systems

Article

Long-Term Strategies for the Compatibility of the Aviation Industry with Climate Targets: An Industrial Survey and Agenda for Systems Thinkers

Chris Pickard [1] and Roberto Pasqualino [2,3,*]

[1] Pickard Associates Ltd., Chippenham SN15 4LX, UK; chris@pickardassociates.co.uk
[2] Department of Land Economy, University of Cambridge, Cambridge CB39EP, UK
[3] Global Sustainability Institute, Anglia Ruskin University, Cambridge CB1 1BG, UK
* Correspondence: rp747@cam.ac.uk

Abstract: Aviation is responsible for nearly 2.5% of the world's anthropogenic carbon emissions. Despite a commitment to reduce these emissions, it is a challenging industry to decarbonise. Very little is known about the attitudes of those working in aviation towards climate change and whether they are motivated to support decarbonisation initiatives. This uncertainty highlights several threats to the industry, with cascading impact on the economy and inequality. To deal with these challenges, this study explores long-term strategies to support compatibility between the evolution of the aviation industry and climate constraints. Using surveys, in-depth interviews, and thematic analysis, this research investigates the views of professionals towards climate change, and the role that they perceive aviation plays. The results of the interviews allow the development of a system map composed of ten self-reinforcing and three balancing loops, highlighting ten leverage points to inform strategies for the industry to respond to threats. This research concludes that the aviation industry should encourage a new generation of sustainability-aware innovators to decarbonise aviation. It also concludes that collaboration both internationally and within the industry is essential, as is the need to encourage an open-minded approach to solution development. It also presents the modelling results in terms of the multilevel perspective technological transition framework and suggests ways forward for modelling using the risk–opportunity analysis.

Keywords: aviation; decarbonisation; systems; reinforcing loop; system dynamics; industrial strategy; climate change; systemic risk; multilevel perspective; risk–opportunity analysis

check for updates

Citation: Pickard, C.; Pasqualino, R. Long-Term Strategies for the Compatibility of the Aviation Industry with Climate Targets: An Industrial Survey and Agenda for Systems Thinkers. *Systems* **2022**, *10*, 90. https://doi.org/10.3390/systems10040090

Academic Editors: Stefano Armenia, George Tsaples and Eduardo Ferreira Franco

Received: 29 April 2022
Accepted: 21 June 2022
Published: 28 June 2022

1. Introduction

Climate change concern continues to grow, and the need to decarbonise is becoming increasingly evident. In 2015, the Paris Agreement set a carbon emission target, with the aim of holding the global average temperature rise to less than 2 °C, compared with preindustrial levels, with a recommendation to limit temperature increases to 1.5 °C [1]. However, the Intergovernmental Panel on Climate Change (IPCC) has warned that global warming is likely to reach 1.5 °C between 2030 and 2052 if emissions continue at the current rate [2]. Evidence of climate change is becoming more apparent, with increasingly common extreme weather [3].

As shown in Figure 1, the growth trend in global flights was +4.6% and +2.1% in 2018 and 2019, respectively. The trend dropped to −56.6% (from 38.9 million to 16.9 million) in 2020 due to COVID-19. Despite the impact of COVID-19, aviation demand is expected to reach 25.8 million flights by the end of 2022 and continue to grow beyond pre-COVID-19 levels [4–6]. Therefore, if using kerosene, aviation will increase greenhouse gas emissions when other industries are limiting or reducing their carbon emissions. Aviation is difficult to decarbonise [7]; therefore, to meet the decarbonisation challenge, aviation will require complex and innovative solutions. In addition, the uncertainty around climate change highlights a number of threats to the industry, with cascading impacts on the economy, inequality, and social resistance, leading to conflicts and unrest around the world. To deal with these challenges, this study explores long-term strategies to support compatibility of the aviation industry's evolution within climate change constraints.

Figure 1. Impact of COVID-19 on flights in the global economy [6].

Literature on aviation's climate change impact focusses on the science, the effect of emissions, and potential solutions for reduction or mitigation. Where research covers the human aspect, it often focuses on the traveller's motives and their willingness to reduce flying [8]. Additionally, news articles effectively pitch the aviation industry against environmentalists and campaigners [9,10]. However, change is more effective when top–down leadership and direction is accompanied by bottom–up engagement and action [11]. While governments can set targets, without industry support, these may be hard to achieve. Little is known about the motivations of those working within the aviation industry, how enthusiastic they are to help generate the change needed to decarbonise and the challenges they see ahead. Therefore, this research seeks to understand how concerned those working in the aviation industry are about climate change and whether they support the changes needed to decarbonise, and to gain further insights into the solutions and challenges they see ahead.

The methodology adopted in this paper follows a mixed qualitative method. First, the views and opinions of aviation professionals working in the industry were investigated. Surveys, in-depth interviews, and thematic analysis enabled an understanding of how concerned aviation professionals are about climate change, and therefore how likely they are to influence and support the decarbonisation of aviation. Further investigations identified what they see as the biggest challenges ahead for the industry, the solutions they think will most likely enable decarbonisation, the support needed, and the obstacles that may prevent progress. Second, the results of the interviews allowed the development of a system map by focusing on the challenges of the industry in dynamic terms. Several self-reinforcing feedback loops are proposed as elements to target strategies, enabling the industry to respond to threats effectively and in the long-term.

In Section 2, this article reviews current literature covering aviation's impact on climate change, proposed solutions and progress on decarbonisation. Section 3 explains the methodology and why a mixed method of surveys and interviews was used to collect data, and how these were analysed. The data and analysis from the survey and interviews are presented in Section 4, including the output from a coding exercise, identifying the emerging challenges and solutions. Section 5 uses the results of the interviews to propose a system map highlighting ten self-reinforcing feedback loops and three major balancing loops that help in identifying and visualising the leverage points required to engage in meaningful long-term strategies for the aviation industry. Section 6 provides a discussion on the paper aiming at answering the following questions: (i) What do aviation professionals think about climate change and aviation's role? (ii) What do they think are the biggest challenges and threats for the future of aviation? (iii) What solutions do they expect to be most likely to enable decarbonisation? (iv) What do they think is needed to encourage decarbonisation, while considering key barriers? Section 6 also presents the results of the system mapping exercise based on a theoretical framework for technological transitions (multilevel perspective) and suggests future modelling work based on a complexity theory modelling framework (risk–opportunity analysis). Section 7 concludes the paper and highlights future steps.

2. Literature Review

2.1. Aviation's Climate Impact

Aviation contributes nearly 2.5% of the world's anthropogenic carbon emissions [12], which, although less than many other industries, is emitted by a disproportionately small percentage of the world's population. In 2018, only 11% of the world's population flew, with at most 4% taking international flights. Estimates suggest that 1% of the world's population is responsible for more than half of global aviation emissions [13]. Aviation is responsible for 7% of carbon emissions in the UK, which is likely to grow further as other industries begin to decarbonise [14].

Aircraft also contribute to climate change through non-carbon impacts, such as nitric oxide (NO_x) and contrail formation from water vapour. Therefore, it is anticipated that aviation's total impact on climate change is significantly above 2.5%. Although there is more uncertainty over non-CO_2 effects, one paper in 2020 suggested that aviation's total global warming potential could even be three times that associated with CO_2 emissions alone [15].

Aviation is particularly difficult to decarbonise. However, the International Civil Aviation Organisation (ICAO) agreed on two goals for the international aviation sector; to improve efficiency by 2% per year and to limit carbon emissions beyond 2020 levels [16]. This limit is to be achieved through a "basket of mitigation measures", including improvements in aircraft technology, operational efficiencies, sustainable aviation fuels (SAF) and market-based measures through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [17].

However, the UK has set more aggressive targets, with aviation targeted to be net-zero by 2050 [18]. This target maintains the basket-of-measures approach but sets more challenging targets [19]. The UK was also the first major economy to set a net-zero emissions law [20]. In the recent UK Government Net-Zero Strategy, Prime Minister Boris Johnson says that, by 2050, "our planes will be zero-emission, allowing us to fly guilt-free" [21]. In addition, the strategy outlines that, as an interim target, by 2030, 10% of aviation fuel will be SAF [22].

2.2. Decarbonisation Solutions and Progress

Limiting flying would reduce emissions immediately. However, it is argued that aviation is essential for social cohesion and the economy, supporting many of the UN's Sustainable Development Goals (SDG) and contributing USD 3.5 trillion to the global gross domestic product (GDP) [23]. While there is a link between labour productivity (GDP/hour) and connectivity, this link diminishes at higher GDP levels [24]. However, other studies suggest that economic output remains the main factor influencing demand [25]. Nevertheless, the question as to whether people should fly less remains, with a recent UK poll suggesting that the majority of the population felt that some limits on flying should be introduced to tackle climate change [26]. The Swedish flygskam (meaning "flight shame") movement also highlights the concern [27]. However, the right to fly is often considered an "entitlement" [28] and restricting it is deeply unpopular. In regions of the world where flying is considered the norm, there is minimal incentive to limit flying unless the cost to do so makes the choice an obvious economic decision [29]. A study in New Zealand found that travellers are unwilling to stop travelling and that limiting travel was seen as unacceptable, suggesting only societal changes are likely to bring about behavioural change [30].

Aligned with the ICAO basket of measures, efficiency improvements to airspace and aircraft technology continue to be targeted, with significant steps taken to improve aircraft efficiency. For example, aircraft such as the Airbus A220 achieves 25% lower fuel burn per seat kilometre than the previous aircraft generation [31]. Between 1968 and 2014, the average fuel burn of aircraft decreased by approximately 45%, or at a rate of 1.3% per annum [32]. Furthermore, since 2000, fuel efficiency has improved by 37.8% [23]. However, research suggests that these improvements are unlikely to enable aviation to meet the ambitious decarbonisation 2050 goals set by the Air Transport Group (ATAG) and the International Air Transport Association (IATA) [33]. These goals are particularly challenging as aviation growth is likely to continue at a rate faster than efficiency improvements [34]. Similarly, airspace design improvements continue, with measures such as continuous descent, contrail avoidance, and ICAO's proposed performance-based approach [35] being implemented.

Using efficiency and technology improvements, some argue that it is possible to reduce carbon emissions without limiting activities [36], or as Boris Johnson says, without a "hair shirt in sight" [21]. They argue that the solution is to rely on technology as a way of reducing carbon emissions. While many technological developments will undoubtedly help, others argue that we cannot wait for technology to deliver net-zero by 2050 [37]. At the 26th Conference of Parties (COP 26) in November 2021, the Barbados Prime Minister emphasised the concern of relying on technological developments, saying that "... commitments made by some are based on technology yet to be developed, and this is at best reckless and at worst dangerous" [38].

One of the most promising technologies currently available, but only in small quantities, is SAF, or sustainable aviation fuel. SAF is important to ICAO's basket of measures, and the ICAO Assembly has encouraged its development and deployment [39]. Unlike hydrogen or battery–electric, SAF can be used with existing jet engine technology with minimal impact when blended with existing jet fuel [40].

However, SAF is not without issues. Various sources, or feedstocks, can be used to develop SAF, and the methods used are at different stages of technological readiness. These feedstocks can be summarised as biomass to liquid (BtL), waste to liquid (WtL) and power to liquid (PtL) [41]. Biomass to liquid, or biofuels, use naturally grown biomass that has absorbed carbon as it grows, which is then released when the fuel is burnt. However, biofuels, particularly first-generation biofuels using edible food crops, require a feedstock potentially competing with land required to grow food [42]. Campaigners have accused biofuels of resulting in "land grabs, deforestation, biodiversity loss, water scarcity, rising food prices and land-use emissions, which can be worse than the fossil fuel they are replacing" [43]. Waste to liquid fuels use carbon in waste from various sources, such as food waste. If sent to landfill, food waste produces methane and is responsible for around 6% of greenhouse gas emissions worldwide [44]. Alternative pathways plan to use non-recyclable household waste, such as the proposed bio-refinery in Ellesmere Port, Cheshire [45]. While using waste for energy is attractive, it is also argued that it may discourage recycling initiatives and the desire to reduce primary waste [46]. The most promising SAF, resulting in the most significant CO_2 reduction, is PtL SAF. PtL SAF uses CO_2 from the atmosphere or industrial processes, combined with hydrogen, which if green hydrogen, produces a near-zero-carbon fuel [47]. However, PtL SAF technology is in its infancy and is currently only produced at very low levels [48]. Costs for PtL SAF are expected to be three–five times more expensive than conventional fuel until renewable energy costs decrease [49].

There has been an increasing focus on hydrogen-powered aircraft, with trials of gaseous hydrogen aircraft, such as ZeroAvia, taking place and the first test flight of a hydrogen–electric passenger aircraft [50]. ZeroAvia plans to fly the first commercial flight with a 19-seater aircraft from the UK to the Netherlands by 2024 [51]. However, due to the volume of gaseous hydrogen required, liquid hydrogen has been proposed as an alternative form of hydrogen for larger and longer-range aircraft [52]. Airbus has also announced plans to develop a range of liquid-hydrogen-powered aircraft through its ZEROe initiative [53]. In addition, the UK government funded feasibility studies through the Aerospace Technology Institute's Fly Zero Programme [54]. However, the success of these projects remains many years away, with a potential timeline for introduction of at least 10–15 years.

As well as developing a liquid-hydrogen-powered aircraft, providing the ground infrastructure capability is also a significant technological and investment challenge [55–57]. In addition, currently, most hydrogen is manufactured as grey hydrogen, using natural gas or methane in production and emitting CO_2 into the atmosphere [58]. In theory, the development of blue hydrogen, which captures the carbon from otherwise grey hydrogen, provides a low-carbon fuel. However, it remains controversial, as blue hydrogen has been shown to have a potential greenhouse footprint greater than burning natural gas or coal [59]. Therefore, green hydrogen from electrolysis will be required for a zero-carbon solution, but the technology is immature, and the electrical power requirements are very high [60,61].

Due to the safety concerns of hydrogen, battery–electric appears the easiest and potentially safest zero-carbon fuel; however, using current technology, the batteries are heavy, limiting the range and aircraft size. However, there is a significant investment in electric flight, including from Airbus [62], Ampaire [63] and Rolls Royce [64].

While future fuels offer hope for a low-carbon future, carbon offsetting has often been proposed as a mitigation measure [65]. By absorbing the amount of carbon emitted during flight elsewhere, the flight could theoretically be considered net-zero. However, the effectiveness of carbon offsetting is often challenged due to the opportunity for the process to be exploited, with carbon-capturing double-counted or mitigation schemes being ineffective [66]. However, for programs such as ICAO's CORSIA scheme, the ICAO Council has approved a list of emissions units that can be used to ensure the integrity of the scheme [67]. Therefore, while offsetting is subject to much criticism, it is one of the only approaches currently available. Whichever solution is proposed, if not fully zero-carbon, the risk of the rebound effect [68] may negate the carbon-reduction benefit by encouraging further demand.

3. Method

A mixed method including surveys, interviews, and system mapping was adopted to carry out this research. In order to ensure findings were representative of the industry, the surveys allowed quantitative questioning, adding value to the primary qualitative approach. The trial interviews helped inform the specification and recruitment of the quantitative survey questions [69]. Using mixed methods also allowed data triangulation [70]. Therefore, both interviews and an online survey were used for this research.

This research focused on understanding the personal views of those in the industry; therefore, each participant needed to be able to express their personal views without concern over how peers would perceive their answers [71]. The interviews were transcribed and coded after each had been completed to determine when saturation of code words had been reached, indicating whether further interviews would add value [72]. Although the survey and interviews were not identical, they contained many similarities and allowed participants to share thoughts on the same topics. The main difference between the two approaches was that the survey provided a broader cross-section of the industry, whereas the interviews provided more depth within specific questions, each expanding and complementing the other [70]. However, although the results highlighted where each approach gave additional insight, there was a high degree of convergence [69]; therefore, the results were combined when undertaking the analysis and coding exercise.

Figure 2 outlines the complementary benefits of the survey and interviews, highlighting the subsequent joint analysis.

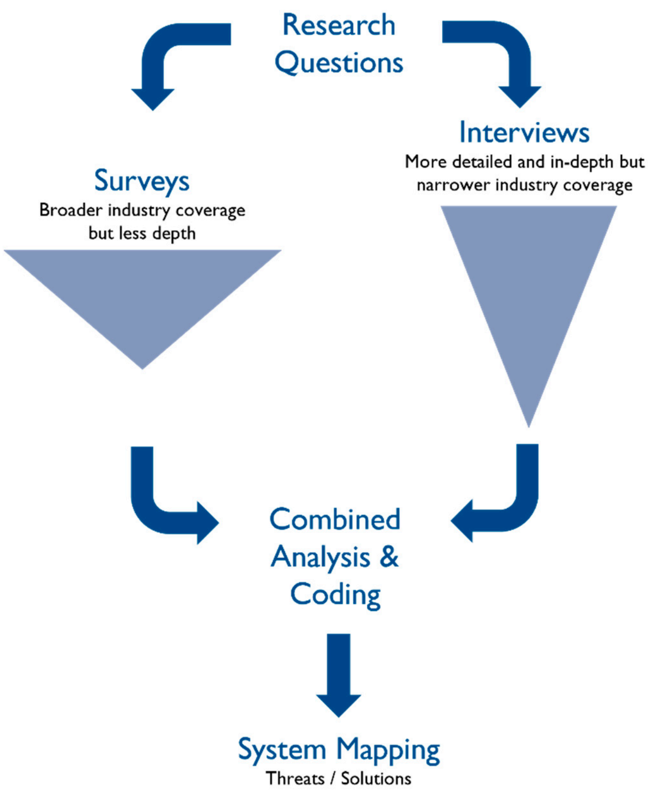

Figure 2. Survey and interview process interaction.

3.1. Participant Recruitment and Data Collection

Interviewees were recruited through the authors' networks drawn from over twenty-five years of working in the aviation industry, helping to overcome some of the potential recruitment difficulties [73] and minimise the potential for bias, discussed further in Appendix C. Participants were screened to ensure a balance and sufficient experience. Participants were required to have at least five years' experience in the industry and to hold an aviation-focused role rather than just working within an aviation-related business.

Participants were selected to obtain a wide spread of industry experience, covering airports, airlines, aircraft manufacturers, consultants, airport planners, government, trade bodies and researchers. Most participants selected had experience working across multiple sectors of the industry. The selection also ensured that the majority of those interviewed were not sustainability or environmental specialists. Participants who were likely to be willing to share openly were also selected [74].

During interviews, participants were asked to recommend others they thought would be beneficial to interview. In total, thirteen interviews took place. Recruitment for the online survey was primarily through the LinkedIn professional network. A link to the survey was posted and subsequently shared by others creating a snowball effect [75]. The survey ran for thirty days from August to September 2021, resulting in ninety completed questionnaires.

For both the interviews and surveys, information was anonymised, and only necessary information was collected. For the surveys, no personal information was collected other than the participants work background. An age range was asked in the interviews, which was split into broad categories to minimise the risk of personal identification. Gender was not asked in the surveys, and the country of the participant's role was asked, rather than their nationality. Quotes used within this report have been carefully selected to ensure no sharing of identifiable information. Audio data were deleted to ensure anonymity.

3.2. Interview Process

Initially, two interviews were held to test the questions and the approach to recording and processing data. The pilot interviews tested for flaws and weaknesses in the interview design [76] that was adjusted for the following interviews. All the interviews took place online using Microsoft Teams. On average, the interviews took an hour, although they ranged between forty and ninety minutes. Interviews started with a brief introduction and confirmation that the participant was happy to give consent and for the interview to be recorded. Although conducted using video conferencing, only the audio of the interviews was recorded, recognising the potential for recording video to make participants feel self-aware.

The interviews were semi-structured, using neutral language and broad open questions to encourage sharing of experience and knowledge without influencing the answers [77]. Participants were not stopped or interrupted while they were talking. Further prompts were, however, given if clarification was needed. Although the question template for all interviews was the same, questions were adapted during each interview to maintain a natural conversation.

After each interview, the audio recording was transcribed. Transcription was carried out in multiple stages. "Otter.ai" software (Otter.ai, San Francisco Bay Area, CA, USA) was used for the initial first pass at transcription, although this resulted in frequent errors. However, this process provided a base transcription and a processing environment to manually review each of the automated transcripts. Although manual transcription was a lengthy process, this was also very valuable. By re-listening to the interviews and editing line by line, topics and responses missed during the initial interview were identified. The manual process also allowed more emotion and context to be reflected in the transcription [78], helping in the later coding stages. Once the interviews were transcribed, they were imported into software called "NVivo" (QSR International, Melbourne, Australia) for coding. The questionnaire template used is included in Appendix A.

3.3. Surveys

The survey consisted of multiple-choice questions and open, free-text questions. Information was asked regarding the participant's most recent role, a broad indication of age, and the country in which their current or last role was based. The remaining questions sought to understand the participants' general thoughts on the future challenges for aviation, climate change and aviation's role within this; whether aviation growth should be restricted; which solutions they thought would be most effective at reducing climate change; whether they felt offsetting was effective; and how decarbonised they thought the industry would be by 2050.

Open-text questions were used to capture as much information as possible. A follow-up question asked the participants to explain their answers in more detail where multichoice questions were used. The risk of asking free text questions was acknowledged, recognising that the response rate would likely be less than a simple multi-choice survey. However, to achieve the richest possible information, the open-text method was preferred [79]. A total of ninety fully completed questionnaires were recorded. Once the survey had finished, the responses were imported to "NVivo". The survey template used is included in Appendix B.

3.4. Thematic Analysis and Coding

Descriptive analysis of the survey and interview data is included in Appendix D. However, due to the amount of content available from ninety completed questionnaires and over ten hours of transcripts, a methodical analysis approach was adopted to ensure all data were evaluated and reflected in the analysis. This methodology also helped us identify the key themes that would later address the research questions.

All transcripts and questionnaires were analysed line by line, identifying key topics, and coding the text accordingly. Coding was data-driven, without the use of a predefined coding framework [80]. By allowing codes to evolve [81], this inductive or data-led approach resulted in over one hundred and twenty individual codewords assigned across all data.

The coding methodology gave structure to the analysis and ensured that feedback was evaluated and weighted appropriately, reflecting the views of the participants. Coding helped to identify issues but on its own resulted in data too disaggregated to provide meaningful insight. Therefore, the codes were sorted and aggregated into key themes. These combinations of codes highlighted the major research topics, allowing a structured approach to evaluation, enabling the research questions to be addressed.

The coding process was helpful in establishing whether enough data were collected. Initially, every questionnaire or interview analysed resulted in many new codes being identified, which did not fit into any of the existing themes. As the process continued, the need for new themes became more infrequent as topics were repeated and new codes fitted within the existing themes. Finally, as the analysis reached the last questionnaires and interviews, no new themes were discovered, indicating that the analysis had reached saturation point, limiting the value of adding more data [82]. This conclusion is relevant within the limitation of the data-collection methods used, e.g., surveys and interviews carried out in English, focussed mainly within Europe. However, new sample sets may have resulted in additional codes and themes, although within the limitation of the data-collection methodology, saturation was reached.

3.5. Systems Mapping and Reinforcing Feedback

The thematic analysis of the interview was then used to develop a systems map identifying the fundamental leverage points that trigger change and threats in the aviation industry. The systems map is founded on the concept of system thinking, reinforcing loops and balancing loops that are very common in the context of complex systems and systems dynamics [83]. As this analysis does not provide precise numbers for developing a formal computer model, this task is left as a next step for further research. However, this research supports the understanding of wider aviation–ecological systems. This understanding informs action-driven research and policy supporting the avoidance of sector decline while improving the economic and environmental benefits that the aviation industry can provide. This section draws from literature on system dynamics and explains the concept of causal loop diagrams, reinforcing loops and balancing loops as fundamental tools for understanding complexity and systems [84].

As the system of the aviation industry is a complex system, system thinking is adopted as the means to support its understanding and inform meaningful change. Systems thinking emphasises the whole rather than the parts that compose a system. In such a view, the essential properties of the system emerge from the interaction and relationships between parts, resulting in additional complexity in comparison to the mere sum of the various components [85].

One powerful tool used to understand the complexity of systems is called the causal loop diagram (CLD) [84]. CLDs focus on the feedback structure of a system and are the first step in developing formal computer models. After the interacting elements are identified, causal relationships between them can be drawn as arrows indicating the dependence of one element on another. Causal dependencies can be differentiated according to a polarity: a "plus sign" (+) indicates that a positive/negative variation of one element would increase/decrease the element it is feeding into, whereas a "minus sign" (−) would indicate that a positive/negative variation would decrease/increase the subsequent element, respectively.

A closed path between one element and itself passing through other system elements is referred to as a feedback loop. These feedback loops are responsible for the dynamic behaviour and the complexity of the system. Feedback loops can be distinguished as either reinforcing (or positive) and balancing (or negative). The positive feedback loops generate disequilibrium and can potentially amplify dynamics that bring the system farther away from any initial condition. This dynamic is true both when leading to growth or to the collapse of a system. The negative feedback loops generate balancing effects bringing the systems towards equilibrium or specified states. The sign of every feedback loop can be found by multiplying the signs of the causal relationships that compose the circular causality. It is a battle among reinforcing and balancing forces that the system thinkers attempt to capture using CLDs. Figure 3 shows an example of a CLD with one reinforcing loop and two balancing loops.

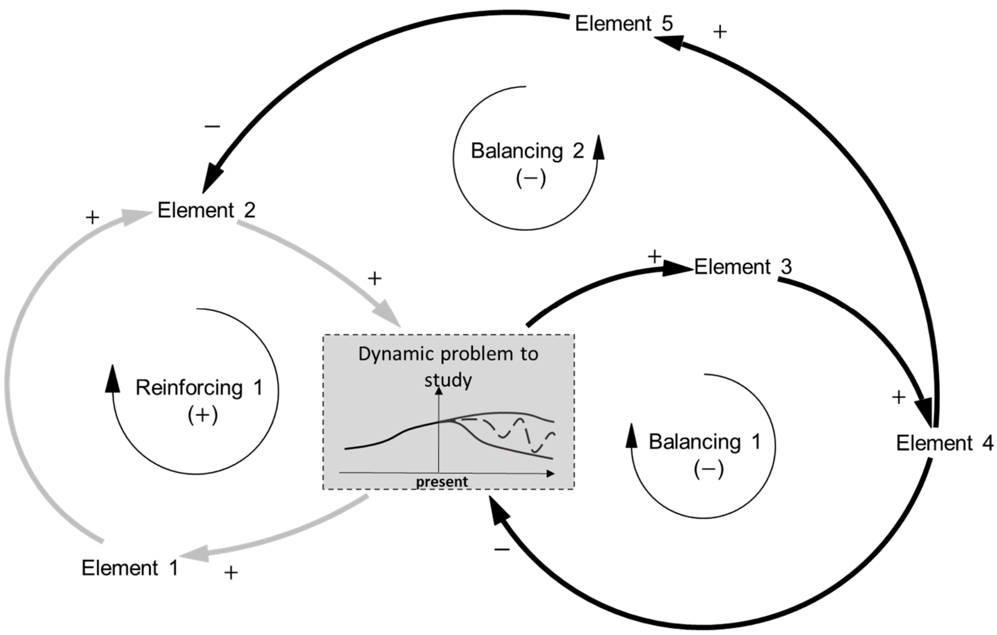

Figure 3. Example of causal loop diagram with one reinforcing loop and two balancing loops (adapted with permission from Ref. [83]. 2020, Taylor & Francis).

One of the key advantages of using CLDs as a mean to capture systems complexity is to simplify the identification of sensitive intervention points that can have a significant impact on the system [83,84]. These are elements that, when stimulated, can generate change in behaviour of the entire system (e.g., from growth to collapse, or from stability to an oscillatory state), as often characterised by more feedback loops converging into them. As sensitive elements of the system, they are often linked to exogenous factors (e.g., policy levers or exogenous shocks) that can be used as a means to influence the sensitive points with the objective of mitigating risks or dynamically pushing the system towards a desired state. In this study, a total of ten leverage points were identified that can act on the aviation industry (some controllable, some uncontrollable) and represented alongside the CLDs with the shape of a "hexagon" (see Figures 6–10, and Table 8 for further explanation).

Developing a Causal Loop Diagram from Interview Data

Modelling work often emerges from qualitative data gathered through interviews with experts in a particular field or an organisation [82,86–92]. Surveys can be considered as a good source of information, but interviews can be more effective. Semi-structured interviews allow specific questions that require complex thinking to be answered, leading to a number of further avenues that can be explored while interviewing participants. Such an approach can strengthen survey data, and further be developed with a number of methods for data analysis that are not explored in this paper [84].

For the specific case of this research, the causal map was not proposed to the participants to support in the development of a formal model, but it rather emerged from the learnings from the interviews and survey data. The resulting picture of the aviation industry and the question of understanding the future of aviation is a difficult one to solve, with multiple caveats and resulting complex systems behaviours. The development of a system map was necessary as a means to communicate the complexity and find the resulting leverage points to engage with management and policy decisions as an outcome of this study. Further formal modelling work is considered as a next step of this research and described in the discussion section of this paper.

4. Material

Classification of Participants

Of the ninety questionnaires completed, the majority classified themselves as airport planners (24%), airport operators (14%), consultants (11%), aircraft designers and manufacturers (10%) and engineers (10%). In addition, the questionnaire captured the views of other aviation professionals such as airlines, airspace, control authorities, government and researchers. The full breakdown is shown in Figure 4.

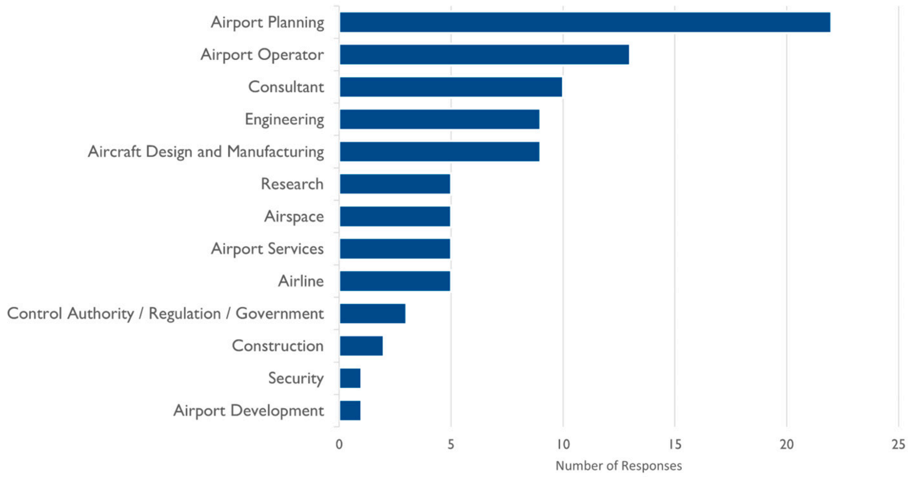

Figure 4. Role of survey participants.

The majority (76%) had roles based in the UK. A proportion of 8% were based in the United Arab Emirates, with 1–2% in each of several other countries, including Spain, Poland, New Zealand, the USA and Denmark. Two percent also classified themselves as having global roles. Due to the survey being posted initially through the authors' business networks and then subsequently attracting further participants through the snowball effect, the high UK percentage was expected. Therefore, it is recognised that the results of these surveys will be reflective of the UK industry and, to some extent, other countries with a similarly mature aviation industry and economy. However, despite the UK focus, the authors' opinion is that the surveys and data collection are representative of an important section of the aviation industry, enabling valid relationships and conclusions to be developed. Further work, repeating this study in multiple regions of the world, would allow interesting comparisons and a wider and more robust global conclusion. The majority of those providing information about their age were between 35 and 55 years of age. Asking the respondents' age allowed segregation of later questions; however, the small sample size resulting from segregating should be considered. The breakdown is shown in Figure 5.

In addition to the survey respondents, thirteen aviation professionals were interviewed. These interviews represented experience from a cross-section of the aviation industry, including airports, airlines, aircraft manufacturers, government, research, trade organisations, planners and consultants. Experience within the aviation and aerospace industry ranged from five to thirty-five years. The majority had worked in the industry for at least 20 years and had held multiple roles within different aspects of aviation. Eight interviewees worked or had worked for airports, eight for consultants and planners, four for airlines, two for government, two for trade bodies, two in technology research, and one in aircraft design and manufacturing. Most of the interviewed participants worked in the UK when the interviews took place. However, many had previously been based outside the UK, and some still worked on projects outside the UK.

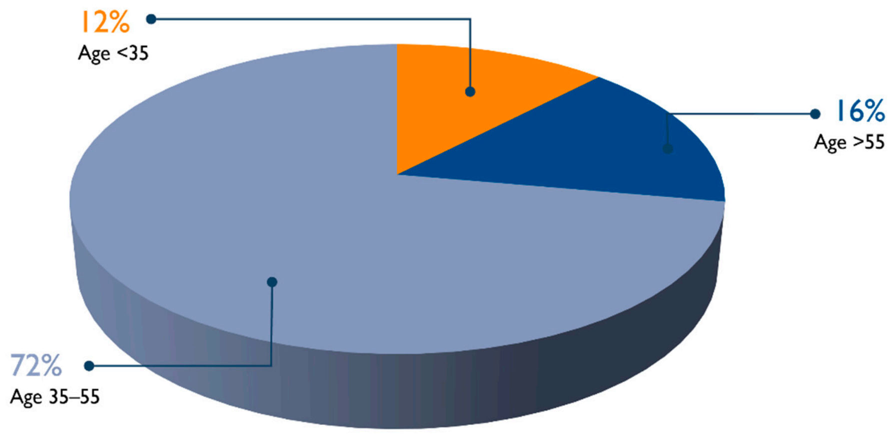

Figure 5. Breakdown of survey participants by age.

5. Results—Thematic Analysis and System Map

5.1. Thematic Analysis

The interviews and questionnaire responses were coded and analysed to identify key themes. One hundred and twenty-six codes were identified, distilled into sixteen themes, and grouped into broad categories.

5.1.1. Challenges

Much of the output from the surveys and interviews focused on the challenges faced by the industry, both in the short and long term. Climate change was an underlying concern across all the challenges faced by the industry. While the short-term issue of COVID-19 recovery was not climate-focused, it was raised as a particular problem in connection with the ability to invest in decarbonising aviation. Table 1 summarises the key challenge-related themes.

Table 1. Emerging challenge-related themes.

Themes Emerging from Surveys and Interviews	Summary Findings
COVID-19 Recovery Recovery from over 18 months of significant restrictions	COVID-19 has caused considerable uncertainty and significant financial impact. Therefore, the challenge of investing in reducing emissions has increased. COVID-19 has also impacted the available skills in the workforce.
Public perception and personal views Increasingly negative public image	Majority agreement on climate change concern, but mixed views on aviation's contribution. However, general agreement that aviation needs to play its part in decarbonisation.
The need for change and the speed of progress The speed of progress to address CO_2 emissions	Most felt that progress is too slow and will not address issues in time unless accelerated; therefore, ways to incentivise are needed. Aviation's safety-first approach needs to find ways to accelerate testing and regulation of new technology.
Future uncertainty Difficulty in planning and investing with an uncertain future	After COVID-19, it is difficult to forecast demand accurately; however, the biggest uncertainty is in determining which technologies will be successful. Airports are unsure when to invest in ground infrastructure, airlines are uncertain over fleet replacement, and aircraft manufacturers are uncertain about which technology to pursue.

Table 1. *Cont.*

Themes Emerging from Surveys and Interviews	Summary Findings
Safety and Legislation Challenge between aviation's safety culture and the need for rapid change	Safety has always been the top priority; therefore, the challenge will be transitioning the industry and pushing boundaries while keeping the industry as safe as it is today. Accelerating certification of new technology will be difficult.
Non-CO_2 impacts Additional environmental impacts not due to CO_2	Contrails will still exist with SAF or hydrogen and need to be considered. In addition, carbon emissions have temporarily displaced local issues such as noise and air quality as the primary concern. However, these will return as the major issues once carbon emissions are addressed.

5.1.2. Solutions

In addition to the focus on challenges for the industry, much of the survey and interview output focussed on the potential solutions for reducing aviation CO_2 emissions. This output ranged from technological solutions, such as aircraft design and developing new fuels, to restricting flights and increasing taxation. Table 2 summarises the primary themes related to solutions.

Table 2. Solutions related emerging themes.

Themes Emerging from Surveys and Interviews	Summary Findings
Alternative Fuels The development of alternative propulsion (e.g., SAF, hydrogen and battery–electric)	SAF was seen as the primary approach for alternative fuels, with battery–electric for short flights. Hydrogen is viewed as a potential long-term option, but there are concerns over technology for all solutions. In addition, most had limited knowledge of alternative fuels.
Technology and design The development of new technology to reduce emissions	Improvements for existing technology are likely to become less rapid. However, there is also likely to be new disruptive technology to support a step-change in capability. Technology may prevent the requirement for travel austerity. However, funding for technology development will be a challenge.
Restricting growth and limiting consumption Reducing flights to reduce emissions	There are mixed views on the need for restrictions. Many feel that growth is needed to encourage investment. However, others think some restriction is needed to incentivise low-carbon solutions, although some recognise the need for differential restrictions between mature and emerging markets.
Taxation and carbon costs Increasing costs to reduce demand	Need a balance of both "carrots and sticks". Many felt that if taxes were raised, they should be ringfenced for investment in sustainable aviation.
Offsetting Carbon offsetting	Most perceive carbon offsetting as ineffective, but some recognise that they are one of the only available solutions and the best option available now. Most concerned about the validity and effectiveness of schemes.
Alternatives to flying The use of lower-carbon travel modes	Rail may compete in some areas but is limited to short-haul journeys, and building new routes is expensive. Video conferencing technology has finally provided an alternative for some business travel.

5.1.3. Other Factors

In addition to the challenges and solutions, participants raised several unrelated factors. These highlighted the underlying global nature of aviation and the social and political framework it impacts and operates within. Table 3 shows the other emerging themes.

Table 3. Other emerging themes.

Themes Emerging from Surveys and Interviews	Summary Findings
Global Collaboration The global nature of aviation	Collaboration was one of the key themes. Aviation is a global industry; therefore, global solutions are required. Collaboration is needed within the industry as well as between countries.
Aviation benefits Recognising the positive aspects of aviation	Many felt that balancing aviation benefits with the need to decarbonise was important. The benefits of aviation were highlighted and the need to balance sustainability's economic, social and environmental aspects.
Fairness and equality Recognising both the current global imbalance and the opportunity that aviation brings	Recognition that there is an imbalance between world regions and that restricting growth in developing nations "hard codes" inequality and prevents global "levelling-up". Nations that have already benefitted from aviation should do more to reduce emissions than developing economies.
Government, politics and investment Recognising the support required	Aviation needs government investment and support to succeed in decarbonisation. However, aviation is multinational, whereas governments are not. Government is driven by short-term thinking, not necessarily the long-term strategic thinking needed for supporting decarbonisation.

5.2. Reinforcing Loops Governing Dynamics of Change

Figure 6 shows the result of the thematic analysis described in terms of the number of reinforcing loops that could trigger change in the aviation industry while dealing with the threat of climate change. The "hexagons" highlight external intervention points or factors that the industry cannot control. These are (i) the impact of COVID-19 on growth; (ii) the alternatives to flying (e.g., land transport, or digital technology that reduces the need for travelling); (iii) the restriction of industry growth to reduce negative impact on the environment; (iv) the taxation of brown technology to drive resources towards clean technology; (v) regulation of the industry that reduces the speed of innovation; (vi) mitigation of the negative effects of climate change; and (vii) offsetting (e.g., absorbing the carbon emitted by aviation with carbon capture systems).

Every effect is represented with a "+" sign where there is a direct relationship between two elements and a "-" sign where there is an inverse relationship. For example, with business-as-usual policies, the possibility of offsetting is assumed to support further growth of the industry as it would allow more carbon emissions (+ sign). It would also improve public opinion of the industry (+ sign) while reducing the net carbon emissions (- sign), and at the same time, increase greenwashing perception, thus resulting in reduced public opinion (- sign).

This section of the document describes ten fundamental reinforcing loops and three balancing loops highlighting the number of threats and opportunities for the industry.

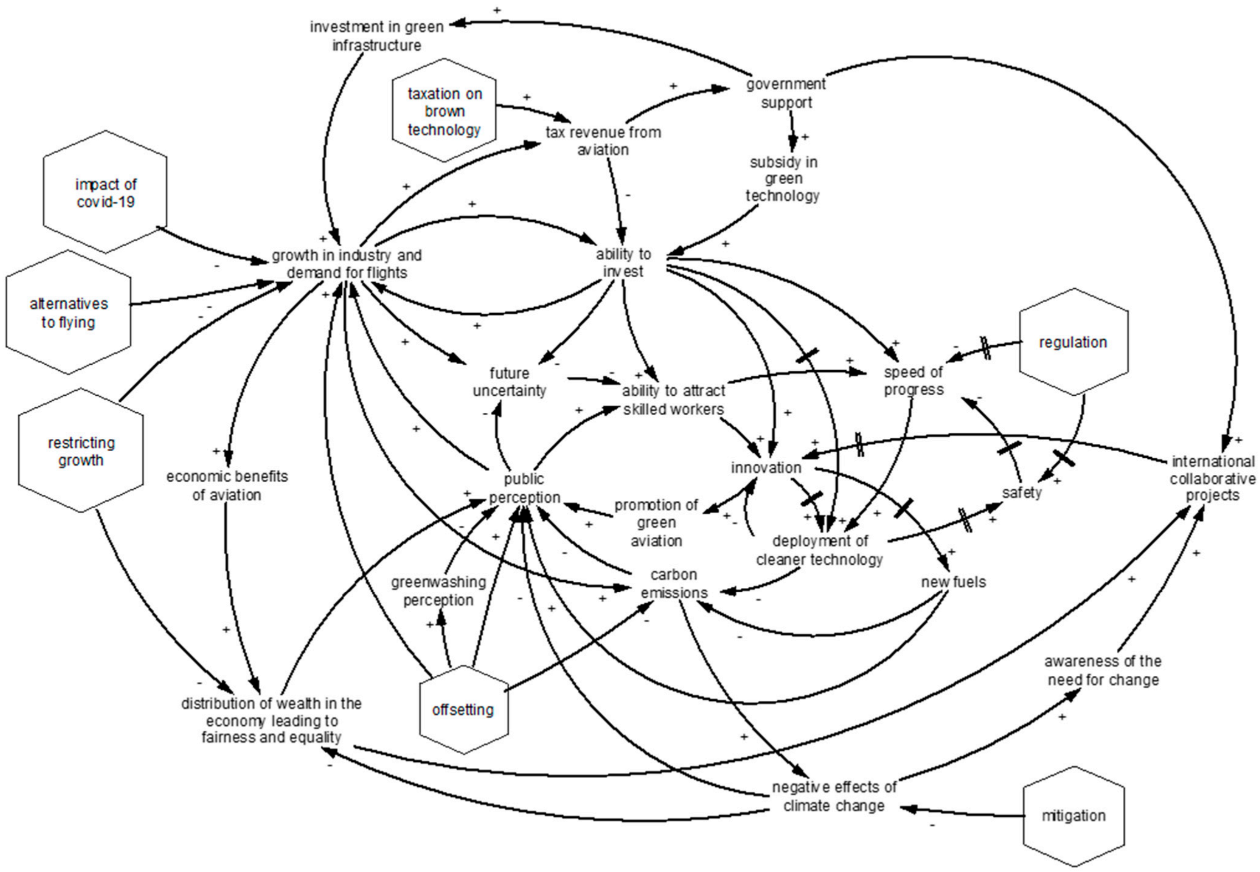

Figure 6. System map of the challenges and solutions for the aviation industry.

5.2.1. Carbon Emissions Loop

The two most important variables that are found to impact the stability and benefits that the aviation industry can provide to society are:

- Degree of innovation;
- Public perception of the industry.

These two variables are connected through four major reinforcing loops, thus leading to either a virtuous cycle for the industry and wider society or a vicious cycle leading to the industry's decline and eventual collapse (Figure 7). The reinforcing or learning loop (R1) is probably one of the most important loops leading to progress and innovation in every industry [84,93]. This loop indicates that investment in innovation leads to new patents and discoveries (i.e., innovation), which over time generates the deployment of operational technology. If this technology reduces carbon emissions per unit of output in the industry, it may improve public perception. In addition, an implemented technology can open the way for scientific and technological progress, supporting more and more innovation and making investments more effective.

The skills attraction feedback loop (R2) supports more innovation, as the improved effectiveness in terms of ecological impact is expected (according to the interviews) to attract the top skilled labour in dealing with such a challenge, which would provide fresh energy to the industry and increase the effectiveness of innovation even further. The green reputation feedback loop (R3) is dependent on changing technology aligned to the design of new fuels that could support lower carbon emissions. Such a reputation would also be triggered via the word-of-mouth or marketing-reinforcing loop (R4), where better availability of green technology and patents, if well promoted, could lead to better public opinion. Often projects with a high level of international collaboration can provide effective results, but if they are not promoted well, they might not provide the same benefits. A good example of industry collaboration is seen in the Aerospace Technology Institute's

FlyZero report [57], which investigates hydrogen aviation fuels and the impact on airports, airlines and air transport management.

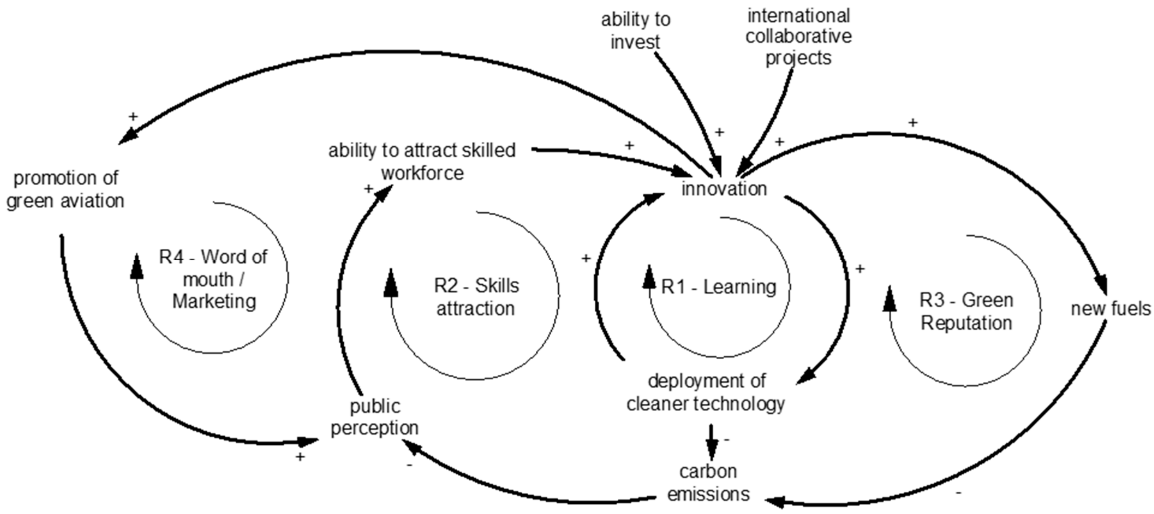

Figure 7. Reinforcing loops driven by investments in innovation.

5.2.2. Growth and Environmental Impact Loops

Figure 8 shows the reinforcing loops that lead from investment to growth (R5, R6, R7, R8) and the negative effect of environmental impact (B1). The business-as-usual reinforcing loop (R5) is the engine of growth for the aviation industry. The more the demand for flights grows, generating revenue for the industry, the more is their ability to invest in new capacity for further growth. This loop can be supported in several ways. When investments are deployed towards less carbon-intensive technology, the industry can be allowed to expand further before reaching a limit cap in emissions (R6). These investments also improve public reputation, making passengers feel more comfortable flying due to better technology (R7) and lower carbon emissions (R8).

On the other hand, Figure 8 also shows the balancing effect on growth driven by the negative impact of climate change (B1), which is the most concerning balancing loop that could lead to the industry's decline. This loop is a well-known declining force explained by Meadows et al. [94] and Pasqualino and Jones [83]. Although R5–R8 are determinant factors for the industry's exponential growth, they increase the burden of the impact on the ecosystems. Such accumulation would lead to an increase in the number of extreme events, which would negatively affect public opinion and decrease demand.

These loops can easily change direction (from growth to the collapse of the system) when external factors impact growth. On the one hand, the main influence of COVID-19 has been to cancel flights at the global level, leading to a negative impact on the industry. This decrease in growth could mean a loss of value and a lower ability to invest, further reducing growth. R5 would, therefore, automatically generate a vicious cycle of industry collapse. This cycle is the same for R6, R7 and R8. Another risk to the industry emerges from "alternatives to flying". These include both surface transport (e.g., road or rail), marine transport (e.g., ships) and digital technologies (e.g., video conference technology instead of travelling). Ultimately, governments or aviation managers could actively restrict growth to decrease its impact on ecosystems. These actions would all represent risks to the industry, leading to vicious cycles of general decline.

On the other hand, two major levers can be considered to support the industry. These include "quality investments", which can boost more clean technology and support green aviation, and "mitigation" policies to reduce the negative impacts of climate change. Although these two options might appear difficult and uncertain, they remain the way for the industry to support its long-term economic security.

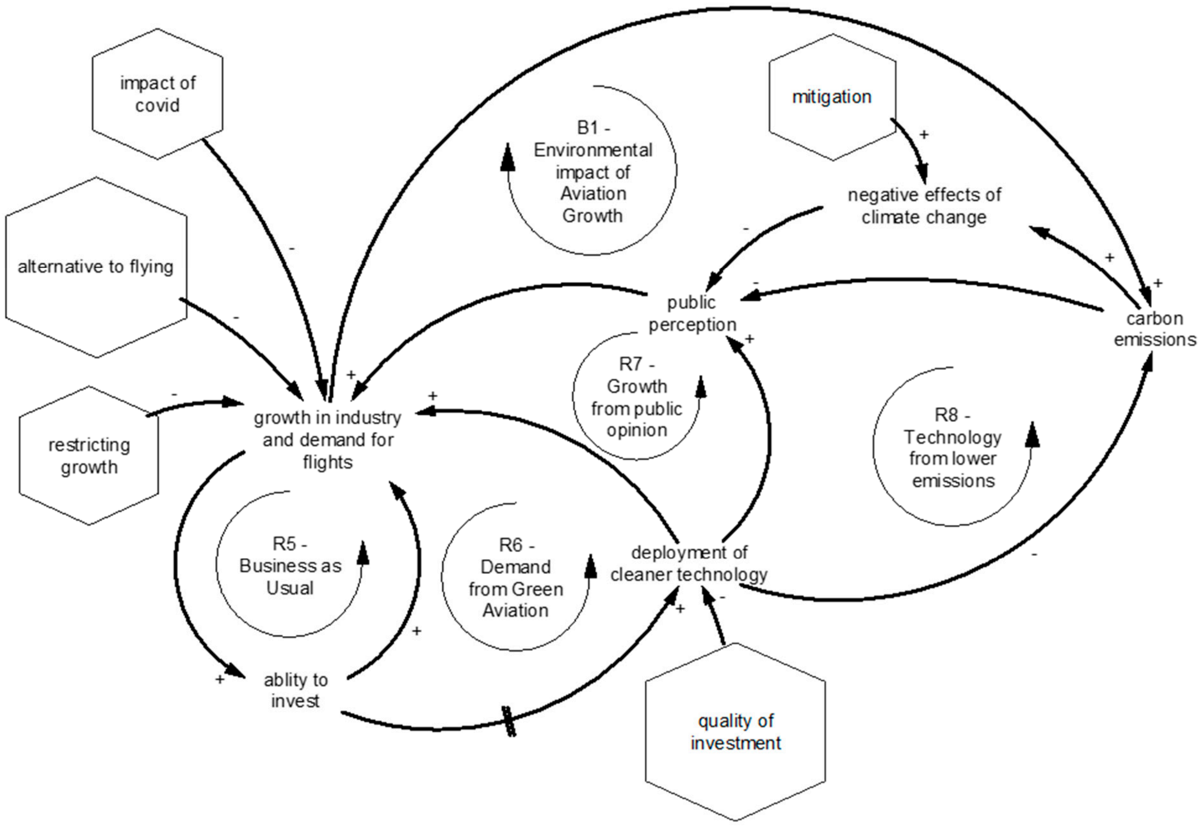

Figure 8. Reinforcing and balancing loops linked with growth of the industry.

5.2.3. Safety Trials and Delay

Innovation is argued to be the most important lever to sustain aviation's future within planetary boundaries. However, Figure 9 shows an important balancing loop, which could offset the entire innovation effort by reducing the pace of innovation through delays caused by testing, safety trials and certification. Every time a new patent is deployed into technology, this technology would need further safety trials and tests to be performed. This process is often governed by regulation and can be supported by testing infrastructure. Interview participants argued that, while safety must not be compromised, bureaucracy and regulation requirements for testing new technology could be an important barrier to innovation. We argue that streamlining regulation and investing in novel testing infrastructure to support faster testing and safety trials would be fundamental to innovation programs.

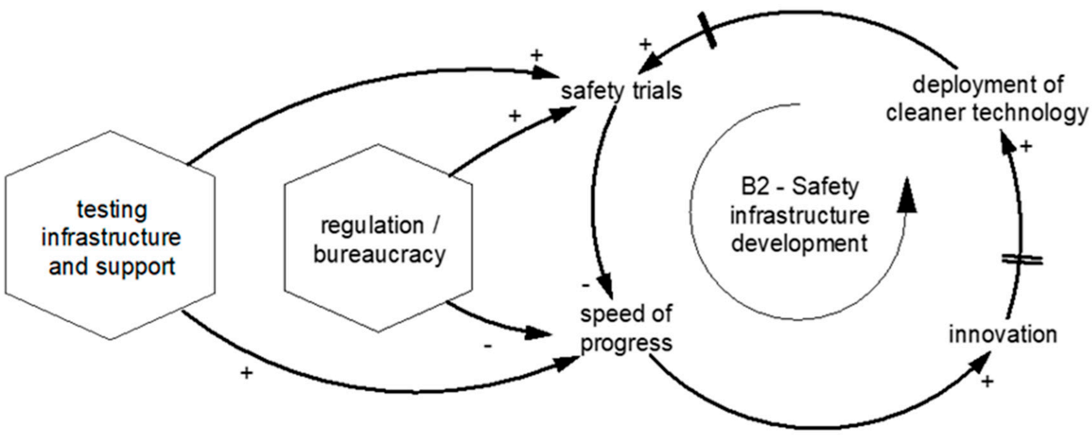

Figure 9. Balancing loop with delay requires investment in infrastructure and lean regulation.

5.2.4. Using Government Support for Collaborative Projects

Figure 10 shows the dangerous disruptive effects of a reinforcing loop leading to worse climate change (R9), the good balancing effect emerging from collaborative projects (B3), and how the government can initiate a positive reinforcing loop using taxation and subsidies to support the industry in the future (R10).

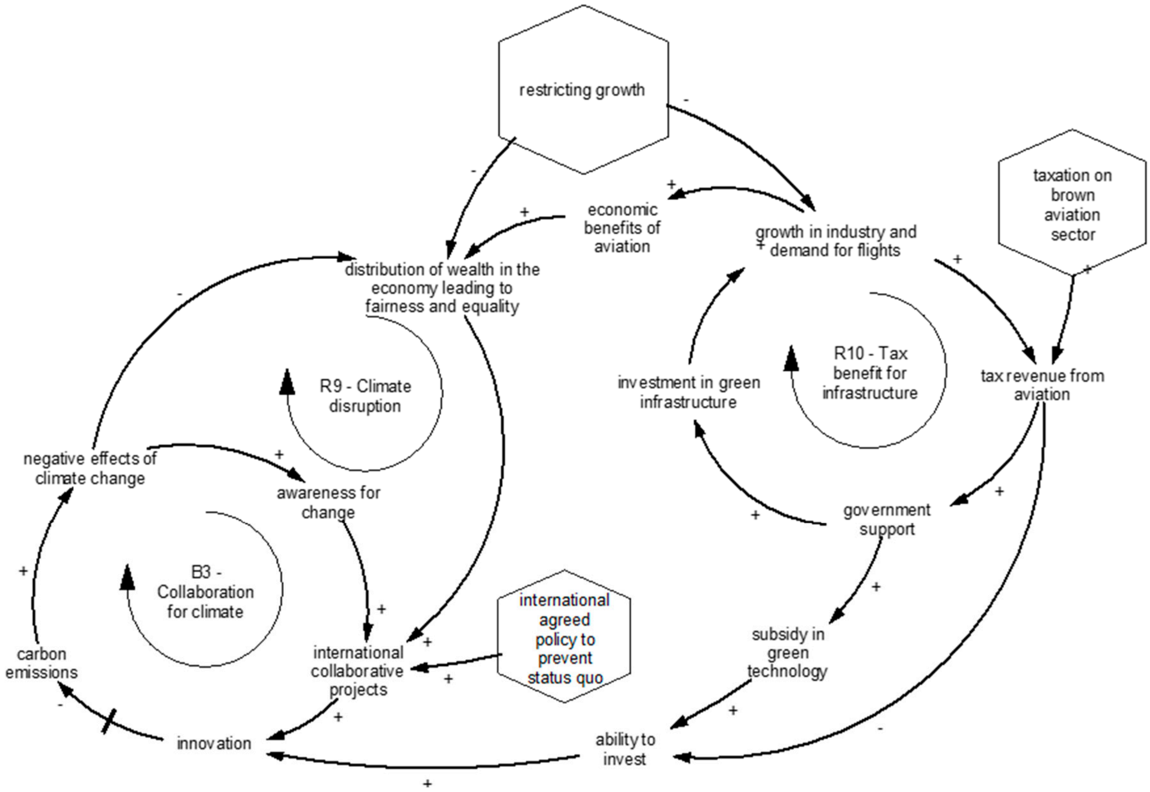

Figure 10. Reinforcing tax benefits and threat of climate change.

Most interviews demonstrated how international collaboration is a key driver for effective innovation, leading to all its positive benefits. As explained in B3, it is assumed that the higher the negative impact of climate change, the more the awareness for change would rise, leading to more collaborative projects and innovation, ultimately acting as a balancing force. On the other hand, it is possible to show that the worse the adverse effects on climate are, the harder it would be to maintain fairness and equality in the industry. Small innovative businesses and airlines could suffer the most if large businesses maintain market share, having reached large economies of scale, effectively pushing small competitors out of the market. This effect could result in less collaborative projects, a lower disruptive technology effect and increased climate consequences in the industry.

As a result, it is fundamental for policymakers and government to support the deployment of collaborative projects. The reinforcing loop, R10, shows that the higher the growth of the industry, the greater its tax contribution, resulting in an increased ability for government to invest in green infrastructure and support further growth. This reinforcing loop can fuel the balancing loop, B3, by supplying subsidies to support the ability to invest in green technology while at the same time supporting with legislation that can foster international collaboration. It is worth noting that the more taxation is applied to the brown aviation sector, the lower is their cash availability to invest in new technology, while, on the other hand, taxation can support subsidies for green technology. This can lead to a trade-off to redistribute resources where they have a less negative impact on ecosystems. In addition, the higher the growth, the larger the industry's economic benefits, supporting more competitiveness of smaller players in the market, leading to better distribution of wealth in the economy, and lowering the strength of the dangerous reinforcing loop R9. In this case, restricting aviation could ultimately lead to a negative spiral leading to the decline of the industry and its positive wider society benefits. While some restrictions may be inevitable if other solutions to reduce aviation's impact are unsuccessful, we believe that restricting growth should be approached with caution if the aim is to protect both the industry and its wider benefits to society. More targeted approaches to restricting growth that incentivise low-carbon technology and discourage carbon emissions are likely to be more successful.

6. Discussion

6.1. Concern about Climate Change: What Do Aviation Professional Think about Climate Change and Aviation's Contribution?

The vast majority of those surveyed and interviewed were concerned about climate change and thought that action needed to be taken. In the survey, 83% of participants said they were worried, with 10% undecided. This response represents a similar percentage to the UK population in general. In a 2021 Department for Business, Energy and Industrial Strategy (BEIS) survey, 80% of respondents expressed some concern over climate change, with 19% not concerned and 2% undecided [95]. This research project is not limited to participants in the UK; however, the majority who took part were in the UK, making the comparison meaningful. In 2020, a global survey [96] found that when considering all countries, 69% of respondents said climate change is an extremely or very serious problem. Only 9% said that they were not worried. In a separate UK survey from the Centre for Climate Change and Social Transformations (CAST), 71% of respondents said they were worried, with 6% unsure [97]. Therefore, it appears that aviation professionals are at least as concerned about climate change as the average population, if not more so. This research also highlighted that the increasing concern in aviation professionals aligned with the CAST 2019 survey, which reported that nearly 70% of respondents were more worried than they had been 12 months before.

While there was a clear majority view on concern over climate change, the participants had mixed views on the significance of aviation's role. As aviation is responsible for approximately 2.5% of the global CO_2 emissions, many felt that the focus should be on other industries, with a sense that aviation was subject to unfair negative publicity. Even many of those who expressed strong views that aviation should decarbonise were defensive of the negative attention that aviation receives. However, as shown in the results, others highlighted the issue of global imbalance and observed that some see aviation as discretionary. However, the discretionary nature of aviation was debated, with, for example, a clear difference seen between weekend city breaks for leisure and Scottish Highland and Island flights used for visits to hospital appointments. As demonstrated earlier, research suggests that only 11% of the population travelled in 2018, with 1% of the world population responsible for half of the total aviation emissions [13]. Therefore, it is easy to see why aviation professionals were split with their views on aviation's impact, as the overall emissions compared to the personal impact on emissions are very different. Actual emissions could be described as low compared with other sectors, and yet flying remains one of the highest-carbon-emitting activities that an individual can do [98]. Some participants' views were also magnified as they considered the non-CO_2 climate effects, alongside CO_2 impacts.

Despite a collective view that aviation needs to reduce its emissions, some felt this should be balanced against the benefits. A frequent argument is that aviation helps promote a strong economy and that there is a clear link to a country's GDP. While this may be true to an extent, as a country become richer, the link becomes weaker [24]. Therefore, arguing, as some participants did, for example, that the UK or the US must allow aviation growth to support their economies is perhaps less justified than arguing that developing nations would benefit from aviation growth and connectivity. This need for developing nations to grow aviation to close the gap between them and countries with a larger aviation industry was highlighted by some participants, with one participant, for example, suggesting that restricting all aviation growth would "hard code" existing imbalances. Others recognised that while it may be justified to suggest that wealthy nations with established aviation industries limit growth, it would be unfair to prevent those in developing nations from experiencing these same benefits. However, it appeared that this was at times used as an argument to allow all aviation growth, rather than just for developing nations. A few referenced the UN Sustainable Development Goals (SDG), highlighting that sustainability is about more than just the environment but includes economic and social standards. This view aligns with a report from the International Civil Aviation Organisation's Industry High-Level Group that highlights the SDGs that rely on advancements in sustainable airport transport [99]. For example, in 2010 when aviation was suspended due to the Eyjafjallajökull volcano, former World Bank president Robert Zoellick stated that African countries lost USD 65 million due to transportation delays, mainly due to the loss of fast-perishing produce [100].

Despite some disagreement on the scale of impact and whether this impact was justified based on the benefits that aviation could bring, there was an overwhelming agreement that change was needed. There was some positivity that changes were starting to happen, such as the ZeroAvia flight trials last year [50]. However, others thought that the speed of change was too slow, and that technology would take too long to develop, as Allwood et al. (2019) argued [37].

Table 4 summarises the answers related to aviation professionals' perception of climate change and their role to face the challenge.

Table 4. Summary answers for research question 1.

Research Question	Answers
Q1. What do aviation professionals think about climate change and aviation's role?	• Aviation professionals are at least as concerned about climate change as the general public. • Concern is continuing to grow. • Views are mixed on the scale of aviation's contribution, and many are defensive of the criticism that aviation receives compared to other industries with larger overall emissions. • Most are aware that aviation's contribution will continue to grow disproportionality as other industries decarbonise. • Regardless of views on aviation's contribution, almost all participants felt strongly that decarbonising aviation was important and indicated that they were willing to help the industry transition. • Research suggests that the industry is self-motivated to change, although the scale of the challenge is significant, requiring support and incentivisation to capitalise on the enthusiasm and willingness of aviation professionals to makes changes.

6.2. Challenges Ahead: What Do Aviation Professionals Think Are the Biggest Challenges for the Future of Aviation?

Aviation has been one of the worst-affected industries by COVID-19, with an unprecedented and long-lasting reduction in flights [101]. Many staff have lost jobs, and there have been substantial airport and airline losses [102,103]. Therefore, it was unsurprising that participants saw COVID-19 as the biggest short-term challenge ahead for aviation. Even after flights stopped during the early pandemic, the aviation industry could not envisage the effects being so significant for so long [104]. Not only has COVID-19 had massive financial impacts on aviation, but it has also resulted in a high level of uncertainty. While many predict a strong demand for leisure travel to return, the widespread use of software such as Microsoft Teams (Microsoft, Washington, DC, USA) and Zoom (Zoom

Video Communications Inc., Santa Clara, CA, USA) has popularised video conferencing and made businesses aware of the convenience and potential financial benefit of reducing travel [105]. While there is no guarantee of future behaviour, this uncertainty may affect airlines and airports' most lucrative business passenger demand [106].

Participants highlighted climate change as the primary challenge in the long term, both from the necessity to decarbonise and from effects on business caused by negative public perception and industry image. It is widely recognised that aviation is one of the most challenging industries to decarbonise [107,108]. Flight requires significant energy, yet aircraft technology is limited by its weight and size constraints. Nevertheless, some were optimistic about aviation's ability to decarbonise, while the majority had some concerns. Although the UK government has now committed to net-zero for aviation by 2050, the more widespread ICAO view effectively accepts, through the basket of measures, that the realistic best-case reduction for aviation is to cap increases beyond 2020. To achieve this includes the allowance to offset flight emissions. Other organisations are now more optimistic, with the UK's Sustainable Aviation committing to net-zero by 2050 [22]. However, even if achievable, the challenge is immense and requires rapid action. Many participants again reiterated the challenge of non-CO_2 effects from flight, such as NO_x and contrails.

While COVID-19 has caused immediate problems affecting short-term demand and the viability of airlines and airports, it also affects the long-term ability of the industry to innovate and invest in solutions required to address climate change. All of the reinforcing loops that can be controllable by the industry (R1–R8) are transformed from virtuous to vicious cycles leading to a long-term decline of the industry without intervening in the correct leverage points. As one participant explained, "We've got to be greener and smarter, under huge financial pressure, in probably a more rapidly changing society than we've ever experienced before". Costs for decarbonising the industry are likely to be high, whether through the high costs of producing SAF or the development of new propulsion technology. Finding the money for these investments would have been difficult even before COVID-19.

Interestingly, some of those who did not feel aviation's emissions were a concern still thought that aviation needed to act due to the challenge of public perception. Visible protestors such as Greta Thunberg and Extinction Rebellion have raised awareness, and movements such as Flight Shaming have focussed on flying and its impacts [27]. Therefore, some participants saw not just climate change as the challenge but public perception and the impact of protests. While some may question the motives behind actions, if a change is due to public perception rather than an actual desire to prevent climate change, the outcomes are the same, in a similar way that buying low-energy light bulbs to save money also benefits the environment [109]. Some saw the recent example of a ban on Air France domestic flights [110] by the French government as the influence of public perception.

The impact of public perception was also raised as a challenge in retaining skills in the industry, especially when combined with the effect of COVID-19 on aviation job security. Attracting new staff and innovative skills into aviation may be easier if the industry is perceived as more sustainable [111].

While climate change remains the highest-profile environmental challenge for the aviation industry, other environmental issues were also highlighted as concerns. There was recognition that noise was the most significant local challenge [112] and that the focus on decarbonisation may be lessening the attention on noise. However, previous studies have highlighted the adverse effects on health that aircraft noise can have [113]. Therefore, whether aviation is decarbonised or not, reducing noise nuisance should not be overlooked.

An interesting emerging theme was the challenge of safety and legislation slowing down the development of new technology. Aviation is one of the safest modes of transport [114,115] but this has evolved through years of regulation, standards, testing and learning from mistakes and accidents. While no participants questioned the importance of this, they did observe that introducing fundamentally different technology would mean challenges with certification, legislation and safety tests, which could considerably slow down the process of reducing emissions. The balancing loop B2 remains slow. The development of COVID-19 vaccines has demonstrated what is achievable with suitable investment and focus. If the same focus and attention were put on evaluating technology, it might alleviate these concerns.

Table 5 summarises the answers related to aviation professionals' perceptions of the biggest challenges for the future of aviation.

Table 5. Summary answers for research question 2.

Research Question	Answers
Q2. What do aviation professionals think are the biggest challenges for the future of aviation?	• COVID-19 recovery is seen as the primary short-term challenge, and aviation's impact on climate change the biggest overall challenge. • COVID-19 financial losses risk limiting available investments for implementing decarbonisation strategies. • The unattractiveness of aviation due to COVID-19 and its negative environmental image may prevent the new generation of skilled workers from joining the industry, reducing its ability to innovate. • The acceleration required in new technology and innovation to help decarbonisation may create safety testing and regulation challenges, potentially delaying further innovation.

6.3. Enabling Decarbonisation: What Solutions Do Aviation Professionals Expect to Be the Most Likely to Enable Decarbonisation of the Industry?

Alternative fuels were seen as the most viable solution to enable decarbonisation of the industry. However, when asked in more detail, knowledge of the differences in fuels was limited in many participants. SAF was most frequently suggested; however, among those interviewed, most were unaware of the different types of SAF. They assumed that due to the name, "Sustainable Aviation Fuel", that all SAFs are fully sustainable. Therefore, they were not aware of any issues or concern regarding feedstock conflicts or the difficulty of scaling up production to the required levels.

Fewer people suggested hydrogen as a fuel in the surveys, which is unsurprising, as technology is less advanced. The interview responses were similar, with limited awareness of hydrogen characteristics and the significant difference between gaseous and liquid hydrogen properties when used as a fuel [55]. While gaseous hydrogen is already used in vehicles such as buses [116] and has been trialled in aviation [50], the liquid hydrogen needed for larger commercial aircraft is a largely untested propulsion technology. Likewise, battery–electric aircrafts were suggested as a solution. However, many were unaware of the challenges and obstacles due to range limitations and power density storage [52]. The rise of battery–electric road vehicles made participants more familiar with battery power than other alternative fuels.

Despite the current limitations, overall, there was a perception that battery–electric would be the potential solution for short-haul and domestic flights, with many expecting the improvements seen in road vehicle battery technology to continue, making flight viable. SAF was seen as the solution in the mid-term for all other flights, with hydrogen, if viable, potentially overtaking these technologies in some cases. However, with these multiple potential solutions, there is an increase in uncertainty, both for airlines investing in aircraft and airports being able to invest in the expensive infrastructure needed to accommodate these aircraft. In addition, whereas airports currently operate with effectively one type of fuel, future airports may need to accommodate existing kerosene (Jet A-1), SAF, electric and hydrogen. This range of fuels highlights the challenges for airports in deciding when to invest and which technologies to invest in.

While technology is seen as the preferred way to reduce carbon emissions, many accept that the timescales involved are long and that these technologies will take many years to mature. Therefore, some suggested that restricting growth, at least to some extent, would be a logical solution. However, there was limited support for restricting the number of flights. Instead, the preference was to introduce environmental caps, incentivising decarbonisation by limiting infrastructure to low-carbon aircraft or introducing a cap on carbon emissions in a similar way to existing noise restrictions [117]. This finding aligns with data suggesting that the UK population also favours capping aviation growth [26]. Limiting new infrastructure for aircraft operating more sustainably is feasible but would require careful planning and stakeholder consultation. However, unless a global agreement can be reached to restrict aviation, achieving decarbonisation through technology potentially provides a longer-lasting solution, likely to be adopted more widely. As expressed by one participant, "Climate change is a serious problem, but we won't get international agreement with austerity".

Offsetting was viewed very poorly by the participants. Offsetting is often criticised [118,119], and even the CEO of Etihad Airways recently said that offsetting is "a short-term stopgap if you haven't got a more sustainable alternative, but it's cheating" [120]. However, aviation has promoted offsetting as a potential solution. Many airlines offer voluntary offsets on flights, and ICAO's CORSIA scheme is dependent on market-based measures such as offsetting [121]. Therefore, more positive support for offsetting may have been expected. However, the participants' views align with passengers' low interest to purchase offsets [122], which may be due to concerns regarding the schemes' effectiveness. A few participants thought that offsetting was effective, and others considered offsetting as "better than nothing" or "the last resort". Much of this negativity appears to stem from a lack of confidence in the accountability of schemes and a feeling that funds raised would do little to reduce emissions. It also appeared that some thought relying on offsets would damage the industry's reputation and subject it to greenwashing claims. In the short term, it is apparent that, with the exception of restricting flights, other solutions are not ready to achieve full decarbonisation or reach net-zero. Therefore, if offsetting is to remain a tool for aviation decarbonisation, more effort needs to be made to educate the industry and demonstrate and verify schemes' authenticity. Some participants suggested increasing the visibility of offsets through localised schemes.

With the range of potential solutions, it was apparent that there is confusion over the best solutions to support, which is likely to delay investment and reduce the speed of implementation. There are also strong views from some regarding which solutions are likely to be the most effective. However, with the uncertainty of technology development, it is too early to discount solutions. The industry must work towards multiple solutions and maintain an open-minded approach to achieving the ultimate decarbonisation objective.

Table 6 summarises the answers related to aviation professionals' expectations with regard to the most likely solutions to enable decarbonisation of the sector.

Table 6. Summary answers for research question 3.

Research Question	Answers
Q3. What solutions do aviation professionals expect to be the most likely solutions to enable decarbonisation?	• There are many proposed solutions for decarbonising aviation, including multiple proposed fuels and feedstocks. • Although aviation professionals are aware of many of these solutions, there is confusion and limited understanding. • It is important to educate the industry and work towards standardisation and the development of roadmaps to enable clarity. • SAF is seen as the most likely short-term solution. • Battery–electric is expected for short-haul flights. • Hydrogen awareness is limited but seen by some as the preferred long-term solution due to the potential for true zero-carbon flight. • It is too early to back a single technology. • Industry must keep an open mind and recognise that there are likely to be multiple solutions. • Some aviation restrictions may be inevitable in the short term; however, without global agreement and collaboration, the long-term effectiveness is likely to be limited compared with technological solutions. • Although carbon offsetting is viewed negatively, it may be essential in the short term.

6.4. Assisting and Encouraging Decarbonisation: What Do Aviation Professionals Think Is Needed to Assist and Encourage Decarbonisation? What Do They Think the Obstacles Are?

Collaboration emerged as an essential theme in this research. Participants highlighted the global nature of aviation in the challenges it faces and the need for collaborative solutions.

Climate change is a global challenge and cannot be solved by one country alone. Many highlighted this as a problem, saying that they found it hard to imagine all nations working together in agreement, giving examples of the challenges of seeking agreement on climate change initiatives globally. However, if constructive, conflict could be seen as a part of collaboration, helping deepen understanding [123]. Aviation is a global industry; however, governments are not. Therefore, participants stressed the importance of organisations such as ICAO and IATA to bring together regulation and drive the decarbonisation agenda. However, there was disagreement on the benefit of unilateral action, with some highlighting that if one country were to impose restrictions on their airports, airlines would be likely to transfer routes to other countries, maintaining carbon emissions but economically disadvantaging the countries taking action. Other research, however, argues that problems resulting from the shared use of resources, referred to as the tragedy of the commons [124], can be avoided [125] but need careful management. In the survey, others also said that someone had to be the first to take the initiative. An example of this initiative is exemplified by Greta Thunberg's solitary protests that snowballed, reaching global participation [126]. Whatever view is held, the need for deep global collaboration is evident. Without collaboration, the risk of developing competing technology and different standards is exacerbated. For example, an aircraft needs standardised ground servicing equipment, wherever it is in the world.

Participants also highlighted the need for industry collaboration between manufacturers, regulators, operators and investors. While competition can be helpful to drive innovation [127] it should not be at the expense of finding the optimum solution. Examples included the potential competition between future propulsion technologies and fuel. SAF, hydrogen and battery–electric all play a role in decarbonising the industry, and promoting one solution at the expense of another does not help the ultimate decarbonisation objective. Therefore, it is vital to keep in mind the overall aim of decarbonisation rather than being side-tracked by personal or business competition that may ultimately prevent or slow progress.

The role of governments was also highlighted as essential by many. The scale of technological innovation needed, the investment required, and the risks involved are potentially too much for the industry to bear alone. Support may be needed to incentivise the industry and enable the financial risk required to research new and untested technology. The car industry is a good example, where the rollout of electric cars has been driven partly by the incentivisation of low taxes for company car drivers [128]. Some participants used the analogy of the Apollo missions or Concorde, where the risks and uncertainty were too high for commercial investment alone. Governments also have a role to play in working towards global collaboration and international standards and agreements. However, for many countries, the political cycle of elections was highlighted as a concern, driving short-term decision making. Decarbonising aviation is a long-term challenge and requires long-term thinking and decisions to be made, even if unpopular, such as taxation or limiting growth.

Governments may also have a role in supporting the rapid testing, certification, and development of standards and regulations. The development of the COVID-19 vaccinations has demonstrated that where there is the motivation to innovate rapidly with governments and industry working together, testing and certification can be effectively accelerated [129]. The challenge for industry and governments is to mobilise efforts to decarbonise with the same urgency as demonstrated for COVID-19.

In addition to needing government support, as highlighted in previous questions, aviation potentially risks losing skills and capability from the industry at a time when more innovation than ever is required. Therefore, attracting new skills, particularly from those enthusiastic about finding solutions to solve aviation's impact on climate change, is increasingly important.

Table 7 summarises the answers related to aviation professionals' opinions of what is needed to encourage decarbonisation and what are the barriers ahead to this challenge.

Table 7. Summary answers for research question 4.

Research Question	**Answers**
Q4. What do aviation professionals think is needed to encourage decarbonisation, and what do they think the obstacles are?	• Aviation is a global business. Therefore, collaboration across industry and governments is essential. • The scale of investment required will be difficult to achieve especially given the uncertainty and risks of developing new technology. • Government support and incentivisation are likely to be required. • The speed of technological development will require an effective and rapid development of legislation, standards and safety certification. • The industry needs skills and capability to accelerate innovation.

6.5. Interpretations of the Results Based on the Multilevel Perspective Technological Transition Framework

This study adopted semi-structured interviews and a survey with experts in the aviation industry to highlight ten self-reinforcing feedback loops and three major balancing loops that can either act as a catalyst for development or initiate a cycle leading to the industry's decline. Ten intervention points are highlighted, seen both as a risk to be mitigated or an option for feeding positive loops to improve the industry and the ecosystem. These are (i) impact of COVID-19; (ii) alternatives to flying; (iii) restricting growth; (iv) offsetting; (v) mitigation; (vi) regulation/bureaucracy; (vii) testing infrastructure and support; (viii) taxation on brown technology—subsidy to green technology; (ix) quality of investment; (x) internationally agreed policy to prevent status quo. Among the most important reinforcing loops, we find that most feed a central variable that we named "innovation". We propose that supporting loops that promote innovation is a way to stabilise the aviation industry towards a new technological regime, which could potentially be more sustainable in the long term. In other words, we argue that a technological transition (TT) is needed [130].

In this process, this study can contribute to the literature initiated in [130] with regard to the multilevel perspective (MLP) to engage with TT studies, which is well accepted in the literature to the point of identifying six leverage points (LPs) for policy within the MLP framework to support innovation transitions [131]. Figure 11 shows a visual representation of the MLP and these six leverage points for policy as extracted from [131] and inspired by [130]. The MLP identifies three areas of focus when looking at TTs as (i) niche, (ii) a socio-technical regime and (iii) a landscape aligned on a time axis. The niches represent those early-stage technologies that require investments to become commercially viable, but that might (or might not) achieve widespread diffusion, and are often linked to the concept of "radical innovation". A number of short arrows pointing to different directions represent the diverse set of activities that are required to push technology beyond the niche threshold. According to [131], the niches should first be stimulated (LP1) with early investments in R&D, and secondly accelerated (LP2) to support the wider market take over and reach regime level.

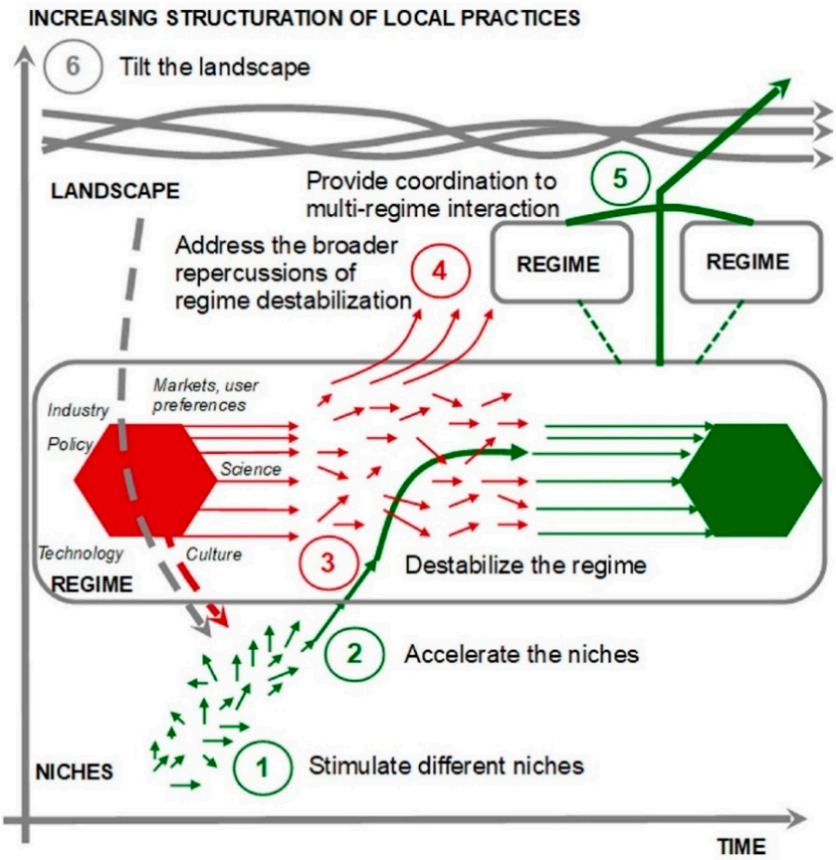

Figure 11. Multilevel perspective framework and six leverage points for policy [131].

A socio-technical regime is the technological state reached by mature technologies that already shape social life. These technologies are socially accepted, involve a number of stakeholders (e.g., industry, policy, science, culture, markets, financial regulators) and link to "incremental innovation". Regime is a path-dependent set of technologies that achieved scale and can sustain themselves economically. As a result, this may create a barrier to the niche technologies that may never be capable of reaching regime and remain in the so-called "valley of death" of innovation [132]. To support the stimuli at the niche level of selected technologies, it would be useful to either push for destabilising the regime (LP3) and address the wider repercussions to such destabilisation to the wider socio-technical environment (or landscape) (LP4). In this line of work, [132] suggests that another way to help niche technologies to avoid the "valley of death" is to fully recognise the practicalities of the innovation process in a modern economy. He divides technological readiness between "technological push" (R&D investments are needed to reach the competitiveness interest of a technology) and "market pull" (the technology is ready to go to market and demand drives development and diffusion). Secondly, they segment the entire innovation process in six steps, that are invention, development, demonstration, commercialisation, deployment and diffusion. The more the technology is early stage (i.e., invention or development) the more it will require "technology push" type of investment. The more it matures (demonstration, commercialisation), the more the market will take the burden to bring it up to regime (deployment and diffusion).

The landscape represents the wider context where technologies might support in making change or being impacted by factors that are out of their control. Factors such as political context, environmental concern, climate impact, energy prices, material costs, competitive technologies, quality of life and public perceptions all fall in this category. The change in the landscape can generate a push for the niche technologies to solve the problem of the industry even though these might not be enough unless fully understanding the complexity of the regime technologies and the barriers to entry. To support niche innovation at the landscape level it is advised to provide coordination to support multi-regime interaction (LP5), or even tilt the landscape (LP6). This latter support might include strong government interventions such as banning one technology and incentivising another one.

Table 8 summarises the connection between our ten leverage points and those proposed in [131].

Table 8. Alignment between our finding and the six leverage points in the multilevel perspective framework (Reprinted with permission from Ref. [131]. 2020 Elsevier B.V.).

Leverage Points from [131]	**Leverage Points from This Study**
1. Stimulate different niches	(vi) Regulation/bureaucracy, (vii) testing infrastructure and support.
2. Accelerate the niches	(ix) Quality of investment.
3. Destabilise the regime	(viii) Taxation on brown technology—subsidy to green technology.
4. Address the broader repercussions of regime destabilisation	(iii) Restricting growth, (iv) offsetting and (v) mitigation
5. Provide coordination to multi-regime interaction	(x) Internationally agreed policy to prevent status quo.
6. Tilt the landscape	(i) Impact of COVID-19 and (ii) alternatives to flying.

In our view, (i) the impact of COVID-19 (or whatever pandemic might happen in the future) and (ii) alternatives to flying (e.g., video conference tools or road transport) represent the wider landscape that can impact the industry and generate demand for structural change and new technology development. However, we believe that, in order to support the takeover of these technologies, the aviation industry should radically reduce their (v) regulation and bureaucracy on new technology and innovation, and (vii) receive investment in infrastructure to reduce the time necessary to test their new products. These together would support streamlining the process and stimulate new technology development. At a more advanced stage of development, we believe that (ix) quality investments would support the acceleration of those technologies pushing them towards the regime state. The objective is to pass the threshold where a technology is gradually shifted from "technology push" to "market pull", thus reducing public investment to remain in the hands of the private sector that is driven by market dynamics of competitiveness [132].

On the other hand, (viii) taxation on the brown aviation sector with relative subsidies on the green technology would support both destabilising the regime as well as supporting the penetration of new technologies in the market. This would generate a number of repercussions that would need to be addressed to reduce the impact on jobs. For example, (iii) restriction on growth, (iv) offsetting and (v) mitigation of the effect of climate change would be relevant at this level.

Finally, the big challenge for the industry would be to keep a strong international community to develop (x) policies that can prevent the status quo. Diversity in the aviation sector would be welcome, such to institutionalise a new normal of green technologies for aviation as part of the socio-technical regime level.

6.6. Modelling Framework for Future Analysis

The picture that emerged from this study on the aviation industry is a complex one. The use of interviews and surveys helped to frame a feedback loops diagram of the industry and more work can be done to bring it to life as a formal computer model. A number of methodologies can be used to continue this line of work to build a model, including system dynamics, agent-based modelling or econometrics [83]. However, it might also be that no data will ever be available to calibrate models in detail for every one of its variables and most likely it will remain useful in terms of exploring future scenarios in terms of risk and opportunities rather than aiming to seek precise predictions.

In this process, we suggest that future studies would need to approach this work with a framework such as the risk–opportunity analysis (ROA), explained in [133]. ROA is particularly suitable for a philosophy of modelling based on disequilibrium and complex systems, as the one proposed in this study. Such a disequilibrium is characteristic of innovation systems that can lead to self-reinforcing mechanisms of growth as well as barriers to change. Path dependency is key, both to accumulate progress and to create inertia in systems to change. The system is dynamic, and the understanding of the behaviour would be more important than aiming to calibrate its parameters to data that cannot be estimated.

The key element of ROA is its focus on fundamental uncertainty that is acknowledged as the basis of every complex system, and assuming that the ability of diverse agents to enumerate and assign probabilities to all possible futures would be limited if not impossible. As a result, we suggest that the current work would be well suited for future analysis of uncertain scenarios to influence policies in the aviation industry.

7. Conclusions and Further Study

This study proposes ten self-reinforcing feedback loops and three major balancing loops that can act as a catalyst for development or initiate a cycle leading to the industry's decline. Ten intervention points are highlighted, seen both as a risk to be mitigated or an option for feeding positive loops to improve the industry and the ecosystem. These are reassessed both in terms of the perspectives of aviation professionals as well as in terms of theoretical frameworks [130–132], while providing a future direction for modelling analysis in the context of risk, opportunities and uncertainty [133].

This research highlighted the potential skills shortage in the industry caused by COVID-19 job losses and the resulting perception of job security, exacerbated by difficulties in encouraging younger generations into jobs with unattractive environmental credentials. However, the need for rapid technological advances demonstrates the requirement to innovate and drive forward the route to decarbonisation through new thinking and skills, feeding most of the reinforcing loops for the aviation industry. Individuals working in the industry are essential to realising the change needed. While the unsustainable image of aviation may create a skills shortage and prevent the younger generation's involvement in the industry, the emergence of new and exciting technology such as electric and hydrogen aircraft may also attract the new skills and thinking needed. If individuals concerned about the environment avoid working in aviation, the industry risks becoming less active in working towards change. The aviation industry needs to attract an innovative workforce to accelerate change.

This research has also shown the importance that the industry places on collaboration both within the industry and internationally. This may be a challenge under the pressure of business survival, exacerbated by COVID-19, but collaboration is essential to encourage the innovation and investment required. Participants were also concerned that COVID-19 had limited the ability of the industry to invest, slowing down the decarbonisation progress and highlighting the increased need for a collaborative and efficient approach.

With a mixture of new and novel technologies being investigated, aviation is undergoing an exciting transformation reminiscent of the period of development of the jet engine. As one participant observed, the industry is undergoing a "revolution".

The conclusions lead toward the following recommendations:

- There is likely to be a potential skills gap in aviation and aerospace at a time when innovation is needed more than ever. Therefore, initiatives to retain existing staff and encourage a new generation of innovators enthusiastic about finding ways to decarbonise aviation are essential.
- The need for collaboration is vitally important. Global cooperation between governments, trade organisations and regulators should be encouraged to work towards aligned solutions.
- Collaboration within the industry should also be encouraged to accelerate innovation and encourage an open-minded approach to solution development.
- While global collaboration should be sought, due to the international nature of aviation, and the difficulty in implementing restrictions on a global basis, the effectiveness of unilateral action by individual countries may be limited. Therefore, the implementation of local environmental restrictions, taxation and carbon pricing should also encourage and incentivise innovation and long-lasting feasible solutions that enable the broadest possible global adoption.

In addition to repeating this research in other global regions, several interesting ways to continue this research are apparent. On the one hand, this research developed a system map to better understand the functioning of the aviation industry within ecological constraints. The natural next step would be to use this map to inform new formal computer models, either qualitative or quantitative, to assess those strategies with simulation and scenario analysis. This modelling can be performed alongside the possibility of improving data with other interviews and surveys. For example, the research showed that the awareness and understanding of specific technologies, such as hydrogen and SAF were limited; therefore, further research into the actions needed to prepare the industry for these technologies would be informative.

On the other hand, as participants talked about future skills shortages affecting the potential transformation of the industry, research specifically focussing on those joining the industry or studying aviation and aeronautical subjects would be enlightening. More comprehensive research into why individuals choose not to work in aviation or study relevant subjects may also be interesting for developing an understanding of the necessary steps for encouraging the skills required for the industry's transition to net-zero. An analysis of the nonlinear behaviour of decision makers linked to the field of behavioural economics could benefit the development of models to support this line of thinking.

All these findings would be capable of informing pre-existing frameworks in the literature such as the multilevel perspective framework for technological transition [130,131] and would be well placed to be modelled as part of the ROA framework [133].

Author Contributions: Conceptualization, C.P.; methodology, C.P. and R.P.; software, C.P.; investigation, C.P.; data curation, C.P.; writing—original draft preparation, C.P. and R.P.; writing—review and editing, C.P. and R.P.; supervision, R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Anglia Ruskin University (protocol code GSISREP-2021-025, 5 July 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Acknowledgments: The authors would like to acknowledge the reviewers of this paper that made it stronger and more compelling.

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

Appendix A. Template for the Interview Questionnaire

The interview template was used as a guide. However, to ensure a natural conversation, questions were adapted, skipped or changed in order depending on the conversation flow.

The survey began with an introduction and general questions, before asking specific targeted questions.

Appendix A.1. Introducing the Questionnaire

a. Objective of the interview;
b. Structure of the questionnaire;
c. Check that that the participant information sheet has been reviewed;
d. Ask for permission to record.

Appendix A.2. Questionnaire

1. Introducing the participant:
    a. Can you tell me a little about your professional background?
    b. What is your role within (your company)?
    c. Do you have any academic or industry qualifications related to aviation, sustainability or energy and fuels?
2. Background questions on climate change to help set the context of their views:
    a. What do you think the main challenges are for the aviation industry by 2050 and what would you consider to be the top three issues?
    b. Expanding on the issue of climate change (or if not mentioned in a. let's talk about climate change), how difficult do you think it will be for aviation to deal with this challenge?
    c. How do you personally feel about climate change and do you feel aviation is a significant contributor?
    d. How important do you think it is that aviation decarbonises?
    e. Do you think aviation growth should be restricted until the climate change impact is reduced?
    f. How likely do you think it is that aviation will be zero carbon by 2050? If not fully decarbonised, what percentage do you think will be?
3. Thoughts on technology and solutions:
    a. What strategies do you think aviation can adopt to address the climate change challenge and what do you think the biggest challenge to overcome is?
    b. How effective do you think that carbon offsetting is in reducing the impact of aviation on climate change? Do you consider this to be a long-term solution?
    c. Thinking about SAF (sustainable aviation fuels) how aware are you of the different potential types? (e.g., biofuels, power to liquid, etc.).

   d. How much impact do you think SAF will have on helping to decarbonise aviation?
   e. Would you consider SAF made from waste or SAF made using industry carbon capture to be a zero-carbon fuel?
4. Focus on hydrogen as a fuel:
   a. Do you think hydrogen is a viable aviation fuel?
5. Follow-on questions if answer to 4a is yes.
   a. How long do you think it would be before hydrogen could be used as a viable solution for commercial aviation?
   b. Do you think hydrogen has the potential to replace kerosene aircraft by 2050? If not, how widespread do you think its use will be?
   c. What do you think the biggest challenges using hydrogen might be?
   d. Thinking about Kerosene, SAF and hydrogen together; how do you see the use of these fuels being balanced between now and 2050?
6. Follow-on questions if answer to 4a is no.
   a. Why do you say that? E.g., technologically not feasible, unsafe, too complex, too expensive etc?
   b. What would need to change to make you think that hydrogen could be a viable aviation fuel?
7. Summary final questions:
   a. Do you have any other thoughts on decarbonising aviation, climate change, the use of alternative fuels, hydrogen, or any other connected topic?
   b. Would you be able to recommend anyone else that would be good for us to interview?

Appendix B. Template for the Survey Questionnaire

This appendix contains the questions used in the online survey system. Questions were designed to maintain anonymity and provide the opportunity for open sharing of thoughts and ideas, by asking open questions to explain responses. All questions were optional to encourage survey completion, however almost all questions were answered in all cases. A total of 90 fully completed survey responses were received.

1. Which of the following best describes your current or most recent role?
   - Aircraft Design and Manufacturing;
   - Airline;
   - Airport Operator;
   - Airport Planning;
   - Airport Services;
   - Airspace;
   - Control Authority/Regulation/Government;
   - Engineering;
   - Handling Agent;
   - Research;
   - Other (please specify).
2. Which country is (was) your role based?
3. How old are you?
   a. <35
   b. 35–55
   c. >55

4. Can you briefly describe what you think the main challenges will be for the aviation industry between now and 2050?
5. How significant do you think aviation's contribution is to climate change and how important do you think it is that aviation decarbonises?
6. Do you think further aviation growth should be restricted until aviation decarbonises?
   a. Yes;
   b. No;
   c. Partially.
7. Can you briefly explain your answer?
8. Are you worried about climate change?
   a. Yes;
   b. No;
   c. Undecided.
9. Can you briefly explain your answer?
10. What solutions do you think will result in the biggest carbon reduction in aviation?
11. How effective do you think carbon offsetting is as a solution for decarbonising aviation
12. By 2050, how decarbonised do you think aviation will be?
    a. Fully;
    b. Significantly;
    c. Partially;
    d. Slightly;
    e. Not at all.
13. Do you have anything else you would like to add regarding aviation, climate change or solutions to decarbonise?

Appendix C. Description of Statistical Bias Risk in Data

Within any research, there are many different potential types of bias that can affect data collection. Unfortunately, within the timescales and resources of this project, it was impossible to avoid all potential bias, but efforts were made to prevent this from affecting the overall outcome.

Table A1 highlights some of the primary risks [134], how this may have affected this research and steps taken to mitigate the effects.

Table A1. Bias risk and mitigation measures.

Bias	Risk and Mitigation
Sampling bias	• Risk in achieving a sample of aviation professionals with representative levels of understanding and interest in sustainability and climate change. • Interviewee screening was used to limit bias; however, the surveys may have attracted those with strong environmental views. Posting on the authors LinkedIn profile and using neutral language aimed to limit the effect. • Preventing all sampling bias is unlikely to be achievable when collecting data on a voluntary opt-in basis. • LinkedIn posts may also have introduced a sampling bias towards professionals; however, this was an intentional audience for this research. • The surveys and interviews were conducted in English and recruited through a UK LinkedIn profile and business network. Although all aviation professionals were encouraged to take part, there will have been a bias towards English-speaking participants. • Output of this research is more representative of the views of those in the UK compared with other countries.

Table A1. *Cont.*

Bias	Risk and Mitigation
Non-response bias	• For interviews, no one who was asked to take part refused. • The survey inevitably suffered from no-response bias. • The survey system also highlighted many dropped out on the ethics approval page, potentially skewing completion towards those with strong views.
Response bias	• Acquiescence bias—questions were asked openly, without asking whether participants agreed or disagreed with statements. The survey link on LinkedIn was accompanied by a post stating that there were no right or wrong answers, and the interviews were introduced with the same statement. • Demand characteristic bias—As participants were aware that this research was part of an MSc in Sustainability, they may have tried to guess the purpose of the research and behave accordingly. However, every effort was made to encourage honest answers by highlighting that there were no right or wrong answers and that the research was to understand the true views of the participants. • Extreme response bias—The majority of the questions avoided using a scale to categorise responses; however, where unavoidable, participants were also asked to explain their answers to dig deeper into their depth of feeling. • Social desirability bias—Ensuring that the survey was anonymous aimed to avoid this effect; however, it remained a potential problem for interviews. This was minimised by ensuring the interviewer did not give any feedback to answers indicating agreement or disagreement. However, the participants' awareness that the interviewer has a strong interest in sustainability may still have affected this. • Interviewer bias—this was a risk for the interviews. However, using video conferencing minimised the opportunity for the interviewer's posture and other non-verbal characteristics from influencing answers. Despite this, awareness of the interviewer's background, may have influenced responses, despite reassurances and requests for the participants to give their honest answers.
Question order bias	• The survey and questionnaire were designed to ask general questions with personal feelings and opinions first to prevent more detailed questions about specific solutions from influencing these answers.
Information bias	• A rigorous data analysis process was implemented to minimise misrepresentation bias. • Following this process aimed to prevent recall bias; however, the author's subjectivity should be recognised [135].

Appendix D. Descriptive Analysis of Survey and Interview Data

Appendix D.1. Participants' Views on Climate Change

Survey participants were asked whether they were worried about climate change. All participants answered the question, with the overwhelming majority saying that they were, as shown in Figure A1. Of those responding "no", two responded that there was no evidence and that climate predictions would not occur. However, other reasons given were less about the participants' thoughts on climate change, but more related to their personal situation, with one participant saying that they were too old for it to be an issue, but they worried for future generations. Others responded that they were concerned and willing to do their part, but as individuals cannot solve the issue alone, they did not worry.

Of those who responded "undecided", similar reasons were given, with one respondent acknowledging their answer as "selfish" since they would not personally be affected. Others had concerns but did not feel that worrying would help. A few also responded that the science was undecided and that although there are some visible effects of a changing climate, this was unlikely to be down to human activity alone.

Most respondents (83%) were worried, saying that the evidence was clear to be seen, scientific data backed this up, and they were concerned about humanity's ability to make the changes needed. Many also mentioned their concern for family and future generations. Although samples sizes are small when considering age distribution, the most worried were those between the ages of 35 and 55 years, with the least worried being those over 55. However, no one below 35 said they were not worried. The breakdown is shown in Figure A2.

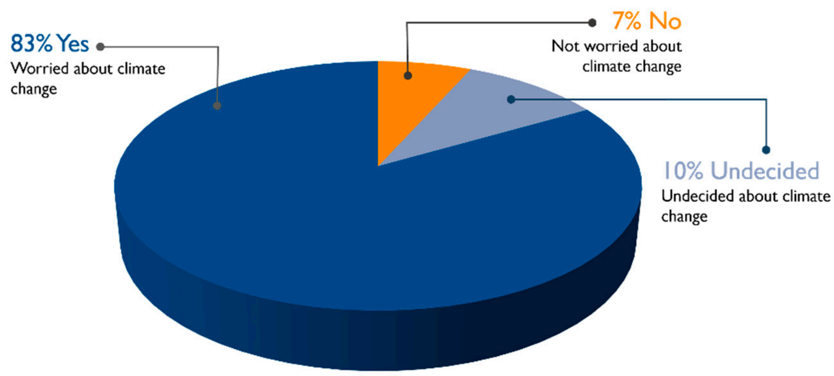

Figure A1. Breakdown of survey participants' view of climate change.

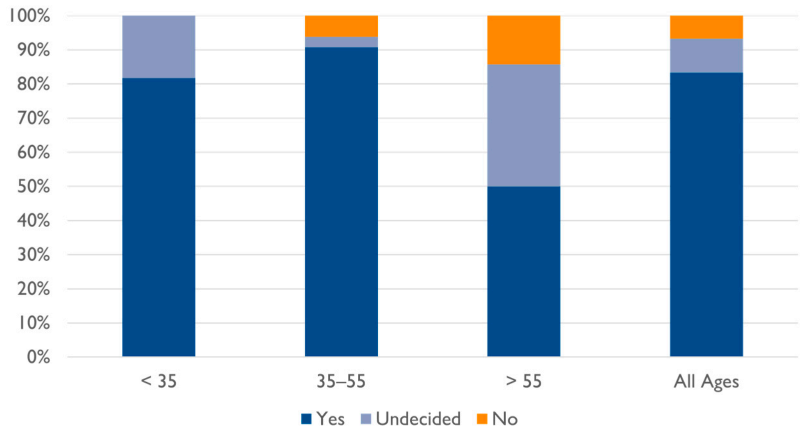

Figure A2. Breakdown of survey participants' view of climate change—by age.

In the interviews, participants were asked open questions about their thoughts on climate change. All participants thought that climate change was a significant problem, with one labelling it the biggest threat to humanity and another saying that not enough was being implemented and that change was too slow.

An underlying theme was that awareness has changed over recent years. One participant said they had not been a strong believer but could now see the changes. Another said that they had become progressively concerned recently, and another that their views had changed over the past five years. Some mentioned their concern for their children or grandchildren. However, one participant did say that, although they believed in climate change, they were not necessarily convinced that the effects would be as drastic as predicted.

Appendix D.2. Participants' Views on Restricting Aviation Growth

Survey participants were asked if they thought that aviation growth should be restricted until aviation decarbonises. The results, shown in Figure A3, were mixed, with just under half saying "no" (48%), with the remaining responses split between "partially" (38%) and "yes" (14%).

Those responding "yes" gave a range of reasons, including suggesting that aviation is not responsible enough to manage itself to reduce emissions and that limiting growth would provide incentives to improve faster. Another stated that unrestricted growth is untenable and must be restricted to prevent carbon emissions. For those answering "partially", a dominant view was that conditions to growth should be defined and that limits should be set on carbon emissions, allowing growth, but only if carbon was reduced. Participants suggested that this balanced approach would provide some restrictions while still encouraging industry investment. Several responses focused on regional differences, saying that limiting all growth would hard code current inequalities between regions and another stating that only mature markets should be restricted.

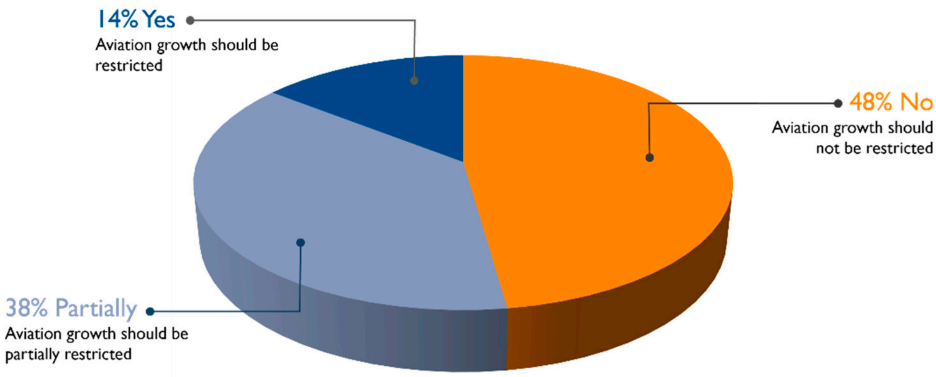

Figure A3. Breakdown of survey participants' view on restricting aviation growth.

The responses were similar for those answering "no", with many suggesting that a lack of growth would affect innovation and the ability to invest in new technology. Others reiterated fairness between regions of the world. It was also suggested that aviation should be given time to decarbonise itself first, as technology was not yet ready. Other themes included the impracticality of restricting a global industry and that restricting could cause resentment and less willingness to change. When considering the age breakdown, the results shown in Figure A4 indicate that those under 35 were the least likely to agree with restricting aviation growth.

In the interviews, the balance of views was similar to the survey, with a split of opinions. Those who thought growth should not be limited believed that growth was essential for encouraging investment. Some also thought that the economic benefits of aviation should be considered and that bringing people together globally was important. A majority, however, expressed a view that there should be some limits to growth but that rather than applying hard limits to flight numbers, growth should only be allowed within environmental limits. For example, some suggested incentivising low-carbon growth through differential pricing. Others proposed allowing growth once carbon reduction targets were met, and others suggested allowing new capacity to be used only by flights operating using SAF or other sustainable fuels. However, some expressed concern that restricting growth unilaterally would not work, as growth would shift to other airports or countries unless there was global agreement and regulation.

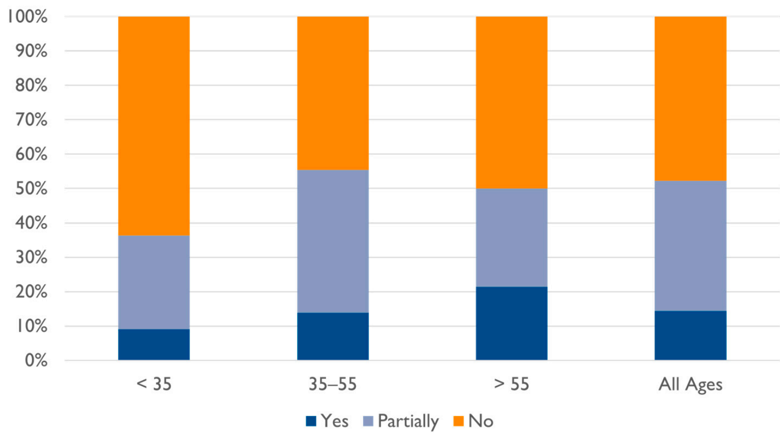

Figure A4. Breakdown of survey participants' view on restricting aviation growth—by age.

Appendix D.3. Participants' Views on the Success of Decarbonisation by 2050

Survey participants were asked to predict how decarbonised they thought aviation would be by 2050. As seen in Figure A5, the majority thought that the aviation industry would have decarbonised to some extent, with 4% thinking that the industry would be fully decarbonised, 37% significantly decarbonised and 46% partially decarbonised.

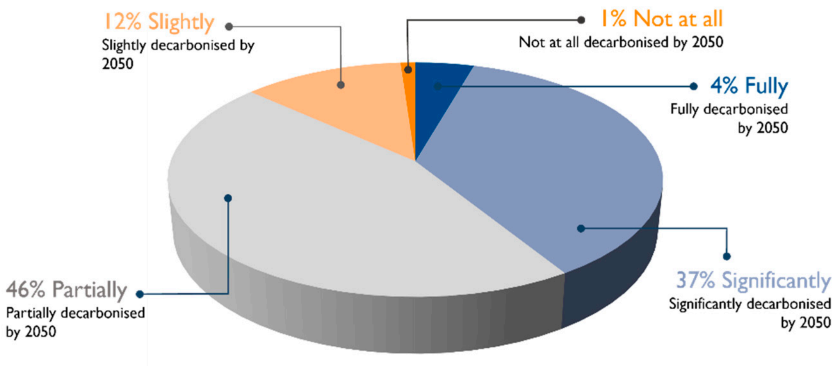

Figure A5. Breakdown of survey participants' view on how decarbonised aviation will be by 2050.

Figure A6 shows that those under 35 were the most optimistic, with 81% expecting aviation to be either entirely or significantly decarbonised.

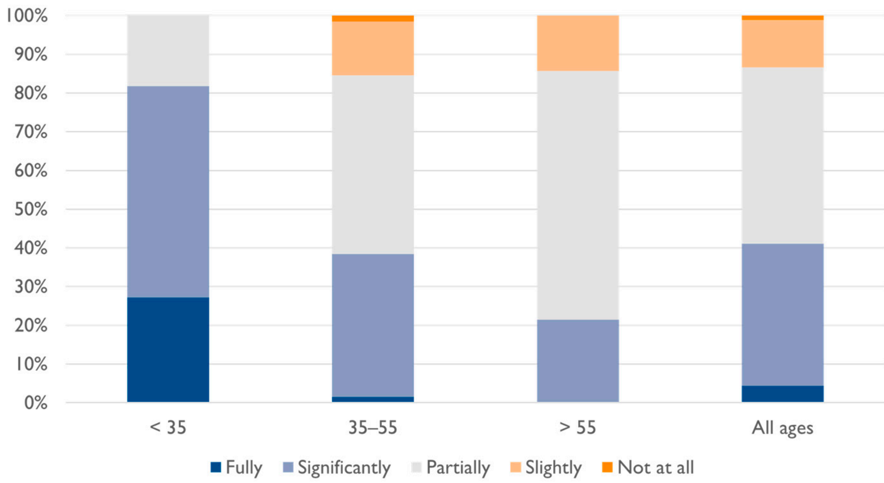

Figure A6. Breakdown of survey participants' view on how decarbonised aviation will be by 2050—by age.

In the interviews, responses varied, with everyone expecting some level of decarbonisation. Some felt that 2060 was a more realistic timescale for significant decarbonisation, while another thought that achieving decarbonisation by 2050 was too late. However, on average, the opinion was that aviation would be halfway towards full decarbonisation.

Appendix D.4. Participants' Views on Anticipated Challenges Ahead

Survey participants were asked to describe what they felt the main challenges would be for aviation between now and 2050. While a mix of results, the responses overall defined two different challenge timeframes. In the short term, the main challenge identified was recovery from the COVID-19 pandemic, both from direct traffic loss and income over the past 18 months, and from a continuing depression of passenger numbers. Furthermore, it was felt that alternatives to aviation, such as video conferencing, in addition to fears of ongoing COVID-19, might continue suppressing demand and revenues. Many suggested that this would reduce the ability of the industry to invest in future decarbonisation efforts.

Longer term, the primary concern was the challenge of meeting the decarbonisation goals, whether to prevent climate change or to prevent negative public opinion and the potential downturn that may result. Most, however, felt that growth would return, particularly in developing economies where the market was less saturated. Therefore, this growth would create a significant challenge in meeting the potential demand while also needing to reduce aviation's climate impact.

Similarly, in the interviews, the short-term concern was recovery from COVID-19. In addition to the direct financial impact, the challenges of restarting a global industry were also discussed. Some expressed concern that aviation had lost too many staff during the COVID-19 pandemic. This loss of staff, combined with aviation's sustainability image, they felt, has made attracting new staff very difficult, resulting in a potential skills shortage when the industry begins to recover. Others also believed that future pandemics would be inevitable; therefore, preparing for these presented challenges for investment and planning.

For the longer-term, sustainability and decarbonisation were seen as significant challenges. Many thought that developing the necessary technology and fuels would be the primary challenge. The highlighted technology challenges included improving efficiency, developing aircraft suitable for new fuels, such as hydrogen, and establishing global collaboration to accelerate development. Several also mentioned that safety has long been aviation's top priority and that maintaining this while pushing the technology boundaries will be difficult.

The development of SAF capability was also raised as a concern, particularly scaling up production to a meaningful level. A view expressed was that there had been little done to lay out the scale of the infrastructure challenge to make SAF a meaningful contribution to decarbonisation. Similarly, others were concerned with the challenge of ground infrastructure needed for hydrogen or battery aircraft. Many thought that future growth in developing markets would be particularly challenging to facilitate while also reducing carbon emissions. In more established markets, post-COVID uncertainty was a concern, with several expecting to see the loss of some airlines and unpredictable changes to the demand. Public perception of the industry was also a concern and the unknown effect this may have on demand.

Appendix D.5. Participants' Views on Aviation's Contribution to Climate Change and the Need to Decarbonise

Respondents to the survey were asked whether they felt aviation had a significant impact on climate change and how important it was for the industry to decarbonise. Many respondents were aware of aviation's percentage of global emissions. However, some also raised the issue that non-CO_2 impacts from aviation, such as contrail formations, resulted in aviation having a more considerable impact than the carbon emissions alone would suggest. Similarly, many recognised that aviation's share would increase if other industries began to decarbonise, and that the UK's contribution was higher than the global average. Additionally, it was identified that aviation is still often seen as a luxury and that a minority of people drive most of the emissions. Therefore, they felt that as aviation's availability reaches a larger population, there will be potential for an even bigger CO_2 increase.

The responses were therefore split between those that felt that it was essential for aviation to decarbonise, others that felt that aviation had a modest impact compared with many other industries but that it should still decarbonise, and a minority who felt that aviation's impact was small and therefore lower priority than other industries. Many also felt that aviation's impact is less than the negative publicity it receives would suggest, with some referring to aviation as a "scapegoat".

Although the interview results were similar, with many thinking that the relative contribution of aviation was low, the majority stressed that this was not an excuse for inaction and that it was still essential to decarbonise. In addition, some felt that aviation attracted an unfair amount of criticism compared to the other industries; however, another recognised that many viewed aviation as discretionary, hence the additional pressure to decarbonise.

Appendix D.6. Participants' Views on Decarbonisation Solutions

Survey participants were asked what solutions they thought would result in the biggest aviation carbon reduction. A wide range of solutions were suggested in the surveys, but the predominant response was to replace kerosene with new fuels. Many thought

SAF would have the most significant effect on decarbonisation, while others suggested hydrogen. Some thought SAF would be effective in the short-term while existing aircraft remained in operation, but with a switch to hydrogen in the long-term. A significant number of participants also mentioned battery–electric. A few participants felt that the only solution in the short term was to reduce flying, as other solutions were not currently viable. Other solutions suggested included new technology and aircraft fleet replacement, airports reducing their land-based emissions, carbon taxes ring-fenced for decarbonisation initiatives and airspace changes to improve efficiency. Only one participant mentioned offsetting as a possible solution.

In the interviews, SAF was highlighted as the most likely solution in the short to mid-term. Others felt that battery–electric would make a significant difference for short-haul flights if battery technology developed further. Some mentioned hydrogen as a potential long-term solution; however, not all of those that mentioned hydrogen were confident in the technology being available by 2050. Several people raised the issue of urban mobility initiatives and the concern that this should not be considered a solution for decarbonisation. They felt that although battery-powered sub-regional electric aircraft may emit no carbon, they would effectively be replacing road transport, which by 2050 would also likely be zero-emission. They thought that as flying requires more energy than road vehicles, these aircraft will add to the future energy burden. Some expressed their concern about SAF, suggesting that many people were not aware of the scale of the challenge and the potential environmental impact remaining. On the ground, it was felt that airports should focus on decarbonising their operation, and additionally, any aircraft ground movements should be carried out without using fossil fuels. It was also apparent from the interviews that the knowledge of SAF and hydrogen was minimal for many participants, with little understanding other than the concept.

Appendix D.7. Participants' Views on Carbon Offsetting

Participants were asked how effective they thought carbon offsetting was as a solution for decarbonising aviation. Although not a multichoice question, analysing the written answers in the survey revealed that an overwhelming 69% of participants thought offsetting was ineffective. Many said that it did not address the real problems, and some said it was, at worst, greenwashing. Some commented that planting trees should be happening regardless and was not an excuse for allowing additional aviation emissions.

Only nine percent felt that offsetting was effective. These participants commented that it was one of the only currently viable solutions and that it could be part of the overall solution if using recognised and adequate schemes. The responses from the remaining twenty-one percent suggested that offsetting was a viable option in the short term, and despite some reservations, thought it had a role to play and could be effective. However, most of these participants felt that it should not be relied on for the long term.

The interviews backed up the survey results. The majority felt that offsetting was "pushing the problem around" or ignoring the source of the issue. However, it was recognised that offsetting has a role to play and could be effective short term. There was also concern that it is difficult to ensure the validity of offset schemes. Another participant said that offsetting should be done to mitigate historical emissions rather than new and future emissions.

Appendix D.8. Participants' Additional Ideas

The final survey and interview question asked participants whether they had any additional comments or thoughts on aviation decarbonisation that had not been covered elsewhere. A key theme emerging from this question was the need for collaboration between countries and within the aviation industry to find global solutions more quickly. The time element was reinforced by other comments that highlighted the lack of time available to make changes, emphasising that action is needed now, not in the future. One participant commented that air travel is not a right and that people should not expect to fly as regularly as they have.

Two participants revealed that they had moved away from the industry into other jobs purely as they felt uncomfortable working in an industry that they perceived to be damaging. However, others commented that the benefits of aviation should be considered, and that the world needs to be connected. Several participants commented that decarbonising the industry did not mean making sacrifices and that technology should be used to solve the decarbonisation challenge.

Finally, one participant commented that it is an exciting time to be working in the industry as aviation is going through a "revolution".

In the interviews, several additional issues were raised. Firstly, energy requirements were discussed, as all solutions to move away from fossil fuels require a large amount of electrical energy. Secondly, another participant said that it was increasingly difficult for airports to know when to invest, as the future was uncertain. However, the investment needed for technology such as hydrogen aircraft would be costly and take many years to implement. Investment financing and the need to balance the "carrot and stick" approach to encourage innovation was also highlighted. Lastly, several participants said they were encouraged to see the acceleration in initiatives and the growing focus on sustainability within the industry.

References

1. United Nations. Paris Agreement. 2015. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 1 October 2021).
2. Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways. 2018. Available online: https://www.ipcc.ch/sr15/chapter/spm (accessed on 1 October 2021).
3. Borunda, A. *Weather Shows Evidence of Climate Change Every Single Day Since 2012*; National Geographic: New York, NY, USA, 2012. Available online: https://www.nationalgeographic.com/science/article/weather-shows-evidence-of-climate-change-every-single-day-since-2012 (accessed on 1 October 2021).
4. Airbus. Airbus Global Market Forecast. 2021. Available online: https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast (accessed on 21 November 2021).
5. Boeing. Commercial Market Outlook. 2021. Available online: https://www.boeing.com/commercial/market/commercial-market-outlook/ (accessed on 21 November 2021).
6. Burgueno, S.E. *Global Air Traffic—Number of Flights 2004–2022*; Statista: Hamburg, Germany, 2022. Available online: https://www.statista.com/statistics/564769/airline-industry-number-of-flights/ (accessed on 1 April 2022).
7. Air Transport Action Group (ATAG). Adding Value to the Economy. 2021. Available online: https://aviationbenefits.org/economic-growth/adding-value-to-the-economy/ (accessed on 1 October 2021).
8. Árnadóttir, Á.; Czepkiewicz, M.; Heinonen, J. Climate change concern and the desire to travel: How do I justify my flights? *Travel Behav. Soc.* **2021**, *24*, 282–290. [CrossRef]
9. Somerville, E. Extinction Rebellion Heathrow Protest. *Evening Standard*, 8 December 2019. Available online: https://www.standard.co.uk/news/uk/heathrow-extinction-rebellion-protest-latest-bulldozer-third-runway-a4308041.html (accessed on 15 October 2021).
10. Gillespie, T. Extinction Rebellion Protestor Climbs on Plane at London City Airport. *Sky News*, 22 October 2019. Available online: https://news.sky.com/story/flight-returns-to-london-city-airport-terminal-as-climate-change-protester-is-arrested-on-board-11832001 (accessed on 14 October 2021).
11. Gallup, J. Top-Down Versus Bottom-Up: Two Approaches to Sustainability. 2018. Available online: https://sustainability.wisc.edu/top-down-bottom-up-sustainability/ (accessed on 14 November 2021).
12. Graver, B.; Zhang, K.; Rutherford, D. CO_2 Emissions from Commercial Aviation, 2018. 2019. Available online: https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf (accessed on 1 October 2021).
13. Gössling, S.; Humpe, A. The global scale, distribution and growth of aviation: Implications for climate change. *Glob. Environ. Change* **2020**, *65*, 102194. [CrossRef]
14. HM Government. Aviation 2050, The Future of UK Aviation. 2018. Available online: https://www.gov.uk/government/consultations/aviation-2050-the-future-of-uk-aviation (accessed on 1 October 2021).
15. Lee, D.S.; Fahey, D.W.; Skowron, A.; Allen, M.R.; Burkhardt, U.; Chen, Q.; Doherty, S.J.; Freeman, S.; Forster, P.M.; Fuglestvedt, J.; et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* **2021**, *244*, 117834. [CrossRef] [PubMed]

16. International Civil Aviation Organisation (ICAO). On Board a Sustainable Future. 2016. Available online: https://www.icao.int/environmental-protection/pages/env2016.aspx (accessed on 1 October 2021).
17. International Civil Aviation Organisation (ICAO). Destination Green, the Next Chapter. 2019. Available online: https://www.icao.int/environmental-protection/Documents (accessed on 1 October 2021).
18. Department for Transport (DfT). Jet Zero Consultation: A Consultation on Our Strategy for Net Zero Aviation. 2021. Available online: https://www.gov.uk/government/consultations/achieving-net-zero-aviation-by-2050 (accessed on 1 October 2021).
19. Sustainable Aviation. Decarbonisation Road-Map: A Path to Net Zero. 2020. Available online: https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf (accessed on 1 October 2021).
20. Department for Business, Energy & Industrial Strategy (BEIS). UK Becomes First Major Economy to Pass Net Zero Emissions Law. 2019. Available online: www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law (accessed on 7 November 2021).
21. HM Government. Net Zero Strategy: Build Back Greener. 2021. Available online: https://www.gov.uk/government/publications/net-zero-strategy (accessed on 1 October 2021).
22. Sustainable Aviation. UK Aviation Industry Strengthens Commitment to Achieving Net Zero and Launches First Interim Decarbonisation Targets. 2021. Available online: https://www.sustainableaviation.co.uk/news/uk-aviation-industry-strengthens-commitment-to-achieving-net-zero-and-launches-first-interim-decarbonisation-targets (accessed on 1 October 2021).
23. Air Transport Action Group (ATAG). Waypoint 2050. 2021. Available online: https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf (accessed on 21 November 2021).
24. International Air Transport Association (IATA). Aviation Economic Benefits—IATA Economic Briefing No. 8. 2007. Available online: https://www.iata.org/whatwedo/Documents/economics/aviation_economic_benefits.pdf] (accessed on 7 November 2019).
25. Eurocontrol. Does Taxing Aviation Really Reduce Emissions? 2020. Available online: https://www.eurocontrol.int/sites/default/files/2020-10/eurocontrol-think-paper-taxing-aviation-oct-2020.pdf (accessed on 1 October 2021).
26. Vaughan, A. Most People in the UK Back Limits on Flying to Tackle Climate Change. *New Scientist*, 18 September 2019. Available online: https://www.newscientist.com/article/2216743-most-people-in-the-uk-back-limits-on-flying-to-tackle-climate-change (accessed on 1 October 2021).
27. Asquith, J. The Spread of Flight Shaming in Europe—Is Greta Thunberg the Reason Why? *Forbes*, 13 January 2020. Available online: https://www.forbes.com/sites/jamesasquith/2020/01/13/the-spread-of-flight-shame-in-europe-is-greta-thunberg-the-reason-why (accessed on 1 October 2021).
28. Barr, S.; Shaw, G.; Coles, T.; Prillwitz, J. A holiday is a holiday': Practicing sustainability, home and away. *J. Transp. Geogr.* **2010**, *18*, 474–481. [CrossRef]
29. Gössling, S.; Hanna, P.; Higham, J.; Cohen, S.; Hopkins, D. Can we fly less? Evaluating the 'necessity' of air travel. *J. Air Transp. Manag.* **2019**, *81*, 101722. [CrossRef]
30. Becken, S. Tourists' perception of international air travel's impact on the global climate and potential climate change policies. *J. Sustain. Tour.* **2007**, *15*, 351–368. [CrossRef]
31. Airbus. Family Figures May 2021 Edition. 2021. Available online: https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft (accessed on 14 November 2021).
32. Kharina, A.; Rutherford, D. Fuel Efficiency Trends for New Commercial Jet Aircraft 1960 to 2014. 2015. Available online: https://theicct.org/publications/fuel-efficiency-trends-new-commercial-jet-aircraft-1960-2014 (accessed on 1 October 2021).
33. Ploetner, K.O.; Rothfeld, R.; Urban, M.; Hornung, M.; Tay, G.; Oguntona, O. Technological and operational scenarios on aircraft fleet-level towards ATAG and IATA 2050 emission targets. In Proceedings of the 17th AIAA Aviation Technology, Integration, and Operations Conference, Denver, CO, USA, 5–9 June 2017.
34. Epstein, A.H.; O'Flarity, S.M. Considerations for reducing aviation's co 2 with aircraft electric propulsion. *J. Propuls. Power* **2019**, *35*, 572–582. [CrossRef]
35. Nava-Gaxiola, C.A.; Barrado, C. Performance measures of the SESAR Southwest functional airspace block. *J. Air Transp. Manag.* **2016**, *50*, 21–29. [CrossRef]
36. Department for Transport (DfT). Decarbonising Transport. A Better, Greener Britain. 2021. Available online: https://www.gov.uk/government/publications/transport-decarbonisation-plan (accessed on 1 October 2021).
37. Allwood, J.; Azevedo, J.; Clare, A.; Cleaver, C.; Cullen, J.; Dunant, C.F.; Fellin, T.; Hawkins, W.; Horrocks, I.; Horton, P.; et al. Absolute Zero: Delivering the UK's Climate Change Commitment with Incremental Changes to Today's Technologies. 2019. Available online: https://www.repository.cam.ac.uk/handle/1810/299414 (accessed on 1 October 2021).
38. Key Moments from Day 1 of the COP26 Climate Change Summit. *The New York Times*, 1 November 2021. Available online: https://www.nytimes.com/live/2021/11/01/world/cop26-climate-change-summit (accessed on 2 November 2021).
39. International Civil Aviation Organisation (ICAO). Sustainable Aviation Fuels Guide. 2018. Available online: https://www.icao.int/environmental-protection/pages/SAF.aspx (accessed on 1 October 2021).
40. Boyd, R. *Why SAF Is the Future of Aviation*; IATA: Montreal, QC, Canada, 2020. Available online: https://www.iata.org/en/programs/environment/sustainable-flying-blog/why-saf-is-the-future-of-aviation/ (accessed on 14 November 2021).
41. Airports Council International (ACI). Sustainable Energy Sources for Aviation: An Airport Perspective. 2021. Available online: https://store.aci.aero/product/sustainable-energy-sources-for-aviation-an-airport-perspective/ (accessed on 1 October 2021).

42. Doliente, S.S.; Narayan, A.; Tapia, J.F.D.; Samsatli, N.J.; Zhao, Y.; Samsatli, S. Bio-aviation fuel: A comprehensive review and analysis of the supply chain components. *Front. Energy Res.* **2020**, *8*, 110. [CrossRef]
43. Baynes, M. Extinction Rebellion Climate Activists Block Entrances to Airport Over Private Jet Flights. *Sky News*, 2 October 2021. Available online: https://news.sky.com/story/extinction-rebellion-climate-activists-block-entrances-to-airport-over-private-jet-flights-12423658 (accessed on 1 October 2021).
44. Doyle, A. Turning Food Waste into Aviation Fuel. *The Chemical Engineer*, 22 April 2021. Available online: https://www.thechemicalengineer.com/news/turning-food-waste-into-aviation-fuel (accessed on 1 November 2021).
45. George, S. UK Oil Major Backs New Waste-to-Jet-Fuel Plant. *Edie*, 15 February 2021. Available online: https://www.edie.net/news/8/UK-oil-major-backs-new-waste-to-jet-fuel-plant/ (accessed on 1 November 2021).
46. Muznik, S. 9 Reasons Why We Better Move Away from Waste-to-Energy, and Embrace Zero Waste Instead. 2018. Available online: https://zerowasteeurope.eu/2018/02/9-reasons-why-we-better-move-away-from-waste-to-energy-and-embrace-zero-waste-instead/ (accessed on 20 November 2021).
47. World Economic Forum (WEF). Clean Skies for Tomorrow. Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. 2020. Available online: https://www.weforum.org/reports (accessed on 1 October 2021).
48. Airbus. Power-to-Liquids, Explained. 2021. Available online: https://www.airbus.com/en/newsroom/news/2021-07-power-to-liquids-explained (accessed on 14 November 2021).
49. International Civil Aviation Organisation (ICAO). Power-to-Liquid (PTL): Sustainable Fuels for Aviation. 2019. Available online: https://www.icao.int/Meetings/a40/Documents/WP/wp_526_en.pdf (accessed on 1 November 2021).
50. ZeroAvia. ZeroAvia Completes World First Hydrogen-Electric Passenger Plane Flight. 2020. Available online: https://www.zeroavia.com/press-release-25-09-2020 (accessed on 1 October 2021).
51. ZeroAvia. First Commercial Hydrogen-Electric Flight between London and Rotterdam The Hague Airport Expected in 2024. 2021. Available online: https://www.zeroavia.com/rotterdam (accessed on 1 November 2021).
52. Webber, H.; Job, S. Realising Zero-Carbon Emission Flight. Primary Energy Source Comparison and Selection. 2021. Available online: https://www.ati.org.uk/resources/publications/ (accessed on 1 October 2021).
53. Airbus. ZEROe Towards the World's First Zero-Emission Commercial Aircraft. 2021. Available online: https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe (accessed on 1 November 2021).
54. Aerospace Technology Institute (ATI). FlyZero. 2021. Available online: https://www.ati.org.uk/flyzero/> (accessed on 1 October 2021).
55. Clean Sky 2. Hydrogen-Powered Aviation. A Fact-Based Study of Hydrogen Technology, Economics, and Climate Impact by 2050. 2020. Available online: https://op.europa.eu/en/publication-detail/-/publication/55fe3eb1-cc8a-11ea-adf7-01aa75ed71a1/language-en (accessed on 1 April 2021).
56. Airports Council International (ACI); Aerospace Technology Institute (ATI). Integration of Hydrogen Aircraft into the Air Transport System. 2021. Available online: https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report.pdf (accessed on 1 May 2021).
57. Postma-Kurlanc, A.; Leadbetter, H.; Pickard, C. Hydrogen Infrastructure and Operations—Airports, Airlines and Airspace. 2022. Available online: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf (accessed on 1 April 2022).
58. World Economic Forum (WEF). Grey, Blue, Green—Why Are There so Many Colours of Hydrogen? 2021. Available online: https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen (accessed on 1 November 2021).
59. Howarth, R.W.; Jacobson, M.Z. How green is blue hydrogen? *Energy Sci. Eng.* **2021**, *9*, 1676–1687. [CrossRef]
60. International Renewable Energy Agency (IRENA). Green Hydrogen Cost Reduction. Scaling Up Electrolysers to Meet the 1.5 °C Goal. 2020. Available online: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf (accessed on 1 November 2021).
61. Nikolaidis, P.; Poullikkas, A. A comparative overview of hydrogen production processes. *Renew. Sustain. Energy Rev.* **2017**, *67*, 597–611. [CrossRef]
62. Airbus. Electric Flight. Laying the Groundwork for Zero-Emission Aviation. 2021. Available online: https://www.airbus.com/en/innovation/zero-emission/electric-flight (accessed on 14 November 2021).
63. Ampaire. Ampaire Demonstrates First Hybrid Electric Aircraft in Scotland. 2021. Available online: https://www.ampaire.com/press (accessed on 14 November 2021).
64. BBC. Rolls-Royce Says Its All-Electric Aircraft 'Is World's Fastest'. 2021. Available online: https://www.bbc.co.uk/news/uk-england-derbyshire-59359263 (accessed on 1 November 2021).
65. Gössling, S.; Broderick, J.; Upham, P.; Ceron, J.; Dubois, G.; Peeters, P.; Strasdas, W. Voluntary Carbon Offsetting Schemes for Aviation: Efficiency, Credibility and Sustainable Tourism. *J. Sustain. Tour.* **2007**, *15*, 223–248. [CrossRef]
66. Hyams, K.; Fawcett, T. The ethics of carbon offsetting. *Wiley Interdiscip. Rev. Clim. Chang.* **2013**, *4*, 91–98. [CrossRef]
67. International Air Transport Association (IATA). CORSIA Fact Sheet. 2021. Available online: https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---corsia/ (accessed on 14 November 2021).
68. Evans, A.; Schäfer, A. The rebound effect in the aviation sector. *Energy Econ.* **2013**, *36*, 158–165. [CrossRef]
69. Doyle, L.; Brady, A.M.; Byrne, G. An overview of mixed methods research–revisited. *J. Res. Nurs.* **2016**, *21*, 623–635. [CrossRef]

70. Greene, J.; Caracelli, V.J.; Graham, W.F. Toward a conceptual framework for mixed-method evaluation designs. Educational evaluation and policy analysis. *Educ. Eval. Policy Anal.* **1989**, *11*, 255–274. [CrossRef]
71. Breen, R.L. A practical guide to focus-group research. *J. Geogr. High. Educ.* **2006**, *30*, 463–475. [CrossRef]
72. Guest, G.; Bunce, A.; Johnson, L. How many interviews are enough? An experiment with data saturation and variability. *Field Methods* **2006**, *18*, 59–82. [CrossRef]
73. MacDougall, C.; Fudge, E. Planning and Recruiting the Sample for Focus Groups and In-Depth Interviews. *Qual. Health Res.* **2001**, *11*, 117–126. [CrossRef]
74. Creswell, J.W. *Qualitative Inquiry and Research Design: Choosing among Five Approaches*, 2nd ed.; Sage Publications: London, UK, 2007.
75. Parker, C.; Scott, S.; Geddes, A. Snowball Sampling. 2019. Available online: https://methods.sagepub.com/foundations/snowball-sampling (accessed on 21 November 2021).
76. Turner, D.W., III. Qualitative interview design: A practical guide for novice investigators. *Qual. Rep.* **2010**, *15*, 754. [CrossRef]
77. McNamara, C. General Guidelines for Conducting Interviews. Available online: https://managementhelp.org/businessresearch/interviews.htm (accessed on 1 August 2021).
78. Markle, D.T.; West, R.E.; Rich, P.J. Beyond transcription: Technology, change, and refinement of method. *Qual. Soc. Res.* **2011**, *12*. [CrossRef]
79. Riiskjær, E.; Ammentorp, J.; Kofoed, P.E. The value of open-ended questions in surveys on patient experience: Number of comments and perceived usefulness from a hospital perspective. *Int. J. Qual. Health Care* **2012**, *24*, 509–516. [CrossRef] [PubMed]
80. Braun, V.; Clarke, V. Using thematic analysis in psychology. *Qual. Res. Psychol.* **2006**, *3*, 77–101. [CrossRef]
81. Braun, V.; Clarke, V. Can I use TA? Should I use TA? Should I not use TA? Comparing reflexive thematic analysis and other pattern-based qualitative analytic approaches. *Couns. Psychother. Res.* **2021**, *21*, 37–47. [CrossRef]
82. Glaser, B.G.; Strauss, A.L.; Strutzel, E. The discovery of grounded theory; strategies for qualitative research. *Nurs. Res.* **1968**, *17*, 364. [CrossRef]
83. Pasqualino, R.; Jones, A.W. *Resources, Financial Risk and the Dynamics of Growth: Systems and Global Society*; Routledge: Abingdon, VA, USA, 2022.
84. Sterman, J. *Business Dynamics: Systems Thinking and Modeling for a Complex World*; Irwin/McGraw-Hill: Boston, MA, USA, 2000.
85. Capra, F.; Luisi, P.L. *The Systems View of Life: A Unifying Vision*; Cambridge University Press: Cambridge, UK, 2014.
86. Argyris, C. *Strategy, Change, and Defensive Routines*; Pitman: Boston, MA, USA, 1985.
87. Emmerson, R.; Fretz, R.; Shaw, L. *Writing Ethnographic Fieldnotes*; University of Chicago Press: Chicago, IL, USA, 1995.
88. Kleiner, A.; Roth, G. How to make experience your company's best teacher. *Harv. Bus. Rev.* **1997**, *75*, 172–177.
89. March, J.; Sproull, L.; Tamaz, M. Learning from samples of one or fewer. *Organ. Sci.* **1991**, *2*, 58–70. [CrossRef]
90. Morecroft, J.; Sterman, J. *Modeling for Learning*; Productivity Press: Portland, OR, USA, 1994.
91. van Maanen, J. *Tales of the Field*; University of Chicago Press: Chicago, IL, USA, 1988.
92. Yin, R. *Case Study Research*; Sage Publications: Newbury Park, CA, USA, 1994.
93. Arthur, B.W. *Increasing Returns and Path Dependence in the Economy*; University of Michigan Press: Ann Arbor, MI, USA, 1994.
94. Meadows, D.M. *Thinking in Systems: A Primer*; Chelsea Green Publishing: Hartford, VT, USA, 2008.
95. Department for Business, Energy and Industrial Strategy (BEIS). BEIS Public Attitudes Tracker March 2021, Wave 37, UK. 2021. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/985092/BEIS_PAT_W37_-_Key_Findings.pdf (accessed on 1 November 2021).
96. Reuters Institute and University of Oxford. Reuters Institute Digital News Report 2020. 2020. Available online: https://reutersinstitute.politics.ox.ac.uk/sites/default/files/2020-06/DNR_2020_FINAL.pdf (accessed on 1 November 2021).
97. The Centre for Climate Change and Social Transformation. Public Opinion in a Time of Climate Emergency. 2019. Available online: https://cast.ac.uk/wp-content/uploads/2020/01/CAST-Briefing-paper-02-Pubic-opinion-in-a-time-of-climate-emergency-min.pdf (accessed on 1 November 2021).
98. Wynes, S.; Nicholos, K. The Four Lifestyle Choice That Most Reduce Your Carbon Footprint. 2017. Available online: https://www.lunduniversity.lu.se/article/four-lifestyle-choices-most-reduce-your-carbon-footprint (accessed on 14 November 2021).
99. Industry High Level Group. Aviation Benefits Report. 2019. Available online: https://www.icao.int/sustainability/Documents/AVIATION-BENEFITS-2019-web.pdf (accessed on 9 November 2019).
100. Air Transport Action Group (ATAG). When the System Stops. Available online: https://aviationbenefits.org/economic-growth/when-the-system-stops/ (accessed on 15 November 2021).
101. OAG Worldwide Limited. The Journey to Recovery Starts Here. How and When Will Aviation Recover from COVID-19? 2021. Available online: https://www.oag.com/coronavirus-airline-schedules-data (accessed on 17 November 2021).
102. Heathrow Airport. Heathrow H1 2021 Financial Results. 2021. Available online: https://www.heathrow.com/latest-news/heathrow-h1-2021-financial-results (accessed on 20 November 2021).
103. Georgidis, P. British Airways Owner Records Biggest Ever Loss. *Financial Times*, 26 February 2021. Available online: https://www.ft.com/content/8b6198df-5c75-4758-bdd7-195237cd95be (accessed on 17 November 2021).
104. Galpin, D.; Ozores, C.; Burroughs, L. *The Impact of COVID-19 on Commercial Aviation*; ICF: Fairfax, VA, USA, 2020. Available online: https://www.icf.com/insights/transportation/COVID-19-commercial-aviation-impact (accessed on 15 October 2021).

105. Delaney, K.J. THIS Could Have Been a Zoom Meeting': Companies Rethink travel. *New York Times*, 31 July 2021. Available online: https://www.nytimes.com/2021/07/31/business/business-travel.html (accessed on 16 November 2021).
106. Bower, J.; Saxon, S.; Wittkamp, N. Back to the Future? Airline Sector Poised for Change Post COVID-19. *McKinsey*, 2 April 2021. Available online: https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/back-to-the-future-airline-sector-poised-for-change-post-COVID-19 (accessed on 1 November 2021).
107. Bows-Larkin, A.; Mander, S.L.; Traut, M.B.; Anderson, K.L.; Wood, F.R. *Aviation and Climate Change—The Continuing Challenge*; John Wiley and Sons: Hoboken, NJ, USA, 2016; pp. 1–11.
108. Chiaramonti, D. Sustainable Aviation Fuels: The challenge of decarbonization. *Energy Procedia* **2019**, *158*, 1202–1207. [CrossRef]
109. Whitmarsh, L. Behavioural responses to climate change: Asymmetry of intentions and impacts. *J. Environ. Psychol.* **2009**, *29*, 13–23. [CrossRef]
110. Wilsher, K. France to Ban Some Domestic Flights Where Train Available. *The Guardian*, 12 April 2021. Available online: https://www.theguardian.com/business/2021/apr/12/france-ban-some-domestic-flights-train-available-macron-climate-convention-mps (accessed on 15 November 2021).
111. Turns, A. People Want a Job with Purpose': Why Businesses Are Becoming More Sustainable. *The Guardian*, 19 October 2020. Available online: https://www.theguardian.com/guardian-green-jobs/2020/oct/19/people-want-a-job-with-purpose-why-businesses-are-becoming-more-sustainable (accessed on 17 November 2021).
112. International Civil Aviation Organisation (ICAO). *Aircraft Noise*; IATA: Montreal, QC, Canada. Available online: https://www.icao.int/environmental-protection/pages/noise.aspx (accessed on 20 November 2021).
113. Clarke, C. Aircraft Noise Effects on Health. 2015. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/446311/noise-aircraft-noise-effects-on-health.pdf (accessed on 20 November 2021).
114. Civil Aviation Authority. Aviation Safety. Available online: https://www.caa.co.uk/Consumers/Guide-to-aviation/Aviation-safety/ (accessed on 20 November 2021).
115. Ball, J. How Safe Is Air Travel Really. *The Guardian*, 24 July 2014. Available online: https://www.theguardian.com/commentisfree/2014/jul/24/avoid-air-travel-mh17-math-risk-guide (accessed on 20 November 2021).
116. Major of London and London Assembly. Major Launches England's First Hydrogen Double Decker Buses. 2021. Available online: https://www.london.gov.uk/press-releases/mayoral/englands-first-hydrogen-double-deckers-launched (accessed on 21 November 2021).
117. Heathrow Airport. Noise Action Plan 2019–2023. 2019. Available online: https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/local-community/noise/making-heathrow-quiter/noise-action-plan/Noise_Action_Plan_2019-2023.pdf (accessed on 21 November 2021).
118. Greenfield, P. Carbon Offsets Used by Major Airlines Based on Flawed System, Warn Experts. *The Guardian*, 4 May 2021. Available online: https://www.theguardian.com/environment/2021/may/04/carbon-offsets-used-by-major-airlines-based-on-flawed-system-warn-experts (accessed on 20 November 2021).
119. Abelvik-Lawson, H.; Wockner, S. Airlines are Selling Carbon Offsets as the Solution to Climate Change. Here's Why They're Wrong. *Greenpeace*, 10 May 2021. Available online: https://www.greenpeace.org.uk/news/airlines-carbon-offsets-solution-climate-change-wrong (accessed on 16 November 2021).
120. Etihad Airways Chief Says Carbon Offsets Avoid the Real Challenge of Cutting CO_2. *Arab News*, 17 June 2021. Available online: https://www.arabnews.com/node/1970666/business-economy (accessed on 20 November 2021).
121. International Civil Aviation Organisation (ICAO). Corsia Implementation Plan. Available online: https://www.icao.int/environmental-protection/Documents/CorsiaBrochure_8Panels-ENG-Web.pdf (accessed on 20 November 2021).
122. Bösehans, G.; Wan, J.; Bolderdijk, J.W. Pay more, fly more? Examining the potential guilt-reducing and flight-encouraging effect of an integrated carbon offset. *J. Environ. Psychol.* **2020**, *71*, 101469. [CrossRef]
123. Gardner, D. Ten lessons in collaboration. *Online J. Issues Nurs.* **2005**, *10*, 2. [CrossRef] [PubMed]
124. Hardin, G. The tragedy of the commons: The population problem has no technical solution; it requires a fundamental extension in morality. *Science* **1968**, *162*, 1243–1248. [CrossRef] [PubMed]
125. Ostrom, E.E.; Dietz, T.E.; Dolšak, N.E.; Stern, P.C.; Stonich, S.E.; Weber, E.U. *The Drama of the Commons*; National Academy Press: Cambridge, MA, USA, 2002.
126. Fleming, S. Greta: The Voice of Climate Activism Who Says 'Listen to the Scientists'. *World Economic Forum*, 23 September 2019. Available online: https://www.weforum.org/agenda/2019/09/greta-thunberg-climate-change-strikes/ (accessed on 15 November 2020).
127. Rathi, A. To Encourage Innovation, Make it a Competition. 2014. Available online: https://hbr.org/2014/11/to-encourage-innovation-make-it-a-competition (accessed on 21 November 2021).
128. Deloitte. A Watershed Moment for the Company Car. Available online: https://www2.deloitte.com/uk/en/pages/manufacturing/articles/company-car-tax-rates.html (accessed on 20 November 2021).
129. Kuter, B.J.; Offit, P.A.; Poland, G.A. The development of COVID-19 vaccines in the United States: Why and how so fast? *Vaccine* **2021**, *39*, 2491. [CrossRef] [PubMed]
130. Geels, F.W. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Res. Policy* **2002**, *31*, 1257–1274. [CrossRef]

131. Kanger, L.; Sovacool, B.K.; Noorkoiv, M. Six policy intervention points for sustainability transitions: A conceptual framework and systematic literature review. *Res. Policy* **2020**, *49*, 104072. [CrossRef]
132. Grubb, M.; Drummond, P.; Poncia, A.; McDowall, W.; Popp, D.; Samadi, S.; Penasco, C.; Gillingham, K.T.; Smulders, S.; Glachant, M.; et al. Induced innovation in energy technologies and systems: A review of evidence and potential implications for CO_2 mitigation. *Environ. Res. Lett.* **2021**, *16*, 043007. [CrossRef]
133. Mercure, J.-F.; Sharpe, S.; Vinuales, J.; Ives, M.; Grubb, M.; Lam, A.; Pollitt, H.; Knobloch, F.; Nijsse, F.J.M.M. Risk-opportunity analysis for transformative policy design and appraisal. *Glob. Environ. Chang.* **2021**, *70*, 102359. [CrossRef]
134. Jovanic, N. 5 Types of Bias in Research and How to Make Your Survey Bias Free. 4 July 2021. Available online: https://www.leadquizzes.com/blog/types-of-bias-in-research (accessed on 19 November 2021).
135. Ratner, C. Subjectivity and objectivity in qualitative methodology. *Qual. Soc. Res.* **2002**, *3*. [CrossRef]