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Transition to sustainability in the European Union aviation system

Revealing the Significance of the Place-Based Dimension of European Aviation Transition Policies

Sillero Illanes, C., Gallardo Cobos, R., Moncada Paterno' Castello, P., Haegeman, K.

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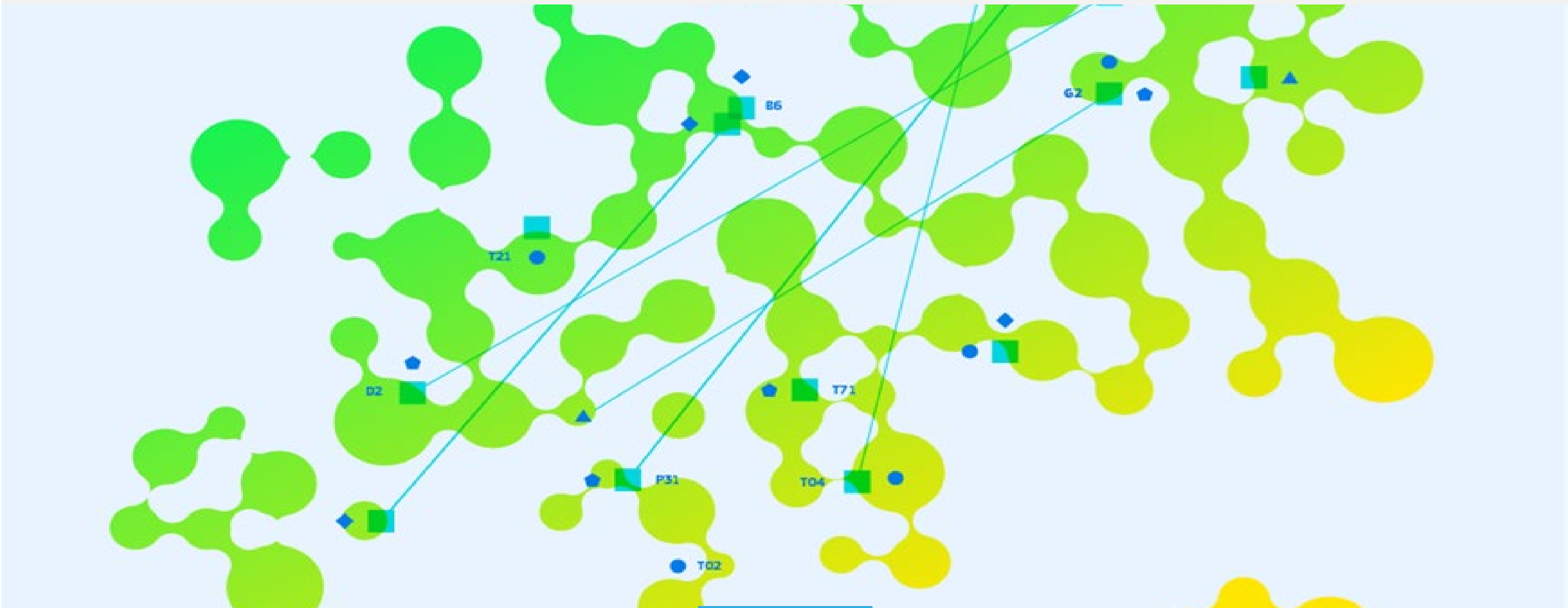

Joint Research Centre

Contact information

Name: Carmen Sillero
Address: Joint Research Centre Seville. Inca Garcilaso, 3. 41092 Seville. Spain
Email: carmen.sillero-illanes@ec.europa.eu
Tel.:+34 670 94 40 30

EU Science Hub

https://joint-research-centre.ec.europa.eu

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Contents

Abstract

To enhance EU competitiveness and foster the transition to sustainability, the Draghi Report underscores the necessity of enhanced policy coordination across EU Member States and European institutions. This paper advocates a systemic approach that integrates subnational governance to expedite sustainability transitions, applying the concept of climate neutrality to the European aviation system.

In 2023, Europe's top 40 airports handled 10.2 million flights and 1.19 billion passengers, driving mobility, tourism, and economic growth. However, aviation is classified by the IPCC as a 'hard-to-abate' sector, contributing 2% of global energy-related CO2 emissions in 2022, with a total warming impact 2.6 times that of CO2 alone. With an expected annual passenger increase of 4.7%, emissions could triple in coming decades, threatening net-zero goals by 2050.

Following a systematic literature review on sustainable aviation, policy initiatives at European, national, and regional levels are mapped and classified according to transition intervention points. Gaps and barriers are identified, and a place-based dimension of the sociotechnical transition is introduced using smart specialisation strategies. The paper argues that effective sustainability transition pathways require a deep understanding of problems and solutions from the perspective of those directly affected, suggesting a place-based approach to align territorial policies with European initiatives.

The conclusions emphasize the need for systemic, transformative, and place-based policies to achieve aviation climate neutrality. Coordinating efforts across local, regional, national, and European levels is vital. The paper illustrates that considering place-based dimensions early in EU policies can enhance sustainability transitions for competitiveness.

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Authors

Carmen Sillero Illanes (Joint Research Centre, European Commission, and Department of Agricultural Economics, Finance and Accounting, University of Córdoba)

Rosa Gallardo Cobos (Department of Agricultural Economics, Finance and Accounting, University of Córdoba, University of Cordoba)

Pietro Moncada Paternò Castello (Joint Research Centre, European Commission, and Solvay Brussels School of Economics and Management, Université Libre de Bruxelles)

Karel Haegeman (Joint Research Centre, European Commission)

Executive summary

A more prosperous and competitive Europe building on the green and digital transitions is one of the central priorities for 2024-2029 of both the European Council and the new European Commission. While the Letta report [1] focuses on the need to further complete the Single Market, Draghi reports [2] proposes a plan for the future of competitiveness, including a plea for better policy coordination between European policies and those of EU Member States. Experimentation with a place-based approach to transformative innovation indicate however a need to also consider better coordination between policies at subnational level [3], [4]. This paper therefore considers the sustainability transition challenge in the European aviation system, with a focus on climate neutrality, from a European, national and regional perspective.

The European aviation sociotechnical system is a complex network that integrates social, technical, research, economic, financial and legal components and facilitates air transport across the continent. This system includes energy, digital and physical infrastructure such as airports and air traffic control centres, advanced technology in aircrafts, helicopters and unmanned vehicles, and communication systems such as satellite-based navigation. It is regulated by the European Union Aviation Safety Agency [5].

The aviation sector in Europe includes over 500 airports, with major hubs such as Paris Charles de Gaulle, Frankfurt Airport and Schiphol airport. Despite a setback in 2020, due to COVID-19, in 2023 there was a rebound in the number of flights to 10.2 million (92 % of the 2019 level), facilitating the movement of 1.19 billion passengers through Europe's top 40 airports [5]. With air travel having fully recovered from the pandemic and even surpassing pre-pandemic demand, an annual growth rate of 4.7 % in passenger traffic has been anticipated, with carriers requiring nearly 44 000 new commercial aeroplanes by 2043 [6] and carbon dioxide (CO_2) emissions potentially tripling by 2050 [7].

The European Green Deal [8] and the fit for 55 package [9] have placed a spotlight on achieving net-zero emissions ([1]) by 2050 across all sectors and reaching 55 % of this goal by 2030 [10]. Aviation is considered a 'hard-to-abate' sector (IPCC, 2023), with a high dependency on liquid fossil fuels and slow fleet turnover times, and with aircrafts having lifespans of around 30 years [12]. In 2022, aviation emissions accounted for 2 % of global energy-related CO_2 emissions. However, the sector's overall impact on global warming is estimated at 2.6 times that of CO_2 alone, due to the emission of nitrogen oxides, sulphate aerosols, particulates and water vapour, although the level of uncertainty for the non-CO_2 effects is eight times larger than that for CO_2 [13]–[17].

This research delves into the policy interventions needed to meet the European Green Deal climate target. In this context, our work proposes the following research questions: what insights does the existing literature offer regarding policy interventions in the transition to net-zero emissions in aviation? What gaps and barriers exist between the current policies in place in Europe and the recommendations to meet the objectives of the European Green Deal and fit for 55 package, and which align with the outcomes of the 28th Conference of the Parties (COP28)? What are the territorial dimensions of these policy interventions?

Following a systematic literature review of 60 academic papers, this study presents an in-depth analysis of policy interventions aimed at achieving net-zero emissions in European aviation. We apply Geels' multilevel perspective [18]–[21] to assess the sustainability transition within the

([1]) The term 'net zero' appears in Article 2(1) of the European Climate Law. EU-wide greenhouse gas emissions and removals regulated in EU law should be balanced within the EU at the latest by 2050, thus reducing emissions to net zero by that date, and the EU should aim to achieve negative emissions thereafter.

aviation sociotechnical system, focusing on key intervention points [22], [23]. Our analysis identifies critical policy measures related to regulation, infrastructure, investment quality, the taxation of environmentally brown technologies, subsidies for green technologies, carbon offsetting and alternatives to flying. These measures are examined at both the European and the national levels. In addition, we explore the regional and regional dimension of innovation policies through an analysis of the 2021–2027 smart specialisation strategies, submitted by EU Member States and regions.

Policy context

This work is framed within the mandate of the European Green Deal [8]; the European Industrial Strategy [24], the fit for 55 package, in particular the 'ReFuelEU aviation' initiative; [25]; and the Net Zero Industrial Act (NZIA) [10]. The consequences of Russia's invasion of Ukraine (since March 2022) and the international agreement reached at COP28 [26] about the transition away from fossil fuels significantly influenced the backdrop against which this paper was developed**.**

Main findings

The added value and originality of this research is based on three elements: (1) the mapping of policy initiatives for the sustainability transition in aviation at the European, national and regional levels, classified according to transition intervention points; (2) the identification of gaps and barriers faced by these interventions; and (3) the proposed solutions for overcoming these burdens, including a place-based dimension in the transition of the aviation sociotechnical system.

From a technological point of view, the systematic literature review revealed that the most promising zero-carbon propulsion technologies for sustainable aviation, electric and hydrogen are still far from the required technological readiness level for widespread deployment. This situation positions sustainable aviation fuels (SAFs) as a crucial element of the transition and the only practical way to decarbonise aviation while other technologies are being developed. However, SAF production needs to be urgently increased. In 2024, SAFs are expected to represent just 0.53 % of the aviation fuel required [27]. Acceleration in the development of hydrogen and electric propulsion, coupled with research on potential side effects (e.g. contrail mitigation systems to reduce non-CO_2 emissions) is taking on new urgency.

However, achieving net-zero emissions in aviation by 2050 will require more than just technological innovation. Our analysis highlights the crucial role of governmental measures, including regulation, research and development investment, subsidies, taxation and promoting alternatives to flying, along with communication strategies to shift public perception and encourage less energy-intensive consumption habits. Green taxes can be an important measure, integrating environmental costs associated with air travel into the pricing of flights. This paradigm shift is supported by the growth of societal movements that recognise the impact of air travel. Notably, the emergence of the flight shame (*flygskam*) movement in Sweden in 2018 catalysed a significant change in citizens' attitudes towards air travel and tourism [28], [29].

Regarding regulations, implementing legislative initiatives, such as the 'ReFuelEU aviation' initiative, the NZIA [10] and the strategic technologies for Europe platform regulation [30], is the right step to promote SAF development and production. However, the lack of sufficient planning and preparation in electric and hydrogen infrastructure at airports could lead to significant bottlenecks.

To accelerate innovation, the primary European actors and mechanisms are the European Climate, Infrastructure and Environment Executive Agency (CINEA), in charge of Horizon Europe 'climate, energy, transport' and Innovation Fund: the Clean Aviation joint undertaking [31] and the air traffic management joint undertaking, SESAR JU, in charge of Single European Sky ATM Research [32]. At the national level, significant innovation agendas aimed at promoting green aviation have been identified in countries such as Spain, France, the Netherlands and Sweden. Given the critical need to advance the technological maturity of technologies for sustainable aviation, there is an urgent requirement to enhance coordination and the creation of synergies. This has been repeatedly emphasised as crucial, yet, after the implementation of several policy frameworks, it remains an unresolved issue.

The inclusion of aviation in the European Union Emissions Trading System (EU ETS) [33] and the carbon offsetting and reduction scheme for international aviation has had little impact on the transition due to limitations in their design [34] Carbon pricing within the European Union Emissions Trading System has not been high enough to generate substantial changes in airlines' behaviour. In addition, if offset credits are less expensive than SAFs, airlines may, indeed, seek to offset rather than reduce their combustion emissions.

Regarding alternatives to flying, France has implemented a ban on regional flights where train travel is a viable alternative. Meanwhile, the Netherlands is enhancing rail connections between major European cities and its airports to facilitate access without flying.

This study also examines the 2021–2027 smart specialisation strategies across 60 European countries and regions that have incorporated the NACE[2] activity H51, 'Air transport', in their national or regional innovation agendas. The analysis emphasises green aviation, smart mobility and sustainable energy as key areas of focus. It unveils a territorial governance layer in Europe that invests resources and customises aerospace industrial policies and air-transport-related measures to align with local industry capabilities, infrastructure, tourism strategies, innovation capacity, environmental objectives and mobility needs.

Our analysis concludes that incorporating a place-based, systemic and transformative approach to the transition to sustainability in the European sociotechnical aviation system is essential, and this requires coordinated efforts at the local, national and European levels. It is crucial to align policies across the innovation, education, environmental, energy and mobility domains, integrating regulation, taxation, infrastructure measures to accelerate the technological readiness of hydrogen and electric propulsion, boost the production of SAFs and offer viable alternatives to flying. Furthermore, airports could be developed into integrated energy and mobility hubs that promote alternative transport modes within a comprehensive mobility system. Finally, engaging all stakeholders through an open discovery process is vital to ensure broad participation, align the sector with the European Green Deal and identify new place based opportunities, thereby enhancing territorial prosperity and resilience.

More generally, the paper exemplifies the argument that strategies to support both sustainability transitions and EU competitiveness may benefit from a well –developed place-based approach, and that policy coordination is required not only at EU and national levels but also involving subnational ones. In view of a new EU industrial policy, as proposed by Draghi, building on sustainability transitions, developing a full territorial dimension in industrial policy could be beneficial.

[2] NACE: Statistical classification of economic activities in the European Union

1 Introduction

The Paris Agreement [35] calls for all economic sectors to contribute to reducing emissions to keep the rise in global surface temperature to 1.5 °C above pre-industrial levels [36]. Aviation is considered by the Intergovernmental Panel on Climate Change a 'hard-to-abate' sector [37]. In 2022, the sector was responsible for 2 % [38] of global energy-related carbon dioxide (CO_2) emissions, 80 % of the peak reached in 2019 before the COVID-19 crisis. However, the most robust scientific assessments indicate that the overall warming impact of aviation is 2.6 times higher than that of CO_2 alone [14]. Apart from CO_2, aviation releases various substances, such as nitrogen oxides, sulphate aerosols, particulates and water vapour, that contribute to radiative forcing and global warming [14]–[16]. The effects of these non-CO_2 emissions are not presently included in any international climate agreements [17].

The European Green Deal [8] and the fit for 55 package aim to achieve net-zero emissions by 2050 [9], with an intermediate target of reducing emissions by 55 % by 2030. However, in the aviation sector, which is expected to see an increase in annual passengers of 4.7 % [6] and has slow fleet turnover times, emissions could potentially triple by 2050. Given this projected increase, achieving climate neutrality poses a formidable challenge.

Domestic CO_2 aviation emissions ([3]) (35 % of global emissions from aviation) are declared in the nationally determined contributions (NDCs). NDCs are an integral part of the Paris Agreement (Article 4(9)) [35], which requires all parties to communicate their post-2020 climate actions, starting in 2020 and every 5 years thereafter. NDCs set out the efforts made by each country to reduce national emissions and adapt to the impacts of climate change. In October 2023, the EU submitted an NDC on behalf of the EU and its Member States, in light of the Fit for 55 legislative package [39]. Directive (EU) 2023/958 [40] ensures that the aviation sector actively contributes to the EU's targets for reducing greenhouse gas emissions in line with the European Green Deal objectives. It includes provisions to ensure the alignment of the European Union Emissions Trading System (EU ETS) with the carbon offsetting and reduction scheme for international aviation (CORSIA), ensuring that flights between Member States and non-EU countries are subject to CORSIA. This alignment aims to streamline international aviation emissions management. As will be discussed in Chapter 8, since 2020, there has been a lack of international agreements on mechanisms for management in global carbon markets; however, the CORSIA offsetting mechanism has provided sensible limits.

Negotiations at the 28th Conference of the Parties (COP28) under the United Nations Framework Convention on Climate Change [26], held in Dubai in December 2023, culminated in a landmark accord to facilitate a global 'transition away from fossil fuels'. This mandate reinforces the aviation industry's need to embrace the transformation of its traditional propulsion systems.

The European aviation industry is a world leader in the production of civil aircrafts, including helicopters, and aircraft engine parts and components. Its complex international supply chain ranges from large system operators and integrators to high-tech, specialised small and medium-sized enterprises, comprising a strategic industrial and knowledge base of great significance for European sovereignty and security [41].

The aviation sector's industrial footprint in Europe is distinctly marked by 35 aerospace clusters that span the EU [42]. These clusters, including major hubs such as France's Aerospace Valley and

([3]) CO_2 emissions from civil aviation include only those from flights within the European Economic Area, departing flights to Switzerland and departing flights to the United Kingdom.

Germany's Hamburg Aviation, along with notable clusters in Spain, Italy, Poland and Sweden, epitomise the integration of business, research and education aimed at advancing aerospace technology. In addition, the incorporation of air transport in the 2021–2027 smart specialisation strategies (S3) by 60 European territories (both and national and regional levels) emphasises the sector's place-based dimension.

However, any transition is marked by a power struggle to change or maintain the status quo [20]. Government intervention is vital to foster the fight against climate change and promote environmental innovation across policies. However, robust global sociotechnical regimes place significant limitations on national and regional policymaking for transition trajectories [43], [44]. Influential works such as Mazzucato's *The Entrepreneurial State: Debunking public vs. private sector myths* and *Mission-oriented Industrial Strategy: Global insight*s [45], [46] stress that the government's role in promoting low-carbon green industrial policies must not only address market failures related to climate change but also focus on climate protection and social welfare, as also stated by authors such as Dani Rodrik [47]–[51].

In the context outlined above, this study addresses the following questions: what insights does the existing literature offer regarding policy interventions in the transition to net-zero emissions in aviation? What gaps and barriers exist between the policies currently in place in Europe and the recommendations derived from the literature for European aviation to meet the objectives of the European Green Deal and the fit for 55 package, and which align with the outcomes of COP28? What are the territorial/geographical dimensions of these policy interventions? To answer these questions, we carried out a systematic literature review. Adopting a multilevel perspective transition framework, we have identified gaps between the policy recommendations gathered from the literature and the current European and national policies. To investigate the place-based dimension of European aviation, we analysed the 2021–2027 S3, and discussed below the role of place-based transformative innovation policies and regional transition pathways.

The structure of this paper is as follows. **Chapter 2** sets the scene of the European aviation sector. In **Chapter 3**, the research questions are delineated along with the methods employed in the paper. **Chapter 4** describes the results of the systematic literature review and **Chapter 5** explores the multilevel perspective of the sociotechnical transition to sustainability in aviation. **Chapter 6** catalogues both European and national policy instruments designed to achieve net-zero emissions in the aviation sector. **Chapter 7** analyses the 2021–2027 S3 in European regions that have included air transport in their priorities. **Chapter 8** proposes elements of systemic and place-based transition pathways in regions specialised in aviation. Finally, **Chapter 9** presents the conclusions.

2 Setting the scene of the European aviation sociotechnical system

The European aviation sociotechnical system integrates the economic, financial, legal and social research and technical components of air transport. This system includes, among other aspects, infrastructure such as airports and air traffic control centres; advanced technology in aircraft, helicopters and unmanned vehicles; communication systems such as satellite-based navigation; and digital control towers. It is regulated by entities such as the European Union Aviation Safety Agency (EASA) and relies on highly trained staff, including pilots and air traffic controllers [5], [13].

Europe is home to over 500 airports with scheduled traffic, with major hubs such as Paris Charles de Gaulle, Frankfurt Airport and Schiphol airport serving millions of passengers annually. The aviation sector supported approximately 9.8 million jobs and contributed EUR 672 billion to gross domestic product in 2018, representing 4.2 % of the total gross domestic product of the EU-28(including the United Kingdom) [52].

Despite a setback in 2020, due to COVID-19, in 2023 there was a rebound in the number of flights to 10.2 million (92 % of the 2019 level), facilitating the movement of 1.19 billion passengers through Europe's top 40 airports [5]. In 2024, with air travel having fully recovered from the pandemic and even surpassing pre-pandemic demand, Boeing forecast a 3 % increase in aeroplane deliveries over the next 20 years, with carriers requiring nearly 44 000 new commercial aeroplanes by 2043. An annual growth of 4.7 % in passenger traffic has been anticipated [6], potentially more than tripling CO_2 emissions by 2050.

Under the EU Industrial Policy, aeronautics is part of the aerospace and defence industrial ecosystem. Scenarios for a resilient, sustainable and digital aerospace and defence industrial ecosystem were developed [53], as well as a transition pathway for the aerospace ecosystem [54] based on the cooperation between industry, public authorities, social partners and other stakeholders. Building on this common pathway, a call for commitments has been launched for ecosystem stakeholders (from SMEs and start-ups to larger companies, local, regional and public administrations, civil society groups and other interested parties) to report on existing strategic commitments or to identify new actions in support of the pathway, Clusters meet Regions events are being organised, including on aerospace [55]

3 Research questions and methods

This paper addresses the following questions: what insights does the existing literature offer regarding policy interventions in the transition to net-zero emissions in aviation? What gaps and barriers exist between the policies currently in place in Europe and the recommendations derived from the literature for European aviation to meet the objectives of the European Green Deal and the fit for 55 package, and which align with the outcomes of COP28? What are the territorial/geographical dimensions of these policy interventions?

In pursuit of answers to these questions, our methodological approach encompassed a systematic literature review, which scrutinised existing academic discourse on sustainable aviation policies. We adopted a multilevel perspective as a theoretical framework for examining the aviation sociotechnical system's sustainability transition [18]–[20], [56], while concurrently pinpointing specific policy interventions [22], [23]. In doing so, we identified policy measures related to regulation, infrastructure, quality of investment, taxation, offsetting and alternatives to flying, at the European and national levels, analysing a selection of EU Member States. To explore the place-based dimension of the aviation system, the 2021–2027 S3 in European regions that have included air transport in their priorities was scrutinised.

Consequently, this paper canvasses the multilevel policy interventions that are shaping the sustainable transformation of the European aviation sociotechnical system. It offers insights for future research that provide a transformative and systemic perspective, as posited by [57].

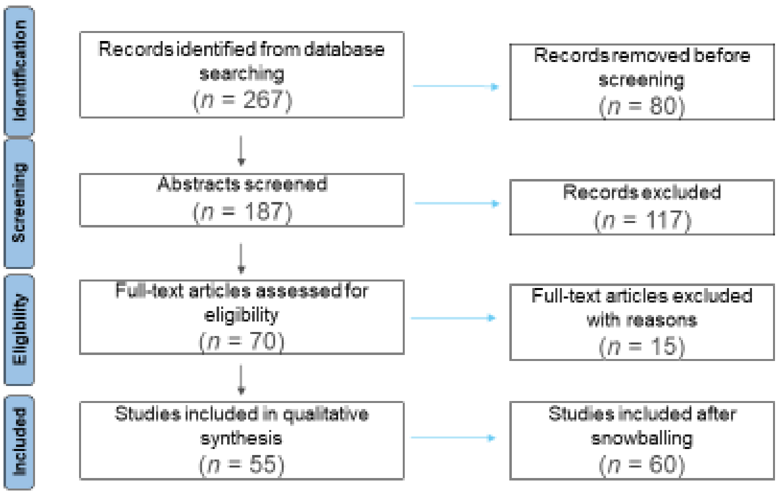
4 Systematic literature review

To address the research questions, we conducted a systematic literature review partially inspired by Preferred Reporting Items for Systematic reviews and Meta-Analyses guidelines [58], using Scopus, Web of Science, Google Scholar and EBSCO.

The systematic literature review focused initially on the aviation industry, emissions, transition strategies and policies. Additional searches included new terms: 'multilevel perspective', 'transformative innovation policies' and 'transition pathways'. Searches were conducted from 30 October 2022 to June 2024. Initial search strings targeted conference papers, articles and book chapters, with an emphasis on highly relevant and qualitative literature. The review focused on literature from Europe (including the United Kingdom) and literature published from 2015 onwards, aligning with the timeline of the Paris Agreement. The subject areas selected were economics, engineering and business management, in line with the scope of the study.

A backward search for papers cited in the selected works was performed without time restrictions, providing a comprehensive view of the research topic and additional insights. Ultimately, 60 academic papers and an extensive and unquantifiable amount of grey literature were reviewed (Figure 1).

Figure 1: Publications selection flow



Source: Authors' own elaboration

Following an examination of the literature assembled through the systematic literature review, three distinct groups of academic works were identified:

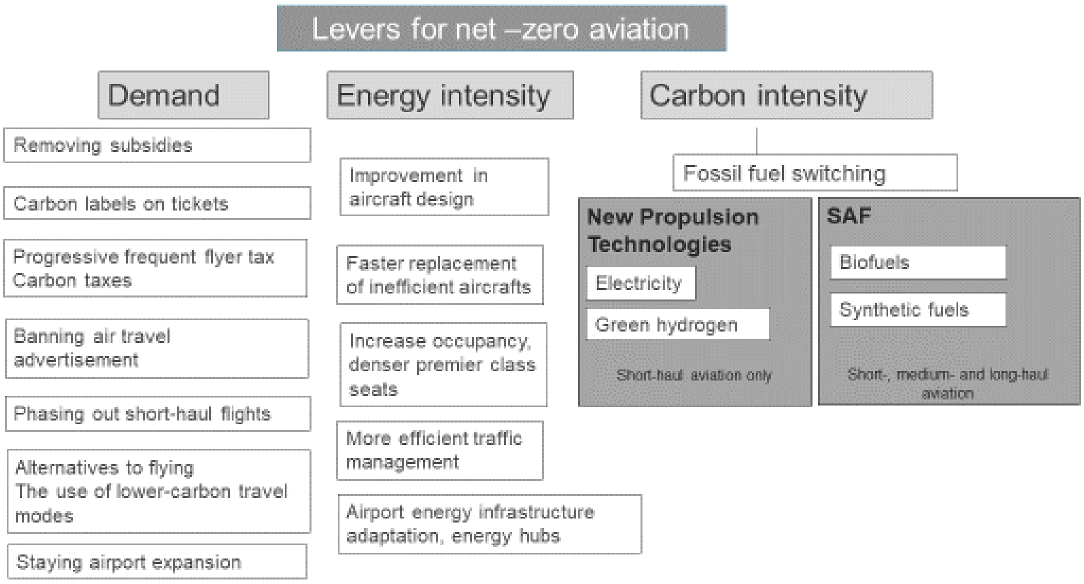
- **Academic literature assessing the impact of aviation on climate change.** This group encompasses scholarly works that evaluate the environmental repercussions of aviation and put forward solutions such as mitigation technologies, technology pathways and market measures for decarbonisation.

- **Analysis of human behaviour in aviation and air travel.** This group comprises writings that examine human behaviour with regard to aviation and air travel, shedding light on the social aspects of these domains.

- **Sociotechnical transition to sustainability in aviation.** Focusing on a broader perspective, this group includes literature proposing a multilevel perspective, addressing the sociotechnical transition to sustainability within the aviation sector.

To summarise the results of the literature review, the available decarbonisation levers have been divided into three main categories: demand, energy intensity and carbon intensity. Figure 2 shows the array of factors that contribute to achieving net-zero emissions.

Figure 2: Levers for net-zero aviation



NB: SAF, sustainable aviation fuel.

Source: Authors' own elaboration based on Bergero et al. (2023), Dray et al. (2022), and Gössling and Lyle (2021).

4.1 Carbon intensity

The transition from kerosene to alternative energy sources in aviation involves three principal pathways, each with its own set of challenges and opportunities. First, all-electric aircraft show substantial potential for emission reduction; however, their deployment is currently confined to short-haul flights due to the limitations of battery energy density [29], [59]–[63]. Second, hydrogen emerges as a promising alternative, despite facing significant technological hurdles, for example necessitating extensive aircraft redesign to accommodate its properties, such as the need for cryogenic storage at temperatures around – 250 °C, and adjustments for its greater volume and lower weight compared with kerosene (it is four times larger in volume and three times lighter in weight). These characteristics pose substantial challenges for its storage and integration into aircraft design. Both pathways require significant advancements in technology and infrastructural changes. Moreover, technological readiness for liquid hydrogen, hydrogen fuel cells and batteries is currently assessed at levels 3–4 [64] This indicates that they are in the early stages of development, though the evaluations may need nuanced approaches for short-haul aviation. This scenario underscores the complexities involved in shifting to alternative energy sources in aviation and highlights the urgent need to accelerate the development and implementation of these sustainable technologies [59], [63], [65]–[68].

Sustainable aviation fuels (SAFs) are highlighted as a third alternative to fossil-based jet; however, they are challenged by the shortage of feedstock and the high level of production needed [69]–[75]. In 2024, SAFs are expected to represent just 0.53 % of the aviation fuel requirement [27]. ASTM International, the organisation responsible for aviation fuel standards, has certified seven different types of SAFs, with maximum blends ranging from 10 % to 50 % [71].

In addition, EASA has carried out a comprehensive analysis of the non-CO_2 climate impact of aviation for the European Commission and has identified potential policy measures to reduce the non-CO_2 climate effect [76]. These measures are financial, and include nitrogen oxide tax or the inclusion of aircraft nitrogen oxide emissions in the EU ETS); related to the use of SAFs; or operational, such as air traffic management measures for avoiding supersaturated areas and reducing contrail and cirrus cloud formation.

4.2 Energy intensity

An analysis of several Swedish airlines [60] identified a range of options to enhance energy efficiency through modifications in airline operations, fleet retrofits and the introduction of new aircrafts. The significant costs associated with these improvements, coupled with the extended lifespan of commercial aircraft – often exceeding 30 years [12] – may deter airlines with limited budgets from engaging in these efficiency efforts. Moreover, the financial viability and technical feasibility of these options can vary, depending on factors such as the age of the aircraft and fleet usage patterns.

The importance of airport infrastructures, particularly their supplies of SAFs, electricity and hydrogen, will be a determining factor in the aviation industry's transition to sustainability, as detailed in **Chapter 8**.

To achieve net-zero emissions by 2050, which is the objective of the European Green Deal and the Net Zero Industry Act (NZIA), almost all the global roadmaps suggest that the aviation sector will need the help of carbon removal strategies to bridge the gap between its residual emissions and net-zero emissions. Even if carbon removal technologies are considered an 'out-of-sector' mitigation measure, it is still critical to develop these technologies as they will play a key role in supplying CO_2 as the feedstock for producing power-to-liquid fuels [62], [77].

4.3 Demand

In terms of demand, Gössling and Humpe [78] highlight that in 2018 only 11 % of the world's population participated in air travel, with, at most, 4 % flying internationally between any two countries. The most frequent fliers – at most, 1 % of the world's population – probably account for more than half of the total emissions from passenger air travel. These emissions are highly skewed on the global, national and individual scales. Surveys indicate that among commercial air travellers, the most frequent 10 % of fliers may account for 30–50 % of all flights taken. The share of fuel used by these air travellers is probably higher, as more frequent fliers tend to travel in business or first class [78].

The emergence of the flight shame (*flygskam*) movement in 2018 catalysed a shift in citizens' attitudes towards air travel. Normative backcasting exercises developed for 2030 in Sweden [79] advocate concepts such as 'an air-free year' and abstaining from aviation in favour of staying on the ground, gaining traction alongside the increasing role of individuals' engagement, perceptions and trust in transitioning to a low-carbon transport system [80]. Public demonstrations such as the march on 3 October 2020 at various airports in France, reflecting the public's growing opposition to airport construction and expansion projects, and the protests at Oslo and Frankfurt airports on 25 July 2024, where protesters demanded an end to the use of fossil fuels by 2030, are becoming more frequent [81]. These actions increase criticism focused on holding the aviation sector accountable for global warming and demanding controlled traffic to align with the Paris Agreement [29].

Following research by Gössling and Lyle [63] policies aimed at transforming the aviation sector can be categorised into three types: voluntary, market based and regulatory. Gössling and Lyle also assess how each policy influences aviation demand, technological advancements and shifts in social norms. For example, introducing a quota for sustainable fuels can catalyse technological changes in fuel development and propulsion systems, leading to a significant reduction in emissions. Similarly, implementing a carbon tax could decrease demand by raising the cost of air travel, while governmental communication strategies that highlight the environmental costs of frequent flying can shift public perception and alter social norms towards less energy-intense consumption.

In summary, achieving the low-carbon transition in aviation extends beyond technology innovation or carbon pricing alone. Transitions should involve systemic change, transitioning from optimisation to transformation and surpassing incremental improvements, and analyse radical and disruptive innovations and new niches capable of replacing fossil-based jet fuels, to break the industry's carbon lock-in and pave the way for a fossil-free future. Authors advocating the multilevel perspective of the sociotechnical transition and transformative change are calling for openness to a wider range of actors in defining an agenda for aviation [18], [21]–[23], [82].

5 Multilevel perspective of the sociotechnical transition to sustainability in aviation

Frank Geels in 2006 [18] utilised the multilevel perspective in analysing the transition within the aviation sociotechnical system from propeller driven to turbojet aircraft (1930–1970), not just examining the technological shifts in aircraft and engines, but also considering broader elements such as airports, fuel stations, air traffic control systems, regulations, cultural implications, markets and user groups. He posited that transitions are complex co-evolutionary processes that encompass technological shifts alongside changes in markets, user practices, regulations, culture, infrastructure and science.

Within the multilevel perspective, novelties emerge in niches, which are 'protected spaces' such as research and development laboratories, subsidised demonstration projects or small market niches in which users have special demands and are willing to support emerging innovations (e.g. in the military). Niche actors work on radical innovations that deviate from existing regimes. They hope that their promising novelties are eventually used in the regime or even replace it. This is not easy, however, because the existing regime is stabilised by many lock-in mechanisms. Nevertheless, niches are crucial for transitions because they provide the seeds for systemic change [20], [21].

System change for transport decarbonisation [83] addressing societal goals will not be achieved solely by technology innovation or carbon pricing strategies [16], [21], [22], [84]–[86]. It will require a combination of increasing niche innovations, weakening existing systems and amplifying exogenous pressures to create opportunities for transitions. Sociotechnical transitions gain momentum when innovations across different domains link, reconfiguring systems towards decarbonisation. This is particularly evident in the connections between the energy, mobility and transport systems.

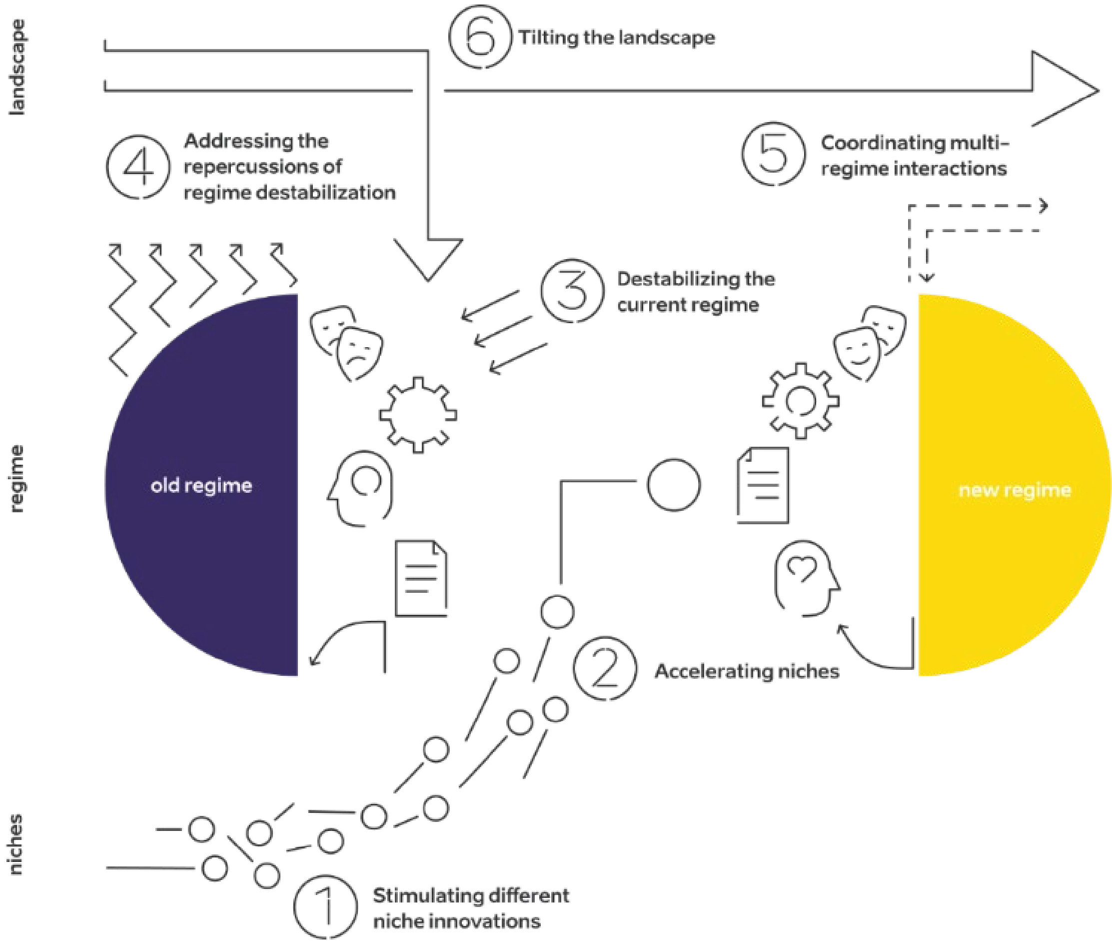
For transitions to accelerate, widespread social acceptance is crucial, as millions of passengers must shift their purchasing decisions, practices, beliefs and skills towards low-carbon alternatives [21]. At the same price, the customer's choice is easy; however, if prices differ, with a very high price for net-zero flights, there will be a considerable gap to close (price discrimination). The role played by the business sector is essential due to its capacity for low-carbon innovation. This innovation is reliant on the technical, organisational and financial capabilities of businesses, and driven by market opportunities shaped by policy instruments (subsidies, taxes, standards) and changing consumer preferences.

In the context of existing economic frameworks, there is a noted reluctance among firms and industries to adopt emission-reducing policies due to potential impacts in profitability and on operational models. This is especially true in the aviation sector, in which transitioning to alternative propulsion technologies poses significant financial challenges [14], [69], [84], [87], [88].

Government intervention is pivotal in fostering low-carbon and environmental innovation through a mix of policy instruments addressing both market and structural failures [89], [90]. Effective aviation policies should address accountability, encompass both CO_2 and non-CO_2 emissions, plan for future propulsion systems and garner broad public support [63].

In 2020, Laur Kanger et al. (2020) [22] highlighted the importance of identifying and leveraging policy interventions to stimulate niches, destabilise existing regimes and coordinate systemic changes towards sustainability. Similarly, Pickard and Pasqualino [23] in 2022, using a system dynamics approach, identified key policy interventions in the aviation sector, stressing the need for regulation, quality investments, fiscal measures and international coordination to foster innovation and sustainability transitions. They also underscore the vital interplay between fostering innovation and attracting the required skills, both of which are indispensable for precipitating shifts in technological regimes. According to Pickard and Pasqualino government backing and international cooperation are crucial in catalysing and maintaining these transitions. The correspondence between the six leverage points proposed by Kanger et al. and the aviation intervention points identified by Pickard and Pasqualino is shown in FigureFigure 3 and Table 1.

Figure 3: Multilevel perspective framework and six leverage points for policy



Source: Infographic by Anna-Kati Pahker, based on Kanger et al. (2020). Reproduced with permission from Laur Kanger

Table 1: Alignment between leverage points for sustainability transitions and aviation intervention points

Leverage points for sustainability transitions (Kanger et al., 2020)	**Aviation intervention points (Pickard and Pasqualino, 2022)**
Stimulating different niches / increasing momentum for niche innovation	Regulation/bureaucracy, testing infrastructure and support
Accelerating niches	Quality of investment
Destabilising the regime	Taxation on brown technology, subsidy for green technology
Addressing the broader repercussions of regime destabilisation	Restricting growth, offsetting and mitigation
Providing coordination for multiregime interaction	Internationally agreed policy to prevent maintenance of status quo
Tilting the landscape	Impact of COVID-19, alternatives to flying

Sources: Kanger et al. (2020) and Pickard and Pasqualino (2022).

6 Review of interventions for the sustainability transition in aviation policies

The results of a previous literature review enabled the compilation of a list of decarbonisation levers. These levers were investigated in relation to the policy instruments currently implemented in the EU addressing (specifically or not) the aviation sociotechnical system. The outcomes of this investigation are detailed in Table 2.

The current chapter examines the main policy tools that the European Commission and a selection of Member States have issued or promoted to meet the 2050 emission objectives of the European Green Deal in the aviation sector. The European and national policy instruments identified in this process have been matched with the sustainability transition intervention points proposed by Pickard and Pasqualino. The principal findings and insights from this analysis are summarised in Table 2.

Table 2: Alignment of intervention points with current policy instruments

Leverage points (Kanger et al., 2020)	Intervention points (Pickard and Pasqualino, 2020)	European policy instruments	Examples of Member States' policy instruments	Gaps and barriers
Stimulating different niches	**Regulation**	Single European Sky (Regulation (EC) 549/2004) European Green Deal Taxonomy regulation (Regulation (EU) 2020/852) European sustainable and smart mobility strategy Fit for 55 package ReFuelEU aviation Regulation (EU) 2023/2405; NZIA Regulation (EU) 2024/1735	Netherlands: Civil aviation policy memorandum 2020–2050 'Responsible flying towards 2050' Sweden: Greenhouse Gas Reduction Mandate Act (2021)	Single European Sky is due to be updated to include incentives to reduce aviation's environmental footprint SAF availability (expected to be 0.53 % in 2024 and high cost) Power to liquids in technological readiness level 3–4
	Testing infrastructure	114 strategic and key research infrastructures in Europe	351 research infrastructures by countries	Research infrastructures need enhancement towards environmental sustainability and alignment with the evolving demands of the industry
	Airport and energy infrastructure	Connecting Europe Facility Alternative Fuels Infrastructure Facility Horizon Europe call on green airports as multimodal hubs for sustainable and smart mobility by CINEA		Insufficient planning and readiness of energy infrastructure in airports
Accelerating niches	**Quality of investment**	CINEA – Horizon Europe Clean Aviation Joint Undertaking – Horizon Europe EASA SESAR joint undertaking CINEA Innovation Fund 'Alliance for zero-emission aviation' initiative 'Renewable and low-carbon fuels value chain industrial alliance'	Spain: Plan Tecnológico Aeronautico France: France 2030 Netherlands: Actieprogramma Hybride Elektrisch Vliegen Sweden: Electric Aviation in Sweden Baltic Sea region hydrogen air transport project	Fragmentation of policies and funding. Better synchronisation is needed between different policy levels Insufficient access to private and public funding European R & D aviation programmes in different European Commission Directorates-General and executive agencies
Destabilising the regime	**Taxation on brown technology**	EU ETS Directive (EU) 2023/958	Germany: Aviation tax France: Civil aviation tax and Solidarity tax Austria: Aviation tax Sweden: Air ticket tax	The price of carbon within the system has not been high enough to generate substantial changes in airlines' behaviour.
	Subsidy to green technology	Strategic Technologies for Europe Platform (STEP), Regulation (EU) 2024/795set up by the EU to support the European industry and boost investment in critical technologies	France: Nation Verte 2030	Currently, the cost of biofuel is about two or three times that of kerosene. The power-to-liquid pathway is only implemented at demonstration level, resulting in a production cost about 5 times higher than that of kerosene.
Addressing the broader repercussions of regime destabilisation	**Restricted growth**	EU's aviation strategy, emphasising the need for sustainable airport development and infrastructure planning	Netherlands: since the end of 2023, Schiphol airport has limited the maximum number of flights to 440 000 per year, a 12 % decrease from its operations in 2019	Demand for travel is increasing. There are conflicts between tourism and businesses' interests due to the role of airports in territorial competitiveness.
	Offsetting	CORSIA Directive (EU) 2023/958		CORSIA carbon-capturing offsets can be double-counted. At COP28, no agreement was reached on Article 6 about mechanism for global carbon markets post-2020
Coordination multiregime interaction	**Internationally agreed policy to prevent maintenance of status quo**	Agreement on SAFs at COP28 of reducing international aviation CO2 emissions by 5 % by 2030, through the use of SAFs and low-carbon alternative fuels		A 1944 agreement by the International Civil Aviation Organization limits taxes on international aviation, and international flights are exempted from value added taxes or kerosene taxes
Tilting the landscape	**Alternatives to flying**	European sustainable and smart mobility strategy	Ban on regional air travel when the journey can be made by train (FR) Plans to speed up and expand passenger rail connections between Dutch airports and other European airports (NL)	There is a lack of measures to promote alternatives to flying.

Source: Authors' own elaboration.

6.1 Regulation

The pivotal role of European regulation in fostering the growth of emerging niches is aptly illustrated by the legislative advancements encapsulated within the fit for 55 package [9] and the 'ReFuelEU aviation' initiative [25]. The latter, effective from 1 January 2024, means that, beginning in 2025, fuel uplift at EU airports must contain at least 2 % SAF. That percentage will increase gradually each year, with mandates including 6 % by 2030, 20 % by 2035 and, eventually, 70 % by 2050. These requirements will apply to all flights originating in the EU, regardless of destination. This will serves as a significant catalyst for invigorating investments in SAFs, a sector currently characterised by production levels below 1 % in Europe and costs that are two to three times higher than those of conventional kerosene. The European Commission has also introduced the NZIA [10]. The recognition of SAFs as a strategic technology and the launching of the Strategic Technologies for Europe Platform (STEP) [30] are expected to significantly contribute to the stimulation and expeditious advancement of its readiness and production. In addition, the establishment of certification standards is needed [9] to boost private and public investment, while maintaining the technological base and leadership in Europe.

Such legislative actions are integral to propelling technological progress, particularly in the field of power-to-liquid pathways. Nevertheless, regarding the gaps in regulation, the updating of the Single European Sky [91], conceived to improve the overall efficiency of the organisation and management of European airspace, has been pending since 2020, and is urgently required to enable the implementation of incentives to reduce aviation's environmental footprint [92]. At the national level, countries such as the Netherlands and Sweden have pre-emptively enacted their respective legislative frameworks to encourage SAF utilisation [93], [94].

6.2 Aviation research infrastructures

Strategic and key aviation research infrastructures, such as wind tunnels, supercomputers, simulators and propulsion benches, serve as crucial facilities where new technological advancements can naturally emerge, showcasing significant transformative potential. The Horizon 2020 project Research Infrastructures-Needs, Gaps and Overlaps (RINGO) comprehensively mapped European and national aviation research infrastructures [95]. This mapping identified 114 strategic and key research infrastructures at the European level and 351 research infrastructures across the EU-27 Member States, with the Netherlands (n = 73) and Germany (n = 60) hosting the highest number of these facilities. The project's analysis emphasises the importance of avoiding redundancy in research infrastructures and highlights the need for timely development and upgrades to meet the evolving demands of the industry. It also underscores the necessity for substantial improvements, particularly in the realm of environmental sustainability.

6.3 Airports and energy infrastructures

Airports and energy infrastructures are vital. After shifting to alternative propulsion systems, existing large airports could consume 5–10 times more electricity by 2050 than they do currently [96]. This underscores that the planning and readiness of energy infrastructure is a key factor in determining the take-up of electric and hydrogen-based aviation [68]. To this end, the EU programme Connecting Europe-Alternative Fuels Infrastructure Facility [97] is deploying charging and refuelling infrastructure in EU airports, and the Horizon 2020 call 'Green airports and ports as multimodal hubs for sustainable and smart mobility programme' selected three ongoing large demonstration projects for airports: STARTGATE, led by Brussels Airport, TULIPS, led by Schiphol Airport in Amsterdam and OLGA, led by Paris-Challes de Gaule Airport [98]–[100] that entail solar panels, SAFs and hydrogen production and supply and highly efficient green operations, among others.

The main European airports have joined the European Airport Carbon Accreditation and NetZero2050 programmes through Airports Council International Europe. By June 2024, 290 European airports had been certified under the programmes [101].

6.4 Quality of investment

To facilitate the expeditious establishment of niches, it is imperative that substantial investments be made in R&D activities, with the objective of enhancing the preparedness of hydrogen and electric propulsion technologies. The current European aviation R&D framework is based on Horizon Europe projects, run by the European Climate, Infrastructure and Environment Executive Agency (CINEA) and two additional institutional public–private partnerships. The Clean Aviation Joint Undertaking [31] is responsible for advancing the demonstration of hydrogen and electric propulsion technologies, while the Single European Sky ATM Research joint undertaking is tasked with accelerating the delivery of the digital European sky. This will be achieved by leveraging the latest digital technologies to transform Europe's aviation infrastructure, while minimising environmental impact [32].

The Innovation Fund, the EU fund for climate policy (with a focus on energy and industry), and other instruments supporting green technology investment, such as InvestEU, are helping the aviation sector to invest in the green transition and reinforce European technological leadership on a global scale

Launched by the European Commission, the 'Alliance for zero-emission aviation' initiative (European Commission, 2022) and the 'Renewable and low-carbon fuels value chain industrial alliance' initiative (4) serve as voluntary European initiatives that bring together a diverse array of private and public stakeholders (aircraft manufacturers, airlines, airports, energy companies, fuel providers, standardisation and certification agencies, and passenger and environmental interest groups and regulatory bodies) with the primary goal of addressing the challenges associated with achieving zero-emission aviation. Both alliances facilitate industry collaboration, allowing partners to engage in matchmaking across the entire value chain, thereby fostering the development and completion of sustainable and integrated value chains.

At the national level, Spain, with Programa Tecnológico Aeronáutico [102], France, with France 2030 [103], and the Netherlands, with Actieprogramma Hybride Elektrisch Vliegen [104], have announced ambitious investments to support their national stakeholders contributing to the development of low-carbon aircraft. The Swedish innovation agency Vinnova funded the project Electric Aviation in Sweden and the interterritorial initiative 'Nordic network for electric aviation' [60].

Important Projects of Common European Interest, (IPCEI) in particular Hy2Move (focusing on hydrogen mobility), support the development of next-generation on-board storage solutions for hydrogen, and seven Member States are participating (Germany, Estonia, Spain, France, Italy, the Netherlands and Slovakia) [105].

(4) The 'Renewable and low-carbon fuels value chain industrial alliance' initiative extends its focus to include the waterborne sectors as well.

6.5 Taxation on brown technology and subsidies for green technology

Taxation could be a significant point of intervention to penalise the use of fossil fuel technology. Some countries impose their own aviation taxes, such as Germany, France and Sweden. However, the framework established by the International Civil Aviation Organization in 1944 restricts the imposition of taxes on international aviation, with international flights enjoying exemptions from both value added taxes and kerosene taxes [84], [106].

The EU ETS [33] overcomes this limitation and is currently the largest emissions trading system and the only multinational emissions trading system in operation. The EU ETS sets CO2 emission limits for airlines and obliges them to acquire and surrender emission allowances to cover their emissions. However, the EU ETS has been criticised for handing out too many free allowances to the aviation industry, indirectly incentivising greenhouse gas emissions [63]. While the scheme covers a portion of flights within the EU, it does not address emissions from international flights outside the EU, which account for a substantial portion of global aviation emissions.

It is evident that the carbon price within the EU ETS has not been high enough to generate substantial changes in airlines' behaviour [34]. Nevertheless, funded by the EU ETS, the Innovation Fund is playing a crucial role in financially supporting the advancement of SAFs and carbon capture and storage technologies. As previously mentioned, the STEP [107] was established by the EU to stimulate investment across several critical technology sectors, including batteries, hydrogen and sustainable fuels. This initiative aims to coordinate and boost funding from a combination of 11 existing EU programmes. These programmes encompass a wide range of funding sources, such as the digital Europe programme, the European Defence Fund, Horizon Europe, the Innovation Fund, InvestEU, the Recovery and Resilience Facility, and Cohesion Policy Funds, including the Cohesion Fund, European Regional Development Fund, European Social Fund+ and Just Transition Fund.

6.6 Offsetting

Directive (EU) 2023/958 [40] includes provisions to ensure the alignment of the EU ETS with CORSIA, ensuring that flights between Member States and non-European countries will be subject to CORSIA. This integration aims to avoid duplicate carbon pricing measures and streamline the management of international aviation emissions.

CORSIA mandates offsetting the post-2020 increase in aviation emissions to prevent net carbon emissions from increasing, through improving aircraft efficiency, using SAFs or adopting measures to offset emissions. While CORSIA began as a voluntary pilot scheme in 2021, numerous authors [59], [60], [73], [106], [108], [109] underline its focus on offsetting increased CO2 emissions after 2020, covering just 35 % of international aviation CO2 emissions between 2021 and 2035, and its failure to address non-CO2 emissions. Furthermore, the efficacy of carbon offsetting is often questioned due to the potential double-counting of carbon capture credits by both selling countries, to meet their Paris Agreement targets, and airlines, to fulfil CORSIA obligations [109]. In addition, it has been suggested that airlines may opt for offsets over emission reductions if offsets are cheaper than SAFs.

Thus, the aviation industry requires enhanced education and verification mechanisms to ensure the legitimacy of offsets, along with increased visibility through localised schemes [23].

6.7 Alternatives to flying

The European sustainable and smart mobility strategy [110] highlights the importance of promoting sustainable alternative transport solutions. Notably, the Government of the Netherlands has shown significant initiative in this regard, by accelerating and expanding passenger rail connections between Dutch airports and major European cities (e.g. London, Brussels, Paris, Frankfurt, Düsseldorf and Berlin). In addition, since the end of 2023, Schiphol airport in the Netherlands has imposed a cap on the maximum number of flights, reducing it to 440 000 per year. This represents a 12 % decrease from its 2019 operations. France has taken a proactive stance by banning regional flights where train travel is a viable alternative.

6.8 Policies and strategies implemented after the 28th Conference of the Parties

The parties at COP28, held in Dubai in December 2023 [111], reached an agreement that limiting global warming to 1.5 °C will require a large, rapid and sustained reduction in global greenhouse gas emissions and highlighted that the fossil fuel era should draw to an end, recognising the need for all to transition away from fossil fuels. The agreement also calls on the parties to triple global renewable energy capacity and double the rate of energy efficiency improvements by 2030 to accelerate efforts globally towards implementing net-zero emission energy systems, making use of zero- and low-carbon fuels well before or by around mid century. While emphasising the importance of a just transition, it also calls for efforts to be accelerated to phase down methane and other non-CO2 emissions and phase out, as soon as possible, inefficient fossil fuel subsidies that do not address energy poverty or vulnerable groups. This will require a shift in investment patterns across the globe to ensure that finance flows are consistent with low-emission and climate-resilient development.

However, COP28 fell short of delivering the operational rules for global carbon markets after2020, which are crucial to establishing a resilient, transparent and operational global carbon market. This market plays a pivotal role as a significant source of the offsets necessary for the International Civil Aviation Organization framework.

Following COP28, on 7 February 2024 the European Commission published a new communication outlining a proposed 2040 climate target for Europe. This proposal provides the aim of achieving a 90 % reduction in net greenhouse gas emissions compared with 1990 levels, setting a clear trajectory towards achieving climate neutrality by 2050. The document emphasises the need for ambitious and coherent actions across all sectors to ensure that the EU meets its long-term environmental objectives, reinforcing the EU’s commitment to sustainable development and significantly reducing emissions [112]. This heightened ambition should increase pressure on the aviation sociotechnical system, compelling stakeholders to adopt bolder measures for reducing emissions. The aviation industry and SAF production will probably face stronger demand and greater investment needs, but also higher scrutiny, necessitating accelerated innovation in sustainable technologies and practices.

6.9 Gaps and barriers

The analysis of the primary gaps within the current EU policy frameworks and those of Member States points to the need for better synchronisation between different territorial levels to ensure best usage of existing funds at the regional, national and EU levels.

Attention must also be focused on the numerous programmes addressing investment in the sustainability transition. Coordination and synergies, both horizontal and multilevel, are needed to develop comprehensive initiatives able to address multiple interconnected challenges (related to sustainability, competitiveness, digitalisation, etc.) simultaneously while making the most of financial resources. One particular synergy that deserves further exploration is that between aviation, defence and space industries [113].

However, insufficient attention to workforce development is observed in this analysis. As the industry transitions to more sustainable practices, there is a growing need for new skills and competencies. This requirement extends beyond the creation of new jobs to include the reskilling of existing employees to adapt to new technologies and processes. The setting up of the net-zero industry Academies, envisaged in the NZIA [10], is expected to contribute to filling this gap, enabling Member States and the European Commission to collaborate.

Finally, a glaring oversight in most of these initiatives is the absence of a place-based perspective. Achieving this sustainability ambition requires an effective innovation-driven policy with clear directionality, necessitating the proper involvement and division of tasks among the European, national and regional/local levels of governance [114]. Additionally, many of the policies involved in sustainability transition pathways (innovation, education, environment, energy, mobility, regulation, taxation, infrastructure,…) are dispersed between those different governance levels and differ across EU Member States. A territorial perspective is crucial for understanding and addressing the distinct challenges and opportunities inherent in varied geographical and socioeconomic environments. Incorporating this place-based focused approach can lead to more ailored and impactful policies that consider the specificities of different regions, thereby making a more substantial contribution to the overarching objectives of global sustainability.

7 Place-based approach to European aviation: Analysis of the S3 (2021–2027)

To illustrate one aspect of the place-based dimension of European aviation, we analyse the 2021–2027 Smart Specialisation Strategies (S3), which were designed in a bottom-up way by European Member States and regions. The S3 establish thematic priorities at the national and/or regional levels, to enhance competitive advantage by aligning research and innovation strengths with business needs and the requisite skills through an entrepreneurial discovery process. Effective governance of national or regional S3 is an ‘enabling condition’ for the European Regional Development Fund under Objective 1, which focuses on facilitating innovative and smart economic transformation through smart specialisation To explore the place-based dimension of European aviation, we analyse the 2021–2027 S3, which were designed from the bottom up by European countries and regions. The S3 establish priorities at the national and/or regional levels, to enhance competitive advantage by aligning research and innovation strengths with business needs and the requisite skills through an entrepreneurial discovery process. Effective governance of national or regional S3 is an ‘enabling condition’ for the European Regional Development Fund under Objective 1, which focuses on facilitating innovative and smart economic transformation through smart specialisation [115].

The data gathered from the S3 Community of Practice Observatory [116] on 8 August 2024 shows that NACE activity H51, ‘air transport’ is included in the S3 of 60 European territories for 2021–2027 at different levels. Three types of regional smart specialisation priorities include Air Transport activity: those related to the aerospace industry, those connected with logistics and smart mobility, and those linking aviation with tourism

Aerospace, is prioritised by regions where the industrial footprint of the European aerospace value chain is present. These regions include hubs such as Hamburg (Germany), Andalusia (Spain), Provence-Alpes-Côte d’Azur (France), Piedmont (Italy) and Podkarpackie (Poland).

The possibility for regions to deploy a tailor-made policy mix for their aeronautics industry, potentially co-financed by the European Regional Development Fund, provides them with a significant boost to industrial investment and the adaptation of business capacities. At the regional level, substantial investments are being made in hydrogen, electrification, and sustainable aviation fuels (SAFs) through R&D projects, research infrastructure, SME competitiveness programs, talent development initiatives, interregional cooperation, cluster support, innovative public procurement, regulatory sandboxes, and other instruments. Regions can develop cutting-edge technologies, attract investment and talent, and improve their regional innovation ecosystems. Additionally, many 'aerospace regions' are making significant investments in unmanned aerial vehicles (including those with dual-use and defence applications), vertical take-off and landing aircrafts, and smart air mobility as part of their commitment to green aviation

However, the majority of regions that have included air transport activities in their smart specialisation strategy are taking a more comprehensive approach. For these territories, air transport is part of their logistic and smart mobility priorities. This is exemplified by regions such as Bremen, Catalonia and Emilia-Romagna, which illustrate a shift from a ‘mode-centric’ to a ‘customer-centric’ transport system, in line with the vision set out by the Advisory Council for Aviation Research and Innovation in Fly the Green Deal: Europe’s vision for sustainable aviation [117].

Finally, two ultra-peripheral regions – Madeira, in Portugal, and Norrbotten, in Sweden – have chosen tourism as a focus of their regional smart specialisation strategy, including air transport. Future research should further explore the territorial dimension of tourism and aviation, especially in light of the post-COVID-19 tourism boom, as suggested by Marques et al. [118] This resurgence in travel is generating significant conflicts across various regions in Europe, where tourism is a core economic driver.

To this end, making more use of the opportunities of interterritorial collaboration can be can better support sustainability transition. Collaborations between regional authorities, such as the hydrogen valleys S3 partnership [119], [120] and the 'Regional innovation valleys' initiative, aiming to reduce reliance on fossil fuel [121], could provide opportunities to be exploited by territories in the promotion of green regional aviation hubs and sustainable airports. Business cooperation across the EU is supported by the Eurocluster Metastars,[122] and several European University Alliances focus on Aerospace (Pegasus groups 31 aerospace engineering universities) [123] or on zero-emission aviation (Alliance for Zero-Emission Aviation - AZEA).[124] In particular AZEA targets involvement of partners across the entire aviation ecosystem. But there is much room for further alignment between all relevant actors. One example is the wide availability of funds at regional level for supporting skills for S3 (from ERDF, ESF, Recovery and Resilience Funds,…), which are often spent at territorial level in an uncoordinated way [125]

The highlighted points underscore the importance of the place-based approach to Europe's sustainability transition in aviation. After analysing the sociotechnical system of aviation [18], and European and national policies as well as territorial S3 policies, it becomes clear that the transition towards sustainability requires the adoption of a multiscale perspective [126] that involves significant governance complexities. The transformation necessary for this transition requires public administration, airports, the aerospace industry, energy providers, airlines, universities, the tourism sector and citizens, all rooted in specific territories [114], to reconfigure their networks for sustainable production, value capture and knowledge diffusion. The evolution of these entities is intricately linked to, and influences, local economies, skills development, and employment and innovation dynamics.

8 Elements of a systemic and place-based transition pathway in regions specialised in aviation

The S3 were initially designed to exploit priority areas where regions could achieve a competitive advantage. However, in order to address the sustainability transition mandate, including decarbonisation, the circular economy and biodiversity, territories need to develop sustainable transition pathways that encompass broader policy agendas. These pathways should not only focus on industrial and technological priorities, but also embrace environmental, social and organisational dimensions. This requires an innovative vision that drives systemic change across various sectors and knowledge domains, adopting a 'challenge-oriented' approach to ecological and socially driven priorities.

As part of the approach of transformative innovation policies [3], [4], [57], territorial policies are comprehensive, spanning the local, regional, national and international governance levels and encompassing a multidomain portfolio of projects. Expanding the focus from sector-specific analysis (aviation) to a challenge-oriented approach could mean encompassing diverse sociotechnical systems (energy, mobility, industry, digital, tourism, infrastructures, etc.) and engaging growing stakeholder coalitions. For example, regional investments in hydrogen development could be of key importance for sustainable aviation and regional airports, which can become energy and logistic hubs, and the development of aviation electrification and vertical take-off and landing aircrafts could entail new approaches, such as advanced air mobility, as part of the mobility as a service approach. Experimentation with anticipation-based policy instruments can open up new areas of exploration, and help to define acceptable transition pathways. The acceptation of this transition pathways requires developing a deep understanding of the problems and the solutions from the point of view of those who face them. The development of the open discovery process, which enables engagement, deliberation and pathway co-creation, paves the way to a fair transition, leaving nobody behind [127].

Effective multilevel governance and coordination is needed to sustain, strengthen and diversify capacities in regions, concurrently contributing to the overall transition of the European aviation system. The role of the European cohesion policy and the Recovery and Resilience Facility is relevant in supporting essential areas such as infrastructure development, R & D, digitalisation of small and medium-sized enterprises, advanced services and technology transfer.

Aligning territorial pathways with European initiatives, such as the clean aviation joint undertaking, the Alliance for zero-emission aviation' (AZEA) initiative, the European sustainable and smart mobility strategy, the green deal industrial plan, NZIA , the drone strategy, the space strategy and the European defence strategy, could enhance local efforts and other territories' wills. Interterritorial cooperation allows regions to pool resources, develop infrastructure, optimise their positioning in the European value chain, exchange talent, foster regulatory alignment and create joint opportunities for research and skills development.

A transformative directionality requires multiple delivery mechanisms. Funding projects with transformative ambitions can be organised into portfolios that share a common challenge and are supported by multiple funding sources, including those not traditionally associated with innovation. It is also crucial to support intermediation mechanisms such as clusters, as well as competence centres and training institutes. In addition, the creation of policy laboratories or regulatory sandboxes may be necessary to pinpoint the most effective delivery mechanisms.

In regions committed to sustainable aviation, transformative innovation policies could be instrumental. These policies actively engage stakeholders, build legitimacy, envisage the transition process, orchestrate collaboration and design support for the ecosystem, creating a comprehensive and adaptable framework. This strategic approach not only facilitates the regional transition pathway but also bolsters territorial resilience, ensuring continuous learning and adaptation throughout the transition process.

9 Conclusions

To boost EU competitiveness and accelerate sustainability transitions, the Draghi Report underlines the critical need for improved policy coordination across EU Member States and European institutions. This paper examines the case of the sustainability transition in aviation and argues for a systemic approach that interweaves sub-national governance to effectively enforce climate neutrality in the European aviation sector.

With demand for air travel projected to grow significantly and CO2 emissions potentially tripling by 2050, achieving the Green Deal goal of a low-carbon transition in the case of aviation goes beyond technological innovation or carbon pricing alone. This transition must involve systemic change. Our multi-level perspective analysis highlights the critical role of levers such as regulation, investment, subsidies, taxation and the promotion of alternatives to flying, as well as communication strategies to change public perceptions and encourage less energy-intensive travel alternatives.

Our research highlights the importance of considering these intervention points at different levels of governance: regional, national and European. Territorial governance plays a crucial role in tailoring aviation, industrial, mobility, energy and environmental policies, and embodies the potential of transformative innovation to create synergies between aerospace, tourism, smart mobility and broader territorial development. Using the case of the aviation ecosystem, this paper illustrates how sustainability transitions for competitiveness can be more successful if the territorial dimension is taken into account.

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List of abbreviations and definitions

Abbreviations	Definitions
ACARE	Advisory Council for Aviation Research and Innovation
ACI	Airports Council International
ATM	Air Traffic Management (ATM)
AZEA	Alliance Zero Emission Aviation
CINEA	European Climate, Infrastructure and Environment Executive Agency
CORIS	Challenge Oriented Regional Innovation Systems
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COP28	Conference of the Parties (COP28). 28th United Nations Climate Change Conference
EU ETS	European Emissions Trading System
GHG	GreenHouse Gas
HAPs	High Altitude Platforms
IATA	International Air Transport Association
IPCC	Intergovernmental Panel on Climate Change
ICAO	International Civil Aviation Organization
MLP	Multilevel Perspective
MaaS	Mobility as a Service
PRI	Partnerships for Regional Innovation
PtL	Power to Liquid
EU NZIA	European Net Zero Industrial Act
S3	Smart Specialisation Strategies
RIs	Research Infrastructure

RLFC	Renewable and Low-Carbon Fuels Value Chain Industrial Alliance
SAF	Sustainable Aviation Fuel
STEP	Strategic Technologies for Europe Platform
TIP	Transformative Innovation Policies
TRL	Technological Readiness Level
VTOL	A vertical take-off and landing (aircraft)
UAVs	Unmanned Aerial Vehicles

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