent the least fuel-efficient (and, accordingly, the most emission-intense) travel segment with approximately 169 g of CO_{2eq} emissions per available seat kilometer (ASK), probably due to the incidence of energy-intensive LTO procedures over a shorter distance and the lower fuel-efficiency of regional aircraft. Interestingly, the medium-haul flights represent the most environmentally efficient travel segment likely due to the optimal trade-off between aircraft efficiency and distance covered.

These results have key implications from a policy perspective. Strong disparities between the number of movements and associated emissions, heterogeneity in terms of emissions patterns, and the peculiarities of each travel segment need to be considered when designing and prioritizing policy initiatives and mechanisms to reduce aviation emissions. Long-haul flights pose the greatest concern due to their huge amounts of emissions. This requires even more attention because this travel segment is severely under-targeted by current policies, primarily because of the lack of alternative transportation modes operating on such distances. Besides improvements in conventional jet-engine aircraft fuel efficiency, the advent of SAFs — whose extensive use is still strongly undermined by limited production capacity and poor distributive networks — and the possible redesign of current air networks considering an environmental perspective represent the most promising solutions for decarbonizing long-haul aviation. Meanwhile, although regional routes account for a minority of overall emissions, they have the lower fuel-efficiency performance and higher carbon intensity. Therefore, the substitution toward (*greener*) alternative transportation modes should be strongly encouraged for these routes (Baumeister, 2019; Baumeister and Leung, 2021). This is particularly relevant for Scandinavian countries, where regional flights also account for a relatively high proportion of fuel consumption and emissions (approximately 30% in Norway and 20% in Sweden) (Dobruszkes et al., 2022). Where substitution to conventional transport modes is not feasible, the deployment of innovative aircraft models with zero or low emissions, such as electric-powered aircraft, needs to be considered. In fact, the low intensity of demand and short distances of regional routes make this the ideal segment for the deployment of first-generation electric aircraft (Avogadro and Redondi, 2024; Jenu et al., 2021). Regarding short- and medium-haul flights, which cumulatively generate a significant proportion of overall emissions, a wide plethora of measures have already been implemented targeting these routes. Among them, it is worth mentioning policy instruments, including carbon offset and reduction schemes (e.g., EU ETS) and modal shift initiatives toward high-speed rail (HSR). The latter measure has proven to be effective, especially for very dense routes, if supported by infrastructural improvements. For thinner markets, the upscaling of hydrogen- and electric-powered aircraft appears to be a feasible medium-to-long-term solution.

3.2. Distribution of emissions by flight stage

Fuel consumption and associated emissions do not occur evenly during a flight. Various factors such as different thrust settings, aircraft engine rotation regimes, and altitudes impact combustion efficiency, leading to higher or lower levels of fuel consumption and pollutant emissions. Additionally, the impact of aircraft emissions on air quality depends heavily on where they are generated. Low-altitude emissions mainly affect (local) air quality in airports' neighborhoods, causing significant effects on human health and natural ecosystems (Yılmaz, 2017). Conversely, emissions generated during the cruise phase mainly impact regional air quality and contribute to overall climate change. Building upon these considerations, examining emissions based on the flight stage in which they occur provides policymakers and regulators with useful insights that can support the development of appropriate mechanisms and policies for their control and reduction.

Table 2 shows the distribution of GHG emissions during the LTO and CCD cycles and the LTO subphases for different flight lengths. Our analysis revealed a higher incidence of LTO cycle emissions for regional and short-haul flights (31.5% and 18.6% of total emissions, respectively) compared to medium- and long-haul flights (10.4% and 4.3%, respectively). These results were mainly due to the high consumption that occurs during ground and low-altitude operations — characterized by low engine efficiency and the need for a high thrust setting (during the take-off and climb-out subphases) — being spread over a shorter flight length (Grimme and Jung, 2018). By considering only intra-European flights, CCD emissions on average account for about 82.9% of the emissions.

Table 2
Distribution of GHG emissions by flight subphase for different route lengths. GHG emissions (thousands of CO_{2eq} tons) for different LTO subphases at European airports in brackets.

	LTO						CCD
	Taxi-out	Take-off	Climb out	Approach and landing	Taxi-in	Total	
Regional	3.6% (996.0)	7.7% (503.8)	3.9% (1,303.9)	10.1% (822.2)	6.3% (463.9)	31.5% (4,089.9)	68.5%
Short-haul	2.1% (2,361.7)	4.6% (1,183.7)	2.3% (3,066.3)	5.9% (1,938.6)	3.7% (1,082.1)	18.6% (9,632.5)	81.4%
Medium-haul	1.2% (1,363.0)	2.6% (690.2)	1.3% (1,775.9)	3.3% (1,110.5)	2.1% (627.8)	10.4% (5,567.4)	89.6%
Long-haul	0.6% (1,095.2)	1.2% (514.2)	0.5% (1,308.0)	1.3% (770.2)	0.8% (656.0)	4.3% (4,344.6)	95.7%

This value is substantially aligned with those reported by Liao et al. (2021) for other major countries.[5] Specifically, the incidence of CCD emissions for intra-European aviation is slightly higher than those of Australia, Canada, Brazil, India, and Mainland China (ranging from 78.5% to 81.1%) and lower than that of the US (83.1%). These minor differences are mainly due to the diverse flight distance mix in the markets considered.

Despite the high incidence of CCD emissions (particularly on long-haul flights), the emissions that occur during LTO and thus impact local communities are not negligible. By examining GHG emissions generated during the LTO subphases (Table 2), we observe that climb-out, approach, and landing cumulatively generate over half of the GHG emissions that occur during LTO for all mission lengths. Notably, ground and apron operations (taxi-out and taxi-in) also constitute a significant portion of LTO (37.6%) and total (3.4%) GHG emissions. These results are primarily attributed to increased taxi-out and taxi-in times — mainly caused by surface congestion at major airports, which typically have a complex layout of taxiways — and the low power settings adopted during taxiing procedures, leading aircraft engines to operate with reduced fuel efficiency and generate a host of emissions at airports and in adjacent areas (Guo et al., 2014; Simaiakis et al., 2014). Recently, as part of a continuous effort to identify fuel-economic control strategies, various innovative solutions, including single-engine taxiing, on-board electric motors installed in aircraft wheels, and aircraft towing by diesel-electric or fully electric tractors, have been proposed to reduce the environmental burden generated during aircraft taxiing. These new technologies are expected to significantly reduce aircraft ground movement-related fuel burn and associated pollutant emissions (Khammash et al., 2017; Salihu et al., 2021; Guo et al., 2014). For instance, the use of electric tractors has been proven to reduce fuel consumption and CO_2 emissions with a limited impact on aircraft taxi time when electric tractor capacity is properly aligned with demand Salihu et al. (2021).

The data in parentheses in Table 2 are the estimates of GHG emissions generated during the LTO subphases at European airports in 2019. Based on these values, we can identify an upper bound on the potential reduction of emissions resulting from the implementation of zero-emission aircraft ground and apron operations at these airports. This objective is a key climate change-related goal in Europe's vision for aviation, as defined in Flightpath 2050 (EC, 2011). Aircraft ground movements at European airports are estimated to generate about 8.65 million tons of CO_{2eq} per year. These emissions are densely concentrated at major airports: more than half of total emissions occur at the top 17 busiest airports at the continental level. Additionally, due to the larger numbers of movements, the majority of these emissions (79.7%) originate from regional, short-, and medium-haul flights, which are typically operated using single-aisle aircraft. This promises large environmental benefits of electrification of ground operations, even when considering the technological limitations of current electric-powered and hybrid tractors regarding handling and towing heavier wide-body aircraft. From a policy perspective, we observe that an average flight (especially a shorter one) burns a relevant portion of its fuel on the ground. Accordingly, we argue that measures for reducing ground congestion at airports and mechanisms for more fuel-efficient taxiing procedures can strongly contribute to reductions in aviation emissions.

3.3. Emissions from intra-European flights

Table 3 summarizes the estimates of GHG emissions from intra-European flights in 2019. Specifically, it includes details on emissions generated by flights on domestic markets (within single countries) and emissions generated on cross-border routes.

Overall, we estimate that the 6.9 million intra-European flights operated in 2019 emitted approximately 102 million tons of CO_{2eq}. This equals an average of 14.72 tons of CO_{2eq} per flight and 96.7 kg per offered seat. Considering only CO_2, the average emission of an intra-European flight is about 12.1 CO_2 tons. For an international comparison, we refer to the average values of CO_2 emissions per flight estimated by Liao et al. (2021) for six major countries. Notably, the average CO_2 emissions per flight in Europe are significantly lower than those estimated for Mainland China (15 CO_2 tons per flight) and slightly higher than those of Brazil, India, and the US (11.1 CO_2, 11.7 CO_2, and 11.5 CO_2 tons, respectively). Australia and Canada exhibit much lower values (7.7 CO_2 and 8 CO_2 tons, respectively). The diverse average mission lengths for the flights in these countries as well as the differences in the aircraft types used (and their age) constitute the main drivers behind the heterogeneity in terms of emissions.

---

[5] For a fair apple-to-apple comparison with Liao et al. (2021), we only considered CO_2 emissions when computing this statistic.

Table 3
GHG emissions from intra-European flights in 2019.

Market	Flights	Offered seats	GHG emissions				
			LTO	CCD	Total	Per flight	Per capita
		('000)	CO_{2eq} ('000 tons)			CO_{2eq} (tons)	CO_{2eq} (kg)
Domestic	2,402,239	317,838	5,106.5	15,196.7	20,303.1	8.45	33.31
Cross-border	4,527,252	736,956	12,331.4	69,398.9	81,730.4	18.05	134.11
Total	6,929,491	1,054,794	17,437.9	84,595.6	102,033.5	14.72	167.42

When considering different market types, domestic flights account for about 20% of overall intra-European aviation GHG emissions but represent slightly more than one-third of the total flights. This imbalance is due to the greater distances of cross-border flights, which result in more than double the average emissions per flight. Overall, the domestic flights in 2019 generated about 20.3 million tons of CO_{2eq}, while the cross-border emissions were about 81.7 million tons of CO_{2eq}.

Other interesting considerations emerge when focusing on GHG emissions per capita. When normalizing emissions by considering the population, we found that the per capita emissions from intra-European aviation are approximately 167.4 kg CO_{2eq}.[6] Of these, 33.3 kg refer to domestic connections and 134.1 kg to cross-border flights. For emissions per capita, we aimed to conduct an international comparison by considering the data reported by Liao et al. (2021). However, Liao et al. (2021) only provided estimates of emissions per capita for June. Therefore, for a fair comparison, we rescaled Liao et al.'s values to derive annual estimates based on the number of flights in each period gathered from the OAG database. We note that intra-European emissions per capita are significantly lower than those of the US, Australia, and Canada (137.8 kg of CO_2 vs. 429 kg of CO_2, 322 kg of CO_2, and 227 kg of CO_2, respectively). Conversely, other countries, such as Mainland China, Brazil, and India, had much lower values (between 44 kg of CO_2 and 8 kg of CO_2). Even in this case, the heterogeneity could be attributed to the diverse average sector length of the flights in these countries, the different aircraft models used, and differences in the propensity to travel by air in developed and developing countries.

When considering single domestic markets (Table 4), we observe a strong polarization of GHG emissions. Emissions from domestic aviation mainly depend on the size of the local market and the specific socio-economic and geographical characteristics of each country, which, in turn, result in a different propensity to travel and incidence of air transportation compared to other transportation modes. Turkey is the domestic market with the highest level of GHG emissions (about 4 million tons of CO_{2eq}), followed by Spain (about 3.7 million tons of CO_{2eq}). These high values, in addition to the high number of flights, are due to the size of these countries as well as connections from and to islands (especially for Spain). Other major domestic markets, such as Italy, France, Germany, and the United Kingdom, are responsible for huge quantities of GHG emissions.

Relevant differences between individual domestic markets emerge when considering GHG emissions per capita. Notably, Norway exhibits the highest emissions per capita level, amounting to about 267 kg of CO_{2eq} per inhabitant. This is likely due to the country's strong dependence on air travel due to the lack of competitive land-based transportation alternatives. Second, Norway is strongly penalized due to its extensive use of less environmentally efficient (and smaller) regional aircraft for domestic connections. Similarly, high emissions per capita characterize Sweden (67 kg of CO_{2eq} per inhabitant), Finland (50 kg of CO_{2eq} per inhabitant), and Iceland (66 kg of CO_{2eq} per inhabitant). The prominent role of regional flights in the thin markets in these countries means that they will likely be among the first candidates to reap the benefits of aircraft electrification. Investigating the GHG emission reduction potentials of electric transportation modes for domestic routes in Finland and across the Baltic Sea, Jenu et al. (2021) found electric aircraft particularly suitable for routes that are longer than 300 km and that have no alternatives in terms of HSR infrastructure or shorter routes across the water. Regarding these connections, the advent of electric-power aircraft could substantially contribute to the reduction of the environmental impact of domestic flights while preserving regional accessibility and connectivity (Kinene et al., 2023; Baumeister et al., 2020; Avogadro and Redondi, 2024). Significant emissions per capita levels also characterize other major European domestic markets such as Spain, Italy, and France.

Besides emissions from domestic markets, the majority of GHG emissions from intra-European aviation occur on cross-border routes. Table 5 reports the number of flights and associated GHG emissions for the top 15 European cross-border markets (by the number of flights), which mainly correspond to connections between major European countries. Connections from Spain to the United Kingdom and Germany represent the two largest cross-border routes in terms of the number of flights (approximately 266,000 and 176,500 flights per year, respectively) and GHG emissions (6.8 million tons of CO_{2eq} per year and 4.4 million tons of CO_{2eq} per year, respectively). Relevant amounts of emissions are also generated from flights between Turkey and Germany and from the United Kingdom to Italy.

From a policy perspective, the huge amount of emissions from international flights necessitates the identification of initiatives and mechanisms coordinated at the European level to cope with emissions from cross-border routes. In this regard, for some of these markets (especially those connecting neighboring countries), significant benefits could be achieved through the strengthening of alternative transportation services, such as HSR and conventional rail services. On the one hand, cross-border markets already served by HSR links, such as those from the United Kingdom to France, Belgium, and the Netherlands, would benefit from HSR

---

[6] The population data for single countries were retrieved from Eurostat.

Table 4
GHG emissions from major domestic markets in 2019.

Market	Flights	Offered seats	GHG emissions				
			LTO	CCD	Total	Per flight	Per capita
		('000)	CO_{2eq} ('000 tons)			CO_{2eq} (tons)	CO_{2eq} (kg)
Spain	385,632	52,807	854.9	2,847.5	3,702.4	9.60	78.88
Turkey	315,587	58,034	1,076.1	3,000.6	4,076.7	12.92	49.71
United Kingdom	294,152	28,782	379.3	1,096.9	1,476.2	5.02	22.15
France	255,759	33,053	536.9	1,755.0	2,291.9	8.96	34.06
Italy	254,576	41,164	651.8	2,247.9	2,899.7	11.39	48.48
Germany	241,405	35,052	575.9	1,457.2	2,033.1	8.42	24.49
Norway	228,291	24,552	400.5	1,023.1	1,423.6	6.24	267.18
Sweden	104,816	11,137	174.7	507.7	682.5	6.51	66.71
Greece	104,191	10,952	151.3	319.1	470.4	4.51	43.86
Portugal	54,757	6,928	99.3	435.7	535.0	9.77	52.06
Finland	42,924	4657	68.7	207.2	276.0	6.43	50.01
Poland	28,771	2581	19.0	67.5	86.5	3.01	2.28
Denmark	26,248	2507	37.9	58.6	96.5	3.68	16.61
Romania	17,285	1636	29.5	62.2	91.7	5.30	4.72
Iceland	11,436	468	7.4	16.3	23.7	2.07	66.46
Austria	9819	830	5.1	21.2	26.3	2.68	2.97
Croatia	9375	843	7.5	24.1	31.6	3.37	7.75
Switzerland	8336	1169	18.7	26.4	45.1	5.41	5.28
Ireland	2906	173	2.5	4.5	7.0	2.40	1.42
Bulgaria	2707	383	6.3	13.8	20.2	7.45	2.88
Estonia	2480	47	2.3	2.8	5.1	2.07	3.88

Table 5
GHG emissions from major cross-border markets in 2019.

Market	Flights	Offered seats	GHG emissions			
			LTO	CCD	Total	Per flight
		('000)	CO_{2eq} ('000 tons)			CO_{2eq} (tons)
United Kingdom – Spain	265,921	49,162	816.7	5,968.8	6,785.5	25.52
Germany – Spain	176,505	32,389	528.7	3,854.8	4,383.5	24.83
Italy – Germany	131,503	19,888	328.5	1,295.9	1,624.4	12.35
United Kingdom – Germany	121,982	18,505	310.3	1,209.2	1,519.4	12.46
Ireland – United Kingdom	113,150	16,400	277.2	622.0	899.1	7.95
United Kingdom – Italy	110,189	18,505	312.0	1,729.2	2,041.2	18.52
Italy – Spain	103,834	18,471	307.5	1,587.5	1,895.0	18.25
Netherlands – United Kingdom	100,486	13,438	233.9	571.2	805.1	8.01
United Kingdom – France	99,277	15,040	251.0	912.3	1,163.3	11.72
Turkey – Germany	99,159	18,929	357.8	2,723.9	3,081.6	31.08
Spain – France	95,372	16,304	273.9	1,230.2	1,504.1	15.77
France – Italy	90,229	14,126	238.4	1,001.5	1,239.9	13.74
France – Germany	80,186	10,927	191.5	678.1	869.6	10.85
Switzerland – Germany	75,187	10,176	156.7	422.9	579.5	7.71
Germany – Austria	73,519	10,361	163.0	540.7	703.7	9.57

service improvements in terms of increasing capacity and cost-competitiveness, which can be achieved by implementing on-track competition. On the other hand, infrastructural investments in HSR links between major European countries — some of which are already planned as part of the Trans-European Transport Network (TEN-T) project — could open up the possibility of reducing the environmental impact of cross-border routes that are not currently served by effective alternative transportation modes. These markets include connections in the core part of Europe as well as connections to and from Mediterranean countries, such as Italy and Spain.

3.4. Spatial distribution of local emissions

Compared to emissions that occur during the en-cruise phase — which are challenging to allocate to specific regions in cases of international and, especially, intercontinental flights — emissions generated at low altitudes during LTO procedures mainly

Table 6
Local GHG emissions from LTO operations in different European countries (ranked by air traffic movements).

Country	Movements		LTO GHG emissions			Taxiing GHG emissions	
		%	Total CO_{2eq} ('000 tons)	%	Per capita CO_{2eq} (kg)	Total CO_{2eq} ('000 tons)	% LTO
United Kingdom	2,184,076	13.7%	3,565.6	15.1%	53.5	1440.5	40.4%
Germany	1,938,594	12.2%	2,957.6	12.5%	35.6	1048.3	35.4%
Spain	1,900,228	11.9%	2,779.7	11.8%	59.2	1030.0	37.1%
France	1,429,754	9.0%	2,221.4	9.4%	33.0	803.1	36.2%
Italy	1,397,142	8.8%	2,067.8	8.7%	34.6	741.5	35.9%
Turkey	1,228,994	7.7%	2,440.4	10.3%	29.8	974.4	39.9%
Norway	647,184	4.1%	662.1	2.8%	124.3	205.0	31.0%
Netherlands	540,011	3.4%	922.5	3.9%	53.4	326.0	35.3%
Greece	477,990	3.0%	569.5	2.4%	53.1	196.1	34.4%
Switzerland	465,246	2.9%	692.8	2.9%	81.1	249.4	36.0%
Sweden	450,283	2.8%	505.8	2.1%	49.4	162.1	32.0%
Portugal	431,243	2.7%	601.0	2.5%	58.5	209.3	34.8%
Poland	375,267	2.4%	422.9	1.8%	11.1	142.5	33.7%
Denmark	313,691	2.0%	406.4	1.7%	70.0	140.3	34.5%
Austria	304,588	1.9%	383.3	1.6%	43.3	131.3	34.2%
Ireland	270,513	1.7%	436.6	1.8%	89.0	171.6	39.3%
Belgium	258,883	1.6%	375.5	1.6%	32.8	124.4	33.1%
Finland	241,722	1.5%	296.6	1.3%	53.8	99.1	33.4%
Romania	177,730	1.1%	228.3	1.0%	11.8	81.0	35.5%
Czech Republic	134,133	0.8%	185.3	0.8%	17.4	63.7	34.4%
Hungary	110,667	0.7%	154.2	0.7%	15.8	51.9	33.7%
Croatia	101,611	0.6%	98.3	0.4%	24.1	31.2	31.7%
Cyprus	92,997	0.6%	156.2	0.7%	178.4	57.3	36.7%
Latvia	80,300	0.5%	62.5	0.3%	32.5	21.1	33.7%
Bulgaria	77,597	0.5%	105.4	0.4%	15.1	35.4	33.5%
Iceland	67,919	0.4%	102.3	0.4%	286.5	36.8	36.0%
Luxembourg	54,178	0.3%	37.7	0.2%	61.4	11.9	31.6%
Lithuania	50,021	0.3%	53.6	0.2%	19.2	16.1	30.0%
Malta	49,136	0.3%	69.9	0.3%	141.7	22.0	31.5%
Estonia	40,695	0.3%	29.5	0.1%	22.3	9.5	32.3%
Slovenia	20,859	0.1%	20.1	0.1%	9.7	7.1	35.1%
Slovakia	18,764	0.1%	23.7	0.1%	4.3	7.1	29.8%
Total	15,932,016		23,634.4		38.8	8646.8	36.6%

affect local air quality and have relevant implications for human health and the local natural ecosystem in the neighborhoods of airports (Yılmaz, 2017; Hudda and Fruin, 2016; Tokuslu, 2020). Therefore, analyzing the spatial distribution of these emissions may provide policymakers with valuable information about the distribution and possible measures for mitigating the local impacts of airport activities.

Table 6 reports GHG emissions occurring during LTO and taxiing procedures in different European countries as well as their per capita values. To compute per capita emissions, we considered the population of the country in which the emissions were generated. Accordingly, the resulting figures implicitly internalize the (negative) effects of the presence of large hubs where high volumes of non-resident passengers interconnect. Overall, we estimated that GHG emissions at European airports due to LTO activities account for approximately 23.6 million tons of CO_{2eq} per year. The European countries with the highest amount of emissions from LTO activities — also due to the presence of major hubs — are the United Kingdom, Germany, Turkey, France, and Italy. Notably, islands nations (Malta, Iceland, and Cyprus) and Norway register the highest emission values per capita, mainly due to their relatively low local populations and strong dependency on air transportation for internal connectivity or connections to mainland Europe because of the lack of effective land-based alternatives. In addition to geographical reasons, the presence of large hubs and the different sizes (and development) of domestic markets contribute to the strong heterogeneity of LTO emissions per capita among the countries. A similar pattern emerges when considering the countries with the highest levels of emissions that occur during ground operations (i.e., aircraft taxiing). However, it is worth noting that the presence of major hubs (leading higher ground congestion and longer taxiing times) contributes to a higher incidence of on-ground emissions on overall LTO emissions in certain countries. This trend is particularly pronounced for Turkey and the United Kingdom, where approximately 40.4% and 39.9% of LTO emissions occur during taxiing procedures, respectively.

More interesting insights emerge when considering LTO and taxiing emissions at individual airports. Fig. 1 shows the emissions from LTO activities at European airports, while Table 7 reports the GHG emissions that occurred during LTO and taxiing at the top European airports by movements.

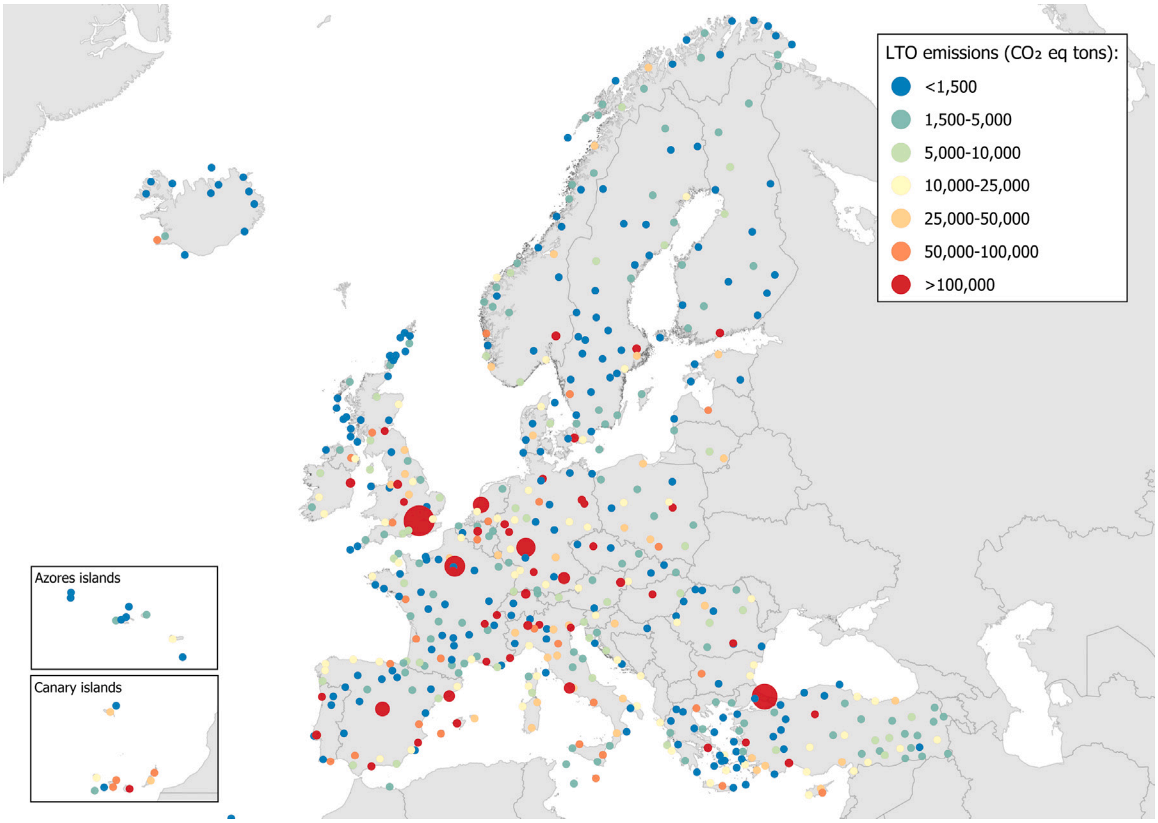

Fig. 1. LTO emissions around European airports.

From a spatial perspective, the airports are evenly distributed across Europe; however, emissions from LTO activities are highly concentrated in a few major airports. Although this primarily depends on the diverse number of movements at each airport, the concentration of LTO emissions still seems to be stronger than that of the movements. The top 20 European airports, ranked by the number of movements, generate more than half of the overall LTO emissions at the European level while accounting for less than 40% of the total movements. Airports with the highest pollution levels mainly correspond to the fulcra of hub and spoke networks on a continental scale. These airports are typically denoted by a huge amount of traffic operated by larger and more polluting wide-bodies aircraft to serve intercontinental destinations. In these hubs, the disparity between the number of movements and emissions is particularly pronounced. London Heathrow is the airport with the highest local environmental impact, generating about 6.07% of LTO emissions at the European level while managing only 3% of the movements, followed by Istanbul airport (4.71% vs. 2.67%), Paris Charles de Gaulle (4.39% vs. 2.93%), Frankfurt (4.15% vs. 3.04%), and Amsterdam Schiphol (3.57% vs. 3.01%). Emissions from ground operations are even more concentrated than those of LTO activities. The top 20 European airports in terms of movements generate approximately 54.5% of emissions from aircraft taxiing at the continental level while approximately 50% of emissions from LTO activities. Besides higher emissions due to the use of larger (and more polluting) wide-body aircraft, large hubs are characterized by significant emissions from ground operations due to higher taxiing times. For the 20 busiest airports in Europe, the average taxi-out time is about 15.6 min compared to an average of 9.6 min for other European airports (+63%). Similarly, taxi-in times are about 7.3 min compared to an average of 4.8 min for other European airports (+53%). The reason for the longer taxiing times at major airports is twofold. First, to manage high volumes of traffic in concentrated periods (i.e., typical hub and spoke wave system scheduling patterns), complex airport facilities with multiple runways and longer taxiways are needed, thus implying longer taxiing times. Second, high traffic volumes lead to congestion, which, in turn, increases waiting times on the ground and associated pollutant emissions.

From a geographical perspective (Fig. 1), all of the top five airports by LTO emissions except Istanbul are concentrated in the core part of Europe. Besides the top five European hubs, we can clearly identify one (or a few) main airport(s) for each country with relevant local emissions. By comparing the distribution of emissions at the European level with the data on other countries reported by Liao et al. (2021), we found that Europe has a similar pattern as other developed nations, such as the US, Canada, and

Table 7
GHG emissions from LTO activities and taxiing at top European airports by movement.

Airport	Movements		LTO GHG emissions		Taxiing GHG emissions	
		%	CO_{2eq} tons ('000)	%	CO_{2eq} tons ('000)	
FRA	484,704	3.04%	981.3	4.15%	365.1	4.22%
AMS	479,713	3.01%	842.8	3.57%	303.7	3.51%
LHR	478,085	3.00%	1,435.3	6.07%	653.9	7.56%
CDG	466,093	2.93%	1,036.6	4.39%	410.3	4.74%
IST	425,017	2.67%	1,112.8	4.71%	492.0	5.69%
MAD	398,351	2.50%	760.4	3.22%	312.9	3.62%
MUC	396,272	2.49%	633.8	2.68%	237.2	2.74%
BCN	328,994	2.06%	591.6	2.50%	243.9	2.82%
FCO	306,375	1.92%	555.3	2.35%	222.1	2.57%
LGW	278,914	1.75%	534.4	2.26%	232.0	2.68%
VIE	258,569	1.62%	349.8	1.48%	122.0	1.41%
CPH	246,163	1.55%	346.6	1.47%	121.5	1.41%
ZRH	244,895	1.54%	407.8	1.73%	148.4	1.72%
OSL	236,048	1.48%	329.6	1.39%	107.2	1.24%
SAW	229,668	1.44%	367.2	1.55%	141.5	1.64%
DUB	226,013	1.42%	384.1	1.63%	154.3	1.78%
ORY	221,720	1.39%	340.6	1.44%	114.8	1.33%
ARN	221,260	1.39%	301.5	1.28%	99.4	1.15%
DUS	213,909	1.34%	281.3	1.19%	101.9	1.18%
LIS	213,306	1.34%	344.3	1.46%	126.3	1.46%
Top 20	6,354,069	39.88%	11,937.3	50.51%	4,710.4	54.48%
Top 50	10,387,267	65.20%	17,511.3	74.09%	6,660.7	77.03%
Total	15,932,018		23,634.4		8,646.8	

Australia. All of these countries have relatively mature aviation markets characterized by a large number of small- and medium-sized airports.[7] Nevertheless, traffic and emissions are concentrated in only a few (major) airports. Furthermore, medium-to-large airports are densely distributed around major urban centers and economically developed regions. Meanwhile, minor airports serve less densely populated and remote regions.

From a policy perspective, the strong concentration of emissions at some airports means that the reduction and mitigation of emissions from those airports must be prioritized. In addition to the most obvious cap on airport growth and movements — already implemented or proposed at some European hubs (e.g., London Heathrow and Amsterdam Schiphol) — some initiatives in this direction include providing incentives to airlines to deploy more efficient aircraft and implementing measures to reduce ground emissions (e.g., the electrification of ground taxiing and the optimization of ground operations). Moreover, the strong concentration of emissions at major hubs opens up the discussion on the environmental implications of the hub and spoke operation model adopted by different airlines. Although, the hub and spoke network structure — through flow consolidation — promises operational efficiency and higher profitability, especially for serving thin markets, an excessive concentration of flows in a few hubs leads to inefficient routings and stimulates ground congestion, resulting in a huge environmental burden (Morrell and Lu, 2007). Thus, a possible solution to cope with emissions from large hubs might involve rethinking the current air network by promoting the re-balancing of hub activities at the continental level to reduce the concentration of movements while preserving the economies of scale deriving from flow consolidation.

4. Conclusions

Reducing aviation emissions is emerging as a key priority for policymakers worldwide. In this context, the present study estimates fuel consumption and GHG emissions from intra-European and intercontinental flights to and from Europe to provide useful insights into the efficiency of airlines and airports in accommodating a given demand. Specifically, it investigates the fuel efficiency and carbon intensity of different mission lengths and flight stages while quantifying emissions generated on single domestic markets and cross-border connections. Special attention is paid to emissions from airport ground movements (aircraft taxiing). While the evaluation of emissions and carbon intensity might be useful for international comparisons, the resulting policy implications are specific to the context analyzed, namely, Europe.

First, when considering flight distance, we found that the majority of aviation emissions originate from long-haul flights (60.3%), which represent a relatively small portion of overall movements (10.7%). Conversely, when considering emissions per ASK, regional

---

[7] Conversely, Liao et al. (2021) observed that developing markets (e.g., China, Brazil, and India) are characterized by a more sparce distribution of airports. However, the number of airports with high emissions is proportionally higher in these markets.

flights are the most inefficient, with more than twice the carbon intensity of the most efficient flight segment: medium-haul flights emitting approximately 78 g of CO_{2eq} per ASK. Second, when analyzing emissions from different flight stages, we observed a higher incidence of emissions from LTO activities during shorter flights (31.5% and 18.6% of overall emissions for regional and short-haul flights, respectively). Furthermore, we estimated that a significant portion of LTO emissions (approximately 8.6 million tons of CO_{2eq} per year) occurred during aircraft ground operations (i.e., aircraft taxiing). This issue is particularly relevant for major airports due to the longer taxiing times caused by surface congestion and the complex layout of runways and taxiways. Third, we found that the majority of emissions from intra-European aviation (80.1%) are associated with cross-border flights. Additionally, considering domestic flights, we observed relevant levels of emissions per capita in countries with limited alternative transportation modes (i.e., major islands or remote areas) or a high propensity to travel. Fourth, by comparing our findings with those of Liao et al. (2021), we identified some international implications. More in detail, we found the incidence of CCD emissions from intra-European flights to be substantially aligned with those of other major countries. Furthermore, similar to other developed countries, we proved that Europe has a substantial number of middle-sized airports. However, both LTO and aircraft ground emissions are densely concentrated at major airports. Lastly, we concluded that the presence of major hubs and poor connectivity offered by alternative transportation modes contribute to higher LTO emissions per capita.

Based on these findings, the implications for policymakers fall under three main areas of interest: (i) aircraft ground movements and operations, (ii) regional flights and internal connectivity, and (iii) cross-border flights.

Regarding emissions from ground operations, the concentration in large hubs of the majority of GHG emissions from taxiing activities, which threaten neighboring communities, highlights the need for emission reduction and mitigation efforts. Within individual airports, infrastructure investments to optimize ground operations (e.g., by reducing ground congestion) can strongly contribute to this goal. In addition to improving operational efficiency (i.e., reducing taxiing times), single airports can investigate solutions to decrease fuel consumption and associated emissions during aircraft taxiing. These initiatives include reducing emissions from conventional aircraft during taxiing using externally powered tractors and incentivizing airlines to deploy more fuel-efficient aircraft. The latter can be achieved by restructuring airport charge schemes and providing all of the necessary infrastructure (e.g., specific tanks and recharging infrastructure) for the extensive use of innovative aircraft models, such as hydrogen-based and electric-powered aircraft. From a system-wide perspective, tackling the significant local emissions generated by major hubs might involve questioning the hub and spoke operational model adopted by various airlines. The theoretical advantages of these network structures may indeed fade when facing stricter environmental requirements. Potential solutions to this challenge include devising mechanisms to stimulate the rebalancing of hub activity at the continental level (reducing the concentration of movements while preserving the economies of scale needed for a profitable hub structure) and transitioning toward a paradigm of sustainable (de)growth for these airports. A more in-depth exploration of these opportunities may constitute the basis for future research.

Regional flights, the most carbon-intense travel segment, typically ensure connectivity to remote regions characterized by a lack of land-based alternative transportation options. Improving the efficiency of regional aircraft and promoting the adoption of innovative aircraft technologies tailored to these routes (such as electric- and hydrogen-based aircraft) should be encouraged for three main reasons: (i) to reduce carbon intensity and overall emissions, (ii) to increase economic sustainability, particularly for thin markets (e.g., those serving remote regions) that are usually subsidized through Public Service Obligation (PSO), (iii) to potentially open new markets and provide better connectivity to these regions.

Lastly, the huge amount of emissions generated by cross-border routes requires the identification of initiatives and mechanisms coordinated at the European level to reduce these emissions. In particular, for neighboring countries, significant results may be achieved by strengthening the provision of cross-border HSR services and, where necessary, implementing infrastructural investments in HSR links between major European countries.

Obviously, this research is not exempt from limitations. Future studies could aim to derive more accurate emissions data by analyzing individual flight-level trajectories and considering actual (rather than average) taxiing times. Moreover, it may be worthwhile to disentangle the effects of specific putative factors, such as fleet composition and age, taxiway length, and congestion, on fuel efficiency and local GHG emissions at major airports. Additionally, future research could estimate emissions for other countries, providing a systematic international comparison and fostering a clearer understanding of more suitable policies to cope with aviation emissions in each country.

Funding

This study was conducted within the National Centre for Sustainable Mobility (MOST) and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023). This manuscript reflects the authors' views and opinions only, neither the European Union nor the European Commission can be considered responsible for them.

CRediT authorship contribution statement

Nicolò Avogadro: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Validation. **Renato Redondi:** Conceptualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

An, H., Wang, Y., Wang, Y., Liu, J., Tang, X., Yi, H., 2024. Civil aviation emissions in China in 2019: Characteristics and abatement potential. J. Environ. Sci..

ATAG, 2019. Aviation Benefits Report. Technical Report, Air Transport Action Group.

Avogadro, N., Redondi, R., 2023. Diverted and induced demand: Evidence from the London-Paris passenger market. Res. Transp. Econ. 100, 101304.

Avogadro, N., Redondi, R., 2024. Demystifying electric aircraft's role in aviation decarbonization: Are first-generation electric aircraft cost-effective? Transp. Res. D 130, 104191.

Baumeister, S., 2019. Replacing short-haul flights with land-based transportation modes to reduce greenhouse gas emissions: The case of Finland. J. Clean. Prod. 225, 262–269.

Baumeister, S., Leung, A., 2021. The emissions reduction potential of substituting short-haul flights with non-high-speed rail (NHSR): The case of Finland. Case Stud. Transp. Policy 9 (1), 40–50.

Baumeister, S., Leung, A., Ryley, T., 2020. The emission reduction potentials of first generation electric aircraft (FGEA) in Finland. J. Transp. Geogr. 85, 102730.

Becken, S., Mackey, B., 2017. What role for offsetting aviation greenhouse gas emissions in a deep-cut carbon world? J. Air Transp. Manag. 63, 71–83.

D'Alfonso, T., Jiang, C., Bracaglia, V., 2016. Air transport and high-speed rail competition: Environmental implications and mitigation strategies. Transp. Res. A 92, 261–276.

Dobruszkes, F., Mattioli, G., Mathieu, L., 2022. Banning super short-haul flights: Environmental evidence or political turbulence? J. Transp. Geogr. 104, 103457.

EC, 2011. Flightpath 2050 Europe's Vision for Aviation. Technical Report, European Commission.

EC, 2019. The European Green Deal. com(2019) 640 Final. Technical Report, European Commission.

EEA, 2019a. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019: Technical Guidance to Prepare National Emission Inventories. Technical Report, European Environment Agency.

EEA, 2019b. Transport: Increasing Oil Consumption and Greenhouse Gas Emissions Hamper EU Progress Towards Environment and Climate Objectives. Technical Report, European Environment Agency.

EEA, 2021. Greenhouse Gas Emissions from Transport in Europe. Technical Report, European Environment Agency.

EP, 2015. Fact Sheets on the European Union: Air transport: Single European Sky. Technical Report, European Parliament.

Eskenazi, A.G., Joshi, A.P., Butler, L.G., Ryerson, M.S., 2023. Equitable optimization of US airline route networks. Comput. Environ. Urban Syst. 102, 101973.

Eurocontrol, 2011. Study into the Impact of the Global Economic Crisis on Airframe Utilisation. Technical Report.

Eurocontrol, 2022. Aviation Outlook 2050. Technical Report.

Eurocontrol, 2023. Eurocontrol Forecast 2023–2029. Technical Report.

Fukui, H., Miyoshi, C., 2017. The impact of aviation fuel tax on fuel consumption and carbon emissions: The case of the US airline industry. Transp. Res. D 50, 234–253.

Grimme, W., Jung, M., 2018. Towards more sustainability?–the development of aviation emissions from Germany between 1995 and 2016. In: Proceedings of the 22nd Air Transport Research Society World Conference.

Guo, R., Zhang, Y., Wang, Q., 2014. Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. Transp. Res. C 44, 98–109.

Hamdan, S., Jouini, O., Cheaitou, A., Jemai, Z., Granberg, T.A., Josefsson, B., 2022. Air traffic flow management under emission policies: Analyzing the impact of sustainable aviation fuel and different carbon prices. Transp. Res. A 166, 14–40.

Hudda, N., Fruin, S., 2016. International airport impacts to air quality: Size and related properties of large increases in ultrafine particle number concentrations. Environ. Sci. Technol. 50 (7), 3362–3370.

IATA, 2021. Net-Zero Carbon Emissions by 2050. Technical Report.

ICAO, 2018. Annex 16, International Standards and Recommended Practices, Environmental Protection. Technical Report Volume IV — Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

ICAO, 2021. Annex 16, International Standards and Recommended Practices, Environmental Protection. Technical Report Volume II — Aircraft engine emissions, 4^{th} Edition.

IPCC, 1999. Aviation and the Global Atmosphere. Technical Report, Intergovernmental Panel on Climate Change.

IPCC, 2014. Fifth Assessment Report (AR5). Technical Report.

Jenu, S., Baumeister, S., Pippuri-Mäkeläinen, J., Manninen, A., Paakkinen, M., 2021. The emission reduction potential of electric transport modes in Finland. Environ. Res. Lett. 16 (10), 104010.

Khammash, L., Mantecchini, L., Reis, V., 2017. Micro-simulation of airport taxiing procedures to improve operation sustainability: Application of semi-robotic towing tractor. In: 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems. MT-ITS, IEEE, pp. 616–621.

Kinene, A., Birolini, S., Cattaneo, M., Granberg, T.A., 2023. Electric aircraft charging network design for regional routes: A novel mathematical formulation and kernel search heuristic. European J. Oper. Res. 309 (3), 1300–1315.

Kito, M., Nagashima, F., Kagawa, S., Nansai, K., 2020. Drivers of CO_2 emissions in international aviation: the case of Japan. Environ. Res. Lett. 15 (10), 104036.

Kousoulidou, M., Lonza, L., 2016. Biofuels in aviation: Fuel demand and CO_2 emissions evolution in Europe toward 2030. Transp. Res. D 46, 166–181.

Künnen, J.-R., Strauss, A.K., Ivanov, N., Jovanović, R., Fichert, F., 2023. Leveraging demand-capacity balancing to reduce air traffic emissions and improve overall network performance. Transp. Res. A 174, 103716.

Liao, W., Fan, Y., Wang, C., Wang, Z., 2021. Emissions from intercity aviation: An international comparison. Transp. Res. D 95, 102818.

Liu, H., Tian, H., Hao, Y., Liu, S., Liu, X., Zhu, C., Wu, Y., Liu, W., Bai, X., Wu, B., 2019. Atmospheric emission inventory of multiple pollutants from civil aviation in China: Temporal trend, spatial distribution characteristics and emission features analysis. Sci. Total Environ. 648, 871–879.

Liu, X., Zhou, D., Zhou, P., Wang, Q., 2017. What drives CO_2 emissions from China's civil aviation? An exploration using a new generalized PDA method. Transp. Res. A 99, 30–45.

Lo, P.L., Martini, G., Porta, F., Scotti, D., 2020. The determinants of CO_2 emissions of air transport passenger traffic: An analysis of Lombardy (Italy). Transp. Policy 91, 108–119.

Makridis, M., Lazaridis, M., 2019. Dispersion modeling of gaseous and particulate matter emissions from aircraft activity at Chania Airport, Greece. Air Qual. Atmos. Health 12, 933–943.

Morrell, P., Lu, C., 2007. The environmental cost implication of hub–hub versus hub by-pass flight networks. Transp. Res. D 12 (3), 143–157.

Murça, M.C.R., Hansman, R.J., Li, L., Ren, P., 2018. Flight trajectory data analytics for characterization of air traffic flows: A comparative analysis of terminal area operations between New York, Hong Kong and Sao Paulo. Transp. Res. C 97, 324–347.

Salihu, A.L., Lloyd, S.M., Akgunduz, A., 2021. Electrification of airport taxiway operations: A simulation framework for analyzing congestion and cost. Transp. Res. D 97, 102962.

Scheelhaase, J., Maertens, S., Grimme, W., Jung, M., 2018. EU ETS versus CORSIA–a critical assessment of two approaches to limit air transport's CO_2 emissions by market-based measures. J. Air Transp. Manag. 67, 55–62.

Schefer, H., Fauth, L., Kopp, T.H., Mallwitz, R., Friebe, J., Kurrat, M., 2020. Discussion on electric power supply systems for all electric aircraft. IEEE Access 8, 84188–84216.

Seymour, K., Held, M., Georges, G., Boulouchos, K., 2020. Fuel estimation in air transportation: Modeling global fuel consumption for commercial aviation. Transp. Res. D 88, 102528.

Sgouridis, S., Bonnefoy, P.A., Hansman, R.J., 2011. Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation. Transp. Res. A 45 (10), 1077–1091.

Simaiakis, I., Khadilkar, H., Balakrishnan, H., Reynolds, T.G., Hansman, R.J., 2014. Demonstration of reduced airport congestion through pushback rate control. Transp. Res. A 66, 251–267.

Tokuslu, A., 2020. Estimation of aircraft emissions at Georgian international airport. Energy 206, 118219.

Wang, R., Huang, C., Ren, H., Yan, S., Hong, Z., Xu, C., Hu, Q., 2018. Air pollutant emission inventory from LTO cycles of aircraft in civil aviation airports in the Yangtze River Delta Region. China Acta Sci. Circumstantiae 38, 4472–4479.

Yılmaz, İ., 2017. Emissions from passenger aircraft at Kayseri Airport, Turkey. J. Air Transp. Manag. 58, 176–182.