Energy Research & Social Science 127 (2025) 104158

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Original research article

Aviation sector decarbonisation as a case of deep uncertainty: The need for an integrative, exploratory, and interdisciplinary approach

A.C. Belcher [a,1,*], M.H.W. Workman [a,b], A. Jefferson [c,d], A. Ostrovnaya [e]

[a] Energy Futures Lab, Imperial College London, South Kensington, London SW7 2AZ, UK
[b] Foresight Transitions Ltd, Ashwood Cottage, Grimstead Road, Farley, Salisbury SP5 1AT, UK
[c] University of Westminster, 35 Marylebone Rd, London NW1 5LS, UK
[d] A&G Jefferson Ltd, 9 Hawkwood Road, Sible Hedingham, Halstead, Essex CO9 3JL, UK
[e] Centre for Climate Finance & Investment, Imperial College Business School, South Kensington, London SW7 2AZ, UK

ARTICLE INFO

Keywords:
Aviation
Whole systems optimisation
Deep uncertainty
Exploratory approaches
Robustness analysis
Stranded assets

ABSTRACT

Global demand for aviation is expected to double by 2050. This is set against the need to cut aviation CO_2 emissions from 1 $GtCO_2$ pa today to net zero over the same period. Using the UK aviation market as a proxy for the global market, we apply a Robust Decision Making (RDM) to develop integrative insights within a single analytical paradigm than discrete orthodox decision support analysis.

This approach is justified based on a critical examination of the sector characteristics and the divergent short-term motivations of aviation actors as a case of deep uncertainty. RDM explicitly embraces deep uncertainty across a number of metrics which allows multiple values and diversity among stakeholders and viewpoints, and in which modelling can exist in an iterative exchange with policy development rather than separate from it. This approach has particularly highlighted the critical significance of asset stranding, the oligopolistic structure in aerospace manufacturers and fuel suppliers, alongside the monopsonies in airlines, as current barriers to progress within a single integrative analytical paradigm.

This contribution highlights the need for the application of exploratory and interdisciplinary approaches to aviation decarbonisation transitions analysis to better inform aviation sector net zero strategies. It can improve the interdisciplinarity of analysis across technology, policy, and finance, and explore the extent of uncertainty so that robust strategies can be designed as well as generate insight into systematic upstream requirements.

1. Introduction

Aviation is integral to fulfilling societies' need to travel and do business. Globally in 2023, 4.4 billion passengers were carried by the world's airlines along with over 61 million tonnes of cargo [1]. In the future demand for aviation is expected to grow further, to handle around 10 billion passengers globally in 2050 [2]. Aviation also makes a significant contribution to economic activity. If global aviation were a country it would rank 20th by gross domestic product (GDP) in the world - generating $1.1 trillion direct, and $4.1 trillion cumulative, GDP in 2023 [1].

This growing demand for air travel is set against the need to reduce aviation's impact on climate change by cutting aviation greenhouse gas (GHG) emissions to net zero by 2050 and significantly reducing aviation's other environmental impacts. Latest data from the International Energy Agency (IEA) shows global aviation is not on track for net zero, generating 950Mt CO_2 in 2023, having grown faster between 2000 and 2019 than rail, road or shipping. This is primarily driven by demand growth, which was around three times higher than fuel efficiency improvements between 2010 and 2019 [3]. Within the energy transition required to address the worst impacts of climate change the sector is considered a "hard to abate" sector [4–7]. As a "hard to abate" sector it is coming under increasing scrutiny about its pathway to net zero and the new technologies this will require [8]. This requires taking these nascent technologies to an industrial scale - the combination, timing and application of which is subject to substantial complexity and uncertainty [9]. It is anticipated to cumulatively cost the industry around $5 trillion globally with a forecast cost of €1.3 trillion across Europe [10]. Failure

* Corresponding author.
E-mail address: anthony.belcher@neso.energy (A.C. Belcher).
[1] Permanent address: 64 Woodsome Road, London, NW5 1RZ

https://doi.org/10.1016/j.erss.2025.104158
Received 27 January 2025; Received in revised form 26 May 2025; Accepted 28 May 2025
Available online 3 July 2025

to achieve such a pathway could result in the sector accounting for an increasing proportion of global emissions.[2]

High capital intensities and a recent history of incremental technology change within the sector has created a barrier to achieving net zero [12] [13]. On the one hand the suppliers - airframes, engines and fuel - exist in an oligopolistic structure with long investment cycles. These suppliers are keen to maintain status quo to maximise their asset value and returns on investment. On the other hand, low margin monopsony airlines don't have the financial appetite to fund material risks on scaling new technologies. Alongside this, airports, financing companies and fuel providers, whilst being critical enablers for aviation activity, are subject to different business incentives and investment cycles and are also often excluded from current aviation decarbonisation analysis. This market structure and culture represents a highly complex, high dimensional, decision-making space where the chain of responsibility for systemic change is unclear. The primary decarbonisation focus to date has been around the next generation airplanes, switch to lower carbon intensive fuel - collectively referred by the industry as sustainable aviation fuel, and more efficient flight operations. However, definitive plans and supporting policies to take these technologies to industrial maturity remain elusive. Therefore, to meet the challenge of net zero requires significant structural changes for all parts of the aviation ecosystem, beyond implementation of new technologies.

Traditional whole systems cost optimised policy decision support tools such as Integrated Assessment Models which cover global energy system e.g., GCAM,[3] DICE[4] etc. and National models, e.g. UK TIMES,[5] dominate the orthodox policy toolkit for decision makers. This paper hypotheses that these tools are unable to manage the extent of complexity inherent to aviation sector decarbonisation, particularly from the perspective of firm-level strategic investment decision making [14]. Assessing these perspectives is fraught with uncertainty that they can be considered deep i.e., there are factors still unknown to decision-makers, as there is a lack of reliable historical precedent, and data needed for future projections would be considered unreliable to allow quantification of risk [15]. This in turn makes the application of optimisation approaches to assess the impact of policy interventions on strategic investment inappropriate. The orthodox policy tools are also anchored in neoclassic economic assumptions i.e., that the resources of firms are mobile, that their foresight is perfect, and that they are profit maximisers which could not be more divorced from actual aviation sector characteristics. This makes policy design for specific interventions to stimulate firms in the aviation industry to allocate resources to rapidly decarbonise the sector problematical. This is amplified within semi-liberalised competitive markets that the aviation sector operates. Finally, such tools tend to hide the uncertainties and multiple trade-offs, which disguises the complexity of the issue and the ability to engage stakeholders. This approach tends to isolate the analysis process to analytical and policy communities with stakeholders only engaged at the end of the analytical process. When encountering such complexity, the need to engage and incorporate values-based input from a range of stakeholders and audiences as part of the process in the interests of full transparency is fundamental to ensuring an enhanced likelihood of strategies to be successfully implementable by policymakers.

This analysis makes the case that there is a need for an overarching integrative analytical paradigm to bring together insights from discrete orthodox analysis as well as integrate the more systematic perspectives as to uncertainty across technology, policy and finance sectors which has resulted in decision-making which is islanded taking place in discrete silos within relevant communities. Such a framing has inhibited the ability for more interdisciplinary approaches which can better identify possible vulnerabilities. For example, in other sectors, loss of value has both been identified and actually materialised through the creation of stranded assets [16]. An interdisciplinary analysis would therefore likely provide the following additional insights:

1. The characteristics of the aviation sector and its need to rapidly decarbonise makes it potentially exposed to substantial value and asset stranding. Stranding is expected to be seen in industries which are "*enormous sunk investments, long operating lifetimes, systemic path dependency, complementary capital investments, and deep embedding in society*" and is further accentuated in fast-changing environments [17]; and
2. Potential stranding risk promotes the creation of carbon lock-ins whereby the owners of existing assets act as inhibitors on the move to decarbonise to protect invested monies [18].

Unpacking these potential issues allows policymakers to design interventions to address this where it is considered warranted.

The remainder of this paper is split into four distinct sections.

- The next outlines the Robust Decision-Making exploratory approach and stranded asset analysis.
- Section 3 unpacks the characteristics of the aviation sector that justifies the deep uncertainty pervasive in the sector. It then assesses the types of policies that have been proposed or enacted to drive sectoral decarbonisation. Demonstration that orthodox decision analysis is incapable of working with the extent of deep uncertainty and distorting policy design is then made.
- Section 4 covers the systemic vulnerabilities to which the aviation sector is exposed, inadequacies of present decarbonisation policy and pervasive extent of asset stranding. Section 5 concludes.

It is hoped that by identifying systemic vulnerability, including asset stranding, from the application of an integrative exploratory approach can justify the introduction of these methods to catalyse greater interdisciplinary analysis of aviation sector decision support. This is justified because only then will the analysis be able to provide policymakers with the relevant insights to assist the aviation sector to realise net zero in a manner that doesn't destroy value for the UK and the wider aviation industry.

2. Research methodology adopted

The approach taken in this paper is to first define the characteristics of the aviation sector and the decision analysis used to engage their stakeholders (see Section 3). It then explores how Robust Decision Making (RDM) could bring multiple decision making tool outputs, together with technology, policy, and finance stakeholders, to generate systemic interdisciplinary insights that can improve the quality and effectiveness of aviation meeting net zero by 2050.

Specifically, our contribution applies: 1) an exploratory approach, specifically RDM, to address the complexity of the aviation sector decarbonisation [19], and 2) an analysis of the role of firm-level decision-making in the aviation sector to assess the impact of decarbonisation on asset values across the value chain. We selected the UK aviation market to study these questions for the following reasons.

- The UK was the first aviation industry wide group [20] and government [21] to commit to net zero emissions by 2050. Consequently, the UK has had a longer time to explore the range of technology-based solutions and other approaches to meet net zero.

[2] Potential future proportion of global emissions = aviation emissions without actions taken to address [9] / total global emissions in 2050 (APS IEA scenario [11]) = 1.9 $GtCO_2$ / 16 GTCO2 = 11.9 %

[3] Global Change Analysis Model - https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model

[4] Dynamic Integrated Climate-Economy model - https://www.i2am-paris.eu/detailed_model_doc/dice

[5] UK TIMES - https://www.ucl.ac.uk/energy-models/user/login?destination=node/31

This experience and knowledge was determined as the most valuable source of information for this research. Given both the European [22] and global aviation [2] markets, and the United Nations International Civil Aviation Organization (ICAO) [23], have all adopted the same approach, developed in the UK, it is reasonable to assume that findings from this research will be scalable beyond the UK.
- In terms of scale, the UK aviation market is expected to grow by around 70 % by 2050 [21]. In 2023, the UK air transport and aerospace sectors (collectively the aviation sector) directly employed around 230,000 people and contributed around £20 billion to the UK's gross domestic product (GDP), facilitating 276 million passenger journeys [24,25]. On emissions, the UK has a significant exposure to aviation which generates 8 % of UK emissions [26], compared to a global average of 1–2 % [9].

To reduce the range of technological assessment we limit the scope of analysis to the UK narrowbody plane segment. It represents nearly half of the UK air fleet, both airframes at 54 % and emissions at 46 % [27], and is a rapidly growing part of the global fleet - with a 43 % increase anticipated over the next 10 years [28]. Furthermore, there is a significant lack of consensus as to the narrow-bodied fleet's decarbonisation technology pathway - which isn't the case with other types of planes; both hydrogen and SAF are being considered.

2.1. Exploratory approaches – robust decision making

Given the pervasive deep uncertainty to which the aviation sector is subjected, which will be explored further in section 3, it is considered necessary to adopt decision making approaches to decarbonisation strategies which are assessed according to their ability to accommodate deep or disruptive uncertainties, as well as the ability to accommodate multi-objective policy design beyond least cost. This is the core idea behind the exploratory Robust Decision-Making (RDM) modelling approach applied in the analysis undertaken in this contribution. RDM uses an iterative approach, refining scenarios and models with the input of industry participants which is defined by the following underpinning concepts:

- **Consider multiple possible futures:** The collection of future scenarios – comprising different combinations of uncertainties exogenous to investment decision making – should be as diverse as possible to thoroughly stress test proposed policy packages.
- **Seek strategies that are robust rather than optimal:** Robust strategies perform well and are able to survive across a wide range of possible futures.
- Use novel computer visualisations: Used to facilitate values-based participatory deliberation and multiple stakeholder perspectives.

In this study iteration takes place between the scenario development and the possible policy response identification. This identifies policies that will provide the most robust results against the competing objectives of the aviation sector - decarbonisation, revenue raising, energy security etc. Fig. 1 presents the overall approach employed in this research, linking the model development (LHS) with the external engagement and strategy assessment (RHS) and the iteration between them prior to the development of policies.

Policy recommendations can be formulated based on multi-variable outcomes derived from a refined model, leveraging scenarios developed through the RDM approach. The model will combine existing industry models (e.g. the Aerospace Technology Institute (ATI)[6] fleet model) and approaches to understanding how assets react to changing policy and economic environments.

As such the methodology in this research combines qualitative data gathering - from semi-structured interviews, and quantitative data gathering, industry models, stranded asset modelling, RDM approaches, and multi-variable policy impact analysis. Details of the methodological approach and the data applied can be found in the Supplementary Material.

2.2. Scenario development and iteration through industry interviews

To help establish the parameters of the analysis two boundary scenarios were developed based on NGFS scenarios: existing policies (“Baseline”), and net zero in the aviation sector by 2050 (“Net Zero”) [29]. A third scenario was also developed. This scenario is synthesised from industry interviews, and academic and grey literature [9,22,30–34] on the most likely outcome as perceived by the industry participants (“Industry”). Table 1 below outlines the key attributes of these scenarios.

Collectively the mix of the SAF costs, blending assumptions, flight destinations, carbon taxes, and Jet A-1 prices create a fuel cost for each year, plane and scenario. Tables S2 and S3 show the details of all revenue, cost and CO_2 sources and calculation basis.

As outlined by Workman et al. (2021) [14] interaction between industry participant is the key factor in scenario development, model refinement, and policy development. This study approaches the problem in a similar manner, using a combination of interviews (which form model outcomes) and then assessing the responses of industry participants to those outcomes under different policy environments. The list of the industry participants engaged with is presented in Table S1.

2.3. 2.3 UK ATI fleet model input

The ATI Fleet Model [36] predicts the changes of the global fleet in a particular scenario. The key plane features and demand metrics are modelled for the three scenarios in this study: 1) Planes: Fleet size, deliveries, age (base year 2016); and 2) Demand: Revenue Passenger Kilometre (RPK), Available Seat Kilometre (ASK), load factors.

2.4. Asset model development

The core of the asset model is a forecast of annual revenues, costs, and profits for each scenario by each asset i.e. planes' age. It uses the outputs of the ATI fleet model [36] and other external sources (Table S6). Retirement parameters were applied to the assets to simulate their anticipated withdrawal from service due to age. The remaining aircraft subsequently determined revenue and costs, calculated according to the methodology detailed in Table S2 of the Supplementary Material. The model is inflation-neutral, discounting all financial metrics to 2024.

The model therefore allows us to test key variables in any chosen scenarios.

2.5. Overlay of policies

A series of aviation decarbonisation policies were identified from a combination of interviewee responses and literature suggestions, as outlined in Table S4 in the Supplementary Material. These were as follows:

- Revenue certainty mechanism
- Scrappage scheme
- Increase price of Jet A-1
- Accelerate blend mandate requirements
- Loans for SAF plant creation

These policies were applied to the asset model, either on their own or in combination with each other.

[6] The ATI is a UK not-for-profit organization funded by the UK government which provides tools, funding, and analysis to support the UK's aerospace industry.

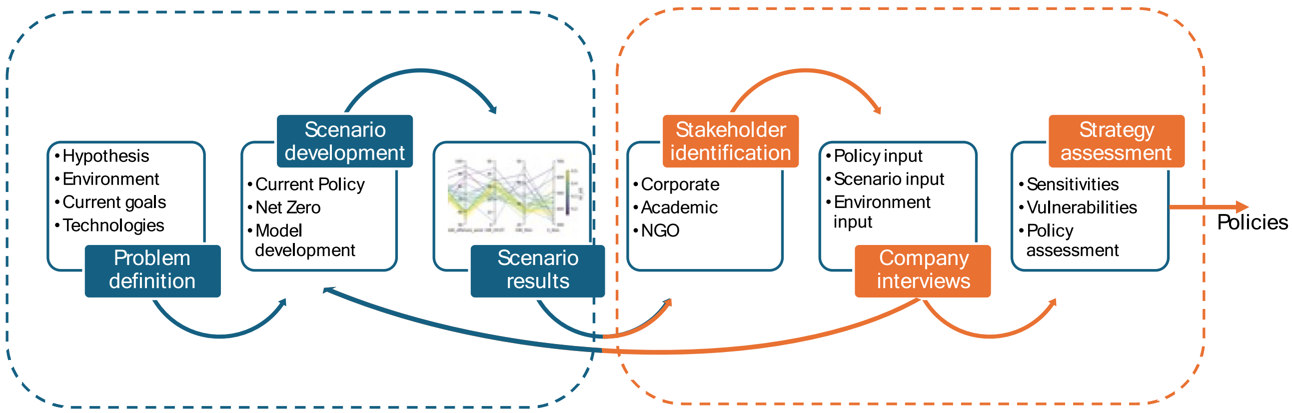

Fig. 1. Process flow to derive policy recommendations. Modelling was involved in Scenario development and results and interviews in company interviews and strategy assessment.

Table 1
Key attributes of different scenarios.

Scenario	Baseline	Net Zero	Industry
Source	NGFS Current Policies [29]	NGFS Net Zero & ICCT Breakthrough [29] [35]	Interviews & industry literature
Aviation Demand growth (p.a.)	2.3 %	0.6 %	3 %
Oil price growth (p. a.)	1.6 %	0.7 %	1.6 %
Global Carbon price by 2050 (per tonne CO2e)	\$200	\$275	\$200
SAF Blending	Only current UK/EU announced levels	100 % in 2045 globally	70 % in 2050 in UK/EU & 50 % in other geographies
Hydrogen plane ready by	No introduction	2035	2040
Operational efficiency improvements (p.a.)	0 %	0.6 %	0.2 %
Fuel efficiency improvements (p.a.)	0.9 %	1.1 % 2019–2035, 2.2 % 2035–2050	1 %
Load factor improvements (p.a.)	0.6 % (90 % maximum)	0.5 % (95 % maximum)	0.5 % (92 % maximum)

2.6. *Application of sensitivities*

Several of the key inputs were stressed to assess the extent to which the results would vary. The inputs with the highest uncertainty were chosen based on the literature:

- Cost of SAF
- Cost of upgrades
- Proportion of fleet with new technology before reduced cost impacts pricing
- Rate of return (WACC)
- Carbon impact of HEFA / Alcohol to Jet (AtJ) fuels

Table S5 in the Supplementary Material shows these factors and the driver for the range used. As with the policies, these were also applied to the model, again either individually or in combination with others.

3. Aviation sector characteristics and decarbonisation agenda - a case of deep uncertainty

3.1. *Characteristics of the aviation sector and decarbonisation pathways*

To critically assess policy support tools for aviation sector decarbonisation, the characteristics of the sector and the decision analysis used to engage stakeholders, needs to be understood.

3.1.1. *Complex emission impacts*

Aviation is one of the highest carbon-intensive modes of transport, twice as impactful as the average car [37]. Globally CO_2 emissions from the combustion of jet fuel are estimated to have grown to over 1 $GtCO_2$ in 2019, representing over 3 % of global anthropogenic emissions [9] and 8 % of the UK's GHG emissions [26]. This impact is increased further through the radiative forcing (RF) impact of aviation non-CO_2 impacts, notably from contrails. These impacts are material (relative to CO_2 impacts) and highly uncertain, with estimates ranging from 60 % of CO_2 impacts up to 315 % - meaning overall impacts of aviation on the atmosphere have a near 50 % uncertainty range [38]. Furthermore, the large uncertainty of the non-CO_2 effects creates difficulties in generating prescriptive transition pathways and provides arguments for the exclusion of the RF from non-CO_2 effects from policy mechanisms such as Emission Trading Schemes (ETSs) [39].

3.1.2. *High risk and investment supply factors*

The sector has high capital values, long-life products, and long development lifecycles. This has created an unusual market structure with actors that are highly sensitive to risk and making significant capital investment spending [13] - as follows

- The supply side is represented by risk averse oligopolies - engines and fuel suppliers which tend to adopt additive technology changes with deceased differentiation of product [12]. Airframe manufacturers have a slightly higher risk appetite by occasionally effectively *'betting the company'* when they design an entirely new plane e.g., Airbus 380 or as would be the case for hydrogen aircraft.
- These dynamic fosters a competitive, buyer-driven market that resembles a monopsony, which is somewhat counterintuitive in industries typically characterized by a high concentration of suppliers.
- The third set of agents, acting as financial intermediaries, are the leasing companies, purchasing and leasing over 50 % of all commercial aircraft sold [40]. The major owners of assets in the industry are the operators and financiers as seen in Fig. 2. These high levels of asset ownership can significantly influence their behaviour around change, especially if there is a high likelihood of asset or profit loss.

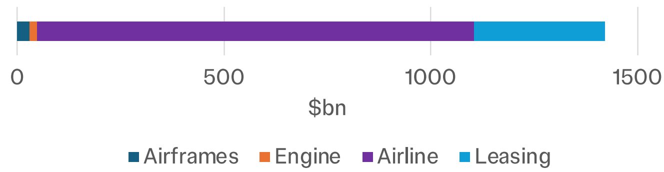

Fig. 2. Fixed assets of global aviation industry participants in US$ billion (Own Analysis).

- Finally, airports struggle to recover the cost of large investments in infrastructure and in a post-covid era are struggling to bolster balance sheets following the travel restrictions put in place to manage the pandemic.

The sector's characteristics are also characteristics of assets which are at risk of stranding. Stranded assets are "*assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities*" [41]. While the term is relatively new [42] the concept is not, linking to value loss in concepts such as creative destruction [43]. The inverse predicament of stranded assets are carbon lock-ins [44], or assets which emit large amounts of carbon and are not retired due to the large values that they represent. This represents the barrier to change from asset owners but results in the loss of the remaining carbon budget rather than financial write-down. It can also be looked at from the loss of assets due to failed technology changes [45], therefore acting as an inhibitor (whether conscious or not) on the investment in new technologies.

3.1.3. Highly competitive operating environment

The tight cost structures of airlines, is driven by the high level of competition in the market. This then inhibits funding the large capital investment needed for decarbonisation. High variable cost [46], leads to both persistent low average profit margins of 1 % [47] and ticket prices that are driven by changes in fuel costs - which make up 50 % of costs [48,49] - and lower-cost competitors [50]. Current safety restrictions prevent utilisation of SAF above 50 % [51] and without costly upgrades[7] existing engines will not be able to meet future blending requirements. This may also exacerbate asset stranding as high penalties for not meeting the mandates [55] will exceed margins on older less efficient planes.

3.1.4. Systemic decarbonisation solutions

Many of the sector's decarbonisation options require systemic interventions that cut across these actors. For example, new airframes such as hydrogen aircraft will require new refuelling infrastructure, ground-handling processes, safety procedures and possibly air-traffic control measures to be put in place. This makes the transformational changes required for deep decarbonisation hard to plan and implement, leading to further uncertainty in investment planning for net zero as a function of its market structure and liberalised competitive structure, which reduces the incentive to invest [56].

Table 2 maps the impact of the possible decarbonisation options for the aviation sector and the implications on different aviation actors. It qualitatively identifies those actors which may be exposed to stranded value or assets as a result of wholesale decarbonisation technology pathway development in the sector.

It therefore emphasises the problematic nature of enacting systemic transformational decarbonisation initiatives within the aviation sector. It also emphasises the need for decision support processes to be able to generate output as part of the analytical processes which can engage multiple stakeholders to capture the complexity of decarbonisation strategy implementation.

3.1.5. Reliance on systems outside of aviation

An underexplored characteristic is the systematic analysis of the upstream implications of certain interventions, many of which rely on collaboration with stakeholders outside the aviation industry's traditional sphere of engagement. For instance, this study found that meeting Power-to-Liquid (PtL) SAF requirements for the UK narrow-bodied sector alone could demand as much as 21.9 GW of electricity generation capacity. As the aviation sector cannot achieve decarbonization solely through internal mitigation measures, it effectively delegates the bulk of its deep decarbonization responsibilities to external actors. This approach results in the industry taking minimal - if any - direct accountability for decarbonization efforts. The outsourcing of these obligations extends beyond electricity for PtL to include land requirements for Hydrotreated Esters and Fatty Acids (HEFA) SAF, as well as reliance on Market-Based Measures (MBM) and Carbon Dioxide Removal (CDR) solutions to address residual emissions. Paradoxically, this strategy exposes the sector to significant systemic risks. By distancing itself from control over its own net-zero transition, the industry becomes vulnerable to regulatory pressures and increased costs of capital, potentially undermining its ability to manage its long-term sustainability goals effectively.

Bringing the fourth and fifth characteristics together the need for analysis to transition from an analytical framework which is based on the premise that aviation sector decarbonisation is a complicated problem rather than one which is complex is fundamental to this contribution (Fig. 3).

When acknowledgement is made as to the complexity - the extent of uncertainty that pervades the aviation sector can be defined as deep. "Deep uncertainty" is described as a circumstance: *where analysts do not know, or the parties to a decision cannot agree on, 1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, 2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or 3) how to value the desirability of alternative outcomes. In particular, the long-term future may be dominated by factors that are very different from the current drivers and hard to imagine based on today's experiences* [19].

The first and second deep uncertainty traits are justified in that atmospheric impacts and market structure are inhibiting a clear trajectory of change nor the quantification of what the likelihood is of the main drivers for decarbonisation. The third is justified in that due to a lack of historical precedent, the anticipated systemic transformational changes needed will lead to differential impacts of asset stranding - makes identifying which metrics would be considered desirable problematical. How the extent of complexity and deep uncertainty characteristics unpacked above are addressed in the present aviation sector decision analysis is assessed in section 3.3.

3.2. Aviation decarbonisation policy

3.2.1. A limited number of options for decarbonisation

With aviation demand growth forecast to double by 2050, in the absence of any emissions mitigation, radiative forcing contribution to climate from aviation is forecast to grow by between 1.7 and 2.7 times [58]. This forecasted increase and subsequent impact are the drivers for the efforts by the industry and beyond to provide technological solutions to reduce the emissions from the aviation sector. While efficiency gains are anticipated to merely offset emissions growth from demand increases [22,34], they fall short of addressing the existing environmental challenge. Innovative approaches and transformative strategies are therefore imperative to tackle the majority of the sector's environmental impact.

Aviation decarbonisation analyses are typified by the UK Sustainable

[7] Engines account for 45 % of the cost of a plane [52]. Average narrowbody planes cost $60 m [53], retrofits cost 1/3 of the cost of an engine [54]. Therefore, cost of retrofit = 60 × 45 % X 33 % = $9 m

Table 2
Heat map (1 (lowest) to 5 (highest)) of likely change to current operations required in response to technological innovation and penetration (column 1). Scores thus identify likely resistance of different players to development of new technologies. Source: Synthesised by this paper's authors from recent industry reports [31,57].

Item	Description	Metric(s) impacted	Technology change needed	External change	Hurdles	Industry Actor					
						Engine	Airframe	Fuel	Airport	Airlines	Leasing co.
Battery propulsion	Use of batteries to drive engines (with green electricity)	Electricity demand (-ve) & carbon intensity (+ve)	Large - remove onboard fuel need, changes to areostructure for weight, changes to engines	Low - Battery tech already focused on in other sectors	Energy density	4	3	3	3	3	2
Hydrogen gas turbine	Cryogenic or liquid green hydrogen burning to drive engines. NB = Still some impact from contrails & Nox	Carbon intensity (+ve). Airplane size & electricity demand (-ve)	Medium - change onboard fuel storage and delivery. Change engines to deal with new fuel	High - need H2 production on huge scale	Mgt of cryogenic H2 (safety)	3	3	5	4	3	2
Hydrogen Fuel cells	Cryogenic or liquid green hydrogen used in fuel cells to drive engines. NB = Still some impact from contrails & Nox	Carbon intensity (+ve). Airplane size & eletricity demand (-ve)	Medium - change onboard fuel storage and delivery. Change engines to electric engines	High - need H2 production on huge scale	Heat management of cells, cryogenic storage of H2, green H2 creation, delivery	4	3	5	4	3	2
SAF	Sustainable aviation fuels (biofuels or PTL) - also positive impact on contrail formation	Carbon intensity(+ve)	Low - much of the infrastructure and airframe remains the same. Will need ammended engines to deal with new fuel type	High - Production from bio-materials or H2/GGR at huge scale	Manufacture from non-foodstocks. Increase efficiencies (and therefore	2	1	4	2	2	3
Ultra-high bypass ratio turbofan	Reduce burn of engines - use on large planes not able to use zero carbon. Increase efficiency by 10%	Fuel efficiency (+ve)	Low - new engines likely to be interchangeable with existing	Low - engine tech. within aviation industry	Conversion of POC level to commercial launch	4	3	1	1	2	2
Aerodynamic Technologies	Dry wings - no fuel storage in wings - impact on structure. Reducing drag of engines - lower impact on structure. V wings - 20% reduction in fuel usage	Fuel efficiency (+ve)	Medium - change in airframe, engines and fuel delivery systems.	Low - aerodynamic changes within aviation industry	Balance of aerodynamics with other factors	3	5	3	3	4	2
Composite Wings	lightweight, high performance composite wing structures and integrated systems. Increase efficinecy by 10% & reduce weight	Fuel efficiency (+ve)	Low - New wings likely added to new planes only. Wings designed to cope with existing infrastructure.	Medium - material science improvements needed	Strength vs weight factor	2	4	1	2	2	2
Energy harvesting	Conversion of energy losses into useful energy	Fuel efficiency (+ve)	Medium - Airframe changes needed and storage of energy	Low - energy harvesting well understood tech.	Storage of saved power	4	3	1	1	2	2
Reduce weight	Reduce weight of landing systems & others	Fuel efficiency (+ve)	Low - new landing systems interchangeable	Low - within aviation sector to manage	Strength vs weight factor	1	3	1	1	1	2
Reduced energy systems (& electrification)	Eg ice and rain protetion - 5% efficiency increase	Fuel efficiency (+ve)	Low - new systems interchangeable	Low - within aviation sector to manage	Conversion of POC level to commercial launch	2	3	1	2	2	2
Free Route Airspace	Allowing planes to chose more efficient routes, reducing fuel use	RTK (-ve)	Low - onboard systems to design optimal routes needed	Low - within aviation sector to manage	Safety of planes in high density areas	1	1	1	1	3	1
eVTOL	electric vertical take-off and landing	Electricity demand (-ve) & carbon (+ve) intensity	High - New type of flight, requires complete change of airframe and engine integration. Also changes to airport infrastructure	Low - Battery tech already focused on in other sectors	Energy requirment	3	4	3	4	4	2
Lighter Than Air (LTA) - airships	Using airships for slower delivery esp. freight	Fuel efficiency (+ve), Airplane size (-ve)	Large - needs gas that is LTA to provide lift. Much lower emissions as much higher efficiency	Medium - materials (skin) need development	Control of airships	3	5	2	1	2	2

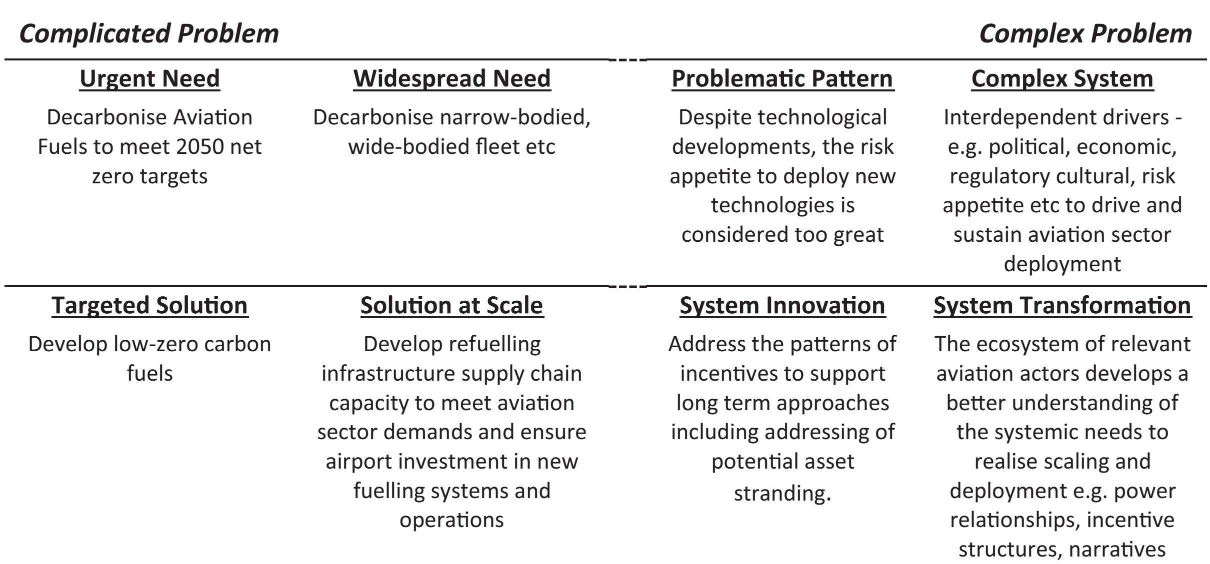

Fig. 3. The complexity spectrum applied to the urgent need for aviation sector decarbonisation technology scale-up globally within and across national economies.

Aviation Roadmap [34] which consists of numerous measures capable of collectively achieving net-zero carbon emissions by 2050, the latest iteration of the which is presented in Table 3. Solely focusing on CO_2 emissions, it sets a clear decarbonisation trajectory. Methods of decarbonisation presented in the roadmap are categorised into three major groups: 1) Energy Efficiency Improvement; 2) Demand Side Decarbonisation; and 3) Supply-Side Decarbonisation.

3.2.2. *Current policy environment*

Current aviation decarbonisation policies of governments are focused on multiple, and often competing goals - decarbonisation, increased revenue, energy security and green economic growth [59]. There are a few policies which are specific to aviation, e.g. inclusion of air transportation in UK and EU ETS, new plane efficiency mandates or Nordic blending requirements [26,32,60]. One of the main difficulties in setting aviation-specific policies on national levels is that the majority of

Table 3
Summary of UK Jet Zero aviation sector path to net zero [34].

Category	Emissions reduction proposals	Key benefits	Emissions reduction potential in 2050
'In-sector' opportunities	Aircraft and engine efficiency improvement.	Cleaner, quieter and efficient flights	8 $MtCO_2$
	SAF deployment	70 % reduction in life cycle emissions relative to fossil fuels	9 $MtCO_2$
	Zero Carbon Aircraft	Battery and hydrogen fuelled aircraft remove much of the in-flight emissions	2 $MtCO_2$
'Out-of-sector' opportunities[a]	Sector focused MBMs - UK ETS and CORSIA	Reduced passenger demand	14 $MtCO_2$
	Non-sector focused MBMs – carbon credits	Achieve net-zero targets by filling gaps left by 'in-sector' opportunities	19 $MtCO_2$

[a] It is noteworthy the lack of clear distinction in reductions and emissions in the roadmap. These have materially different impacts on climate – carbon removal measures net out the impact of an emission whereas offsetting measures avoid a future emission without netting out any CO_2 emissions.

emissions originate from international flights [61]. It is notable that the current policy framework focuses narrowly on operators whereas, as described earlier, the nature of innovation in the industry is heavily reliant on the key suppliers and the manner in which these oligopolies restrict innovation.

In the past year both the EU and the UK have introduced SAF blending mandates, significantly accelerating the policy impact on aviation [55,62]. A number of other possible policies have been suggested and are laid out in Table 4.

3.3. A Critical assessment of present aviation sector decarbonisation policy support tools

Decarbonisation projections for the aviation sector generally combine models and scenarios, such as those from global bodies such as the Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA) and Network for Greening the Financial System (NGFS).[8] Concerns as to the ability for these tools to support decarbonisation are already substantive in the literature with suggestions for the following improvements: the use of a wider set of more regularly updated scenarios; the lack of geographic granularity and hence lack of physical risk feedback; lack of internal consistency of models; and the absence of the access to finance to be accommodated [64,65].

Table 4
Possible additional aviation policies.

Policy	Description
CO_2 taxation	Tax the emissions of CO_2 by the emitter through a carbon price. [32]
Limit flights	Place a limit on the number of flights able to be taken. [32]
Frequent flyer levy	A charge made on people who fly more often. [26]
Alternative provision	Provide alternatives to aviation such as high-speed rail. [26]
Promote non-travel	Promote and support virtual attendance for meetings etc. [26]
UK holidays	Provide financial incentives for UK-based holidays. [63]
Carbon allowance	Create a carbon allowance scheme whereby each individual would have a set amount of carbon emissions per year (similar to ETS). [63]

Furthermore, the actions on the firm level are not reflected in the inputs of the scenarios nor within the models themselves [66]. The lack of understanding of the actions of firms is particularly salient and somewhat surprising considering the sector's unique market characteristics [67]: The assumed transitions of firms - whereby old markets are instantaneously destroyed and then new ones created with associated resources efficiently reallocated - have the potential to create outputs which distort decision-making [68].

Traditional policy support tools based on the whole system cost optimisation are neither able to manage the complexity inherent to the aviation sector as articulated in Section 3.1, nor can assess the impact of policy interventions on firm behaviour [69]. They fail to account for three critical factors:

- Path dependence and collaborative efforts needed for many of the aviation sector decarbonisation interventions;
- Inertia effects stemming from the need to generate completely new upstream industrial value chains for new energy carriers and retrofit new infrastructure into existing capital assets. These efforts face barriers such as regulatory, legal and established standards and therefore entail a significant economic cost and political risk which are challenging to incorporate into models due to their non-parametrisable nature;
- Incumbency effects within value chains which will result in non-financial transaction costs for reallocating resources towards decarbonisation – which are non-trivial in all sectors and all the more salient in an oligopolistic market such as the aviation sector.

This makes policy design and specific interventions to motivate firms to allocate capital to decarbonisation to catalyse the transition highly challenging. There is a need for analysis that bridges the capability gap between the aviation sector's complex characteristics and the orthodox approach. As well as helps to identify how aviation actors can be incentivised to support deep decarbonisation innovations, as with their complementary assets and resources, they might be in a position to accelerate the transition to net zero and avoid capital and market value loss.

The former can be undertaken by the application of exploratory approaches such as Robust Decision Making (RDM) [14]. These analyses challenge the conventional paradigm by:

- Considering multiple possible futures: The collection of future scenarios - comprising different combinations of uncertainties external to investment decision-making - which are as diverse as possible to stress test proposed policy packages' impact on the aviation sector;
- Seeking strategies that are robust rather than optimal: Robust strategies perform well and can survive across a wide range of possible futures; and
- Using novel computer visualization to engage with market participants and stakeholders: to facilitate the deliberation of systemic components of negative emissions from multiple parameters and assess the trade-offs.

[8] IPCC is the body supporting the UNFCCC process through the provision of expert advice and reports. IEA is an intergovernmental organization that provides policy recommendations, analysis, and data on the global energy sector. NGFS is a group of central banks and supervisors which supports the financial sector in the development of climate and environment-related risk management.

Exploratory approaches focus attention on the characteristics of strategic options and not on predictions of the future, and seek answers to different questions, such as: (1) What are the conditions that would affect the performance of a decision makers current or prospective strategies? (2) Under what conditions does a firm's strategy fail to meet different stakeholders' goals? (3) Would the likelihood of such conditions lead to a change in strategy? (4) Which decisions a firm need to make immediately, and which ones can be delayed? [70].

It is as a result of this new approach, the impact of changes of policies, technology or societal norms can be understood at the firm level - be that on revenues, profits or asset values. This new understanding can lead to identification of stranding of those values.

Much of the focus of stranded asset research has been on the sectors of energy generation and fossil fuel extraction [17]. Whilst many papers suggests further research be carried out into the transport sectors [44,71,72] there is minimal evidence this has been acted upon beyond looking at the impact transport has on stranding [73] or considering requirements to retire high carbon assets in return for COVID bailouts [74]. Limited discussion has been made about aviation stranding in grey literature and journalism [75–77]. It is a research gap that, through the use of exploratory approaches, this paper seeks to examine.

4. Results and discussion

Policies proposed from the results of the research will impact different stakeholder groups in different ways with each stakeholder focusing on different key metrics. A single variable optimisation may lead to an erroneous outcome when multiple stakeholders are involved. Therefore different ways to visualise and manage outputs across the full range of variables is required. This approach works with the extensive uncertainty and in providing transparent insight it allows for the identification of vulnerabilities within the outcomes. In doing so, it equips policymakers with valuable insights into the potential impacts of their decisions.

In this study the results are presented as multi-dimensional or parallel coordinate plots. Colours and shades for different factors such as policies selected are used to aid interpretation and use. Another approach as suggested by Lempert (2013) [19] in their outlining of RDM result analysis, which can help identify vulnerabilities, can be a two-dimensional matrix chart. It requires a small number of metrics (under four) however, with some adaptation, this analysis was extended to five metrics and used in conjunction with the parallel coordinate plot.

Results from the model show the impact of changes in the UK narrowbody fleet across a number of attributes. These attributes cross different factors, however, they lack in the ability to suggest relative scale for the UK as an economy or to firms within the industry. To bring these into a more understandable level a number were converted into percentages against different UK relevant levels. Table 5 below shows these relative measures and their derivation.

Table 5
Relative measures for UK aviation.

Attribute	Relative measure	Value
GHG emissions	UK 2050 target GHG emissions for narrowbody planes	20.41 MT CO_2e [a]
Energy	UK wind energy capacity added 2013–2023	21 GW [b]
Land	10 % UK arable land	6045 km^2 [c]
Stranded assets	20 % UK airline market capitalisation	$1.53bn [d]

[a] UK target = 19.3 MT CO2e [21], Narrowbody fleet as proportion of total = 54 % [27], Proportion of flights under target (UK domestic + outgoing international flights) = 51 %. Model target = 19.3 × 54 % / 51 % = 20.41 MT CO2e.
[b] [78].
[c] UK arable land = 133,000 ha / 2.2 % *10 % = 0.605 m ha = 6045 km2 [79].
[d] £0.01bn market cap / narrowbody plane (average of BA (based on BA profit as proportion of IAG, allocated on RPK by aircraft type) [30] and Easyjet [80], [27], [81]) X 658 UK narrowbody planes X 20 % = £1.18 bn / $1.53 bn.

Section 2 described the outputs of the analysis undertaken by the application of an exploratory approach to the decarbonisation of the UK narrowbody plane segment. It is framed around the additional insights that are possible beyond that of orthodox optimisation approaches which focus on cost minimisation at discrete timesteps in a future which is highly uncertain and impossible to predict; whereby sensitivity analysis is the only mechanism to engage with uncertainty.

This study uses the outputs as justification of how exploratory approaches can address the shortfalls of existing analysis which include but are not limited to: (i) the ability to unpack the pervasive extent of uncertainty across and along technology interventions, financial implications and emissions whilst facilitating deliberative engagement with stakeholders and market actors; (ii) the structuring of decisions as well as facilitating multi-sectoral decision making co-ordination; and (iii) intuitively encourages interdisciplinary approaches to identify systemic risks and the policy interventions that might be needed to mitigate those risks.

4.1. *The deep uncertainty of aviation's future necessitates an exploratory approach*

The scenarios, in combination with policy layers and sensitivities, provided 1536 possible futures. Five key metrics were utilised to manage the multitude of results over the duration of the period and variables, assessed against the pertinent thresholds in Table 5:

- GHG emissions in 2050,
- total assets stranded,
- maximum land required, maximum electricity capacity,
- Net Present Value of profits for airlines.

The out of sector metrics relate to the out of sector impacts discussed in section 3.1.5, energy requirements for PtL and land requirements for biofuel SAF. Figs. 4 and 5 show the plotting of these possible futures with the proportion of futures breaching each threshold under each scenario, along with the average percentage of the relevant threshold documented in Table 6.

Fig. 5 identifies a number of the futures which create vulnerabilities where either of the following occurs:

- GHG emission targets >20.41MT CO_2eq - are significantly missed - centre colour of circle is red;
- UK airline industry loses assets >20 % of its current market capitalisation >$7.7bn - rim colour of circle is red;
- >10 % of UK arable land >6000 km2 is required - top area of vulnerability;
- new energy generation greater than the total added UK wind capacity from the past 10 years >21 GW - right side area of vulnerability.

These are all futures which create significant issues that stakeholders will seek to avoid. It is therefore important to identity what might cause them and how the industry and the UK government can influence the outcome.

In the context of applying an exploratory approach, the diverse range of potential futures illustrated in the figures captures both the uncertainty surrounding key inputs and the variability in how actors within the sector might respond to those inputs. By contrast, a singular, optimized approach would fail to reveal the vulnerabilities highlighted in these results, leaving it exposed to unforeseen challenges and future uncertainties.

The ability to explore the uncertainty space via an exploratory approach then facilitates the ability to generate participatory engagement with stakeholders and what is termed `*deliberation with analysis'* – whereby stakeholder insight of a quantitative nature can be fed into

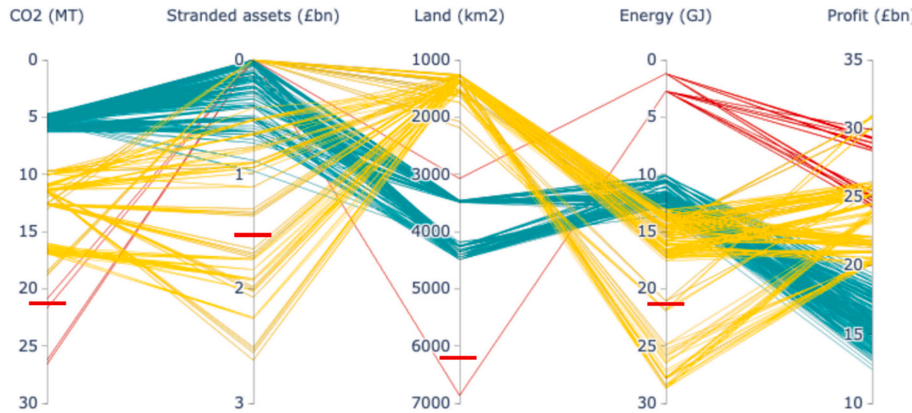

Fig. 4. RDM parallel coordinate plots displaying scenarios across different policy and sensitivities, red bars show thresholds from Table 5 (Red – Baseline, Green – Net Zero, Gold – Industry).

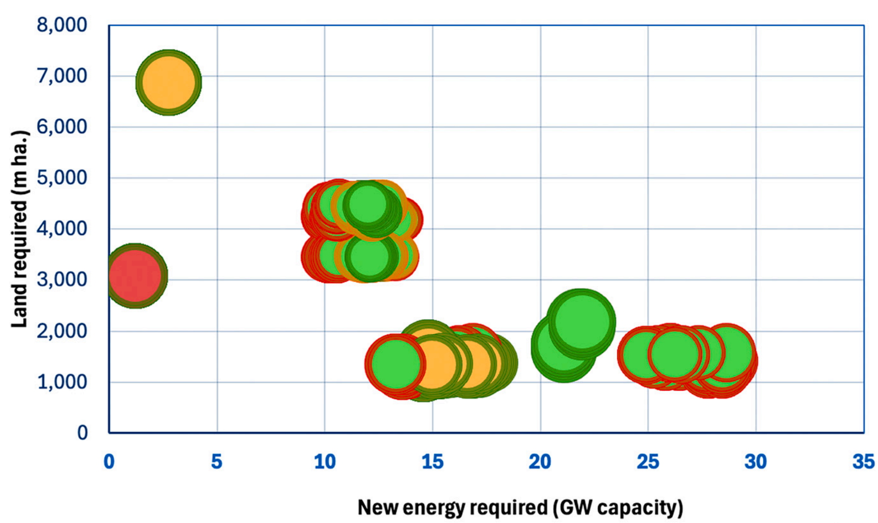

Fig. 5. Scenarios across different policy and sensitivity combinations – each circle represents one possible future with size proportional to NPV for UK narrowbody airline operators.

Table 6
Spread of factor results among futures.

Scenario	CO2e		Stranded assets		Energy		Land		Above one threshold
	Above threshold	Average level	Above threshold	Average level	Above threshold	Average level	Above threshold	Average level	
BAU	100 %	117 %	0 %	0 %	0 %	9 %	50 %	82 %	100 %
Net zero	0 %	26 %	0 %	21 %	0 %	55 %	0 %	60 %	0 %
Industry	0 %	76 %	25 %	48 %	25 %	83 %	0 %	22 %	50 %
Total	**33 %**	**73 %**	**8 %**	**23 %**	**8 %**	**49 %**	**17 %**	**55 %**	**50 %**

analysis. In the case of this study the extent of uncertainty revealed in the analysis was further reflected in the interviews - which emphasised a lack of appetite to invest in transformational aviation sector decarbonisation:

> "…*these questions are almost too difficult to answer without guessing. We don't know the rate of change of engines, we don't know the rate of change of hydrogen, we don't know the rate of change of non-drop-in fuels*" – **Interviewee 3**

> "[We]…*won't make a strategic capital investment case…….it's a phased approach*" - **Interviewee 4**

4.2. *Clarifying decision structuring and need for multi-sectoral engagement*

While there is significant uncertainty from the future, this need not be true for all aspects of decision making. Exploratory approaches can also identify aspects where uncertainty can be managed. Table 6 shows that with the current policy framework (Baseline Scenario) all possible futures (100 % of futures are above the emission reduction threshold in Table 5) will miss the current UK emission reduction targets. As the scenarios differ significantly by the blending mandate, this indicates that the current trajectory is insufficient to meet the target. The insufficiency of the trajectory is supported by industry, who are equally surprised by the later mandates and frustrated with frequently changing regulation:

> "*they're going to need to review the mandate levels …in the long term…an even higher mandate volume than they're currently looking at*" "*it is quite critical that the policy is long term and it's embedded and it doesn't change*" – **Interviewee 4.**

Fig. 6 shows where the decarbonisation over the period 2024 to 2050 is derived from. Here the level of difference and uncertainty is much smaller (as seen from small ranges of results across all scenarios and possible futures in each emission reduction driver) and points towards the focus of the industry on continued operational efficiency predominantly through increasing load factors and migrating to SAF as an energy vector. This derives the following decision paradigm:

- a simple solution would be to minimise hydrogen investment for aviation;
- that would, in turn, miss the hydrogen feedstock requirement for PtL. In 2050 the combination of PtL hydrogen feedstock requirements and pure hydrogen fuelled planes results in an average of 86.4 % of the total emissions reduction relying on hydrogen (combination of PtL SAF benefit % and H_2 benefit %) with a small standard deviation (6.3 %) across all futures in the Industry Scenario.

The aggregated implication of this analysis is that it supports a medium-term focus on hydrogen production for use in SAF but ***not*** the focus on hydrogen fuelled planes.

As Pfeiffer (2018) [82] outlines when making investment decisions with long-lived assets, it is imperative to look at the cumulative impact of the decisions over the whole period, not just on the near-term impacts. The impact of aviation on climate change is a function of its cumulative emissions, not the level at an arbitrary period in the future [83].

Therefore, it becomes important to support the aviation industry in decision-making through the development of approaches that deliver robust outcomes. This study has introduced such an approach which will facilitate market actor engagement and broader stakeholder groups, upstream of the technologies, energy vectors being considered for aviation sector decarbonisation (i.e., PtL, energy generators, feedstock providers), cross-sector investment co-ordination and mitigate concerns as to disintermediation such as the over dependencies of the sector on a MBM/CDR sector which as yet does not exist.

4.3. Stranded asset risk becomes clear with an interdisciplinary approach applying multiple scenarios

As shown in Table 6 only a small number of futures (8 %) in this case study exceed the stranded asset relative measure (20 % of the current market capitalisation of UK airlines, the Market Capitalisation Threshold (MCT)) – see Table 5. However, this still masks a few aspects which are exposed in Tables 7 & b:

- There is a high concentration of futures in excess of the MCT in the `*Industry Scenario'*;
- Across the `*Industry Scenario'* an average of nearly 50 % of the MCT is reached across all futures; and
- It is particularly susceptible to sensitivity of faster impacts on revenues than from industry cost changes.

Picking one future to investigate further, with only the change of technology introduction sensitivity and no policies applied, Table 8 shows when the stranding occurs, to which age of planes, and the financial loss.

These values are similar to those suggested by Caldecott et al.[9] [74] with an average of 0.9 % of asset values on average stranded and a maximum of 7.0 % stranded. This also highlights the high ratio of assets to market capitalisation (5:1) for airlines and therefore the level of debt (or leverage) which they have, positioning them at a riskier position than other companies in the sector.

The stranded planes are those which are entering into service over the next decade. Those entering service later will have a greater fuel efficiency and so will still be able to operate profitably even with a lower revenue.

Although stranding only takes place in the Industry Scenario futures with the accelerated impact of the technology change, this is only true for the time period which we are reviewing, up to 2050. If the model were to be extended beyond that year, using an extrapolation of fleet turnover mirroring that of the last 2 years of the period, stranding would happen in 2051 (when over 20 % of the fleet is hydrogen) even without applying that sensitivity. Therefore, in modelled futures with this scenario it is more of a question of *when* rather than *if* stranding will occur.

This result has material implications for the aviation industry beyond the UK. Extrapolating to the global narrowbody fleet would result in stranded assets of $63.6bn[10] by 2050. This size and frequency (20 %) of risk will impact not just the owners of the assets (airlines), but also financers (leasing companies) and investors (asset managers). The existing reluctance of financers to provide capital for airlines to buy older planes may increase if this additional risk is considered – as per interviewee, below.

> "*you're not going to get finance to operate those older aircraft*" – **Interviewee 3.**

This level of risk provides a material reason for current asset owners to act to prevent the introduction of new technologies [44]. Other industries e.g., cameras and solar panels - have seen new technology entrants creating significant stranding of assets and value [84]; [85]. Policymakers therefore need to be aware of these underlying risks which drive the aviation industry to seek to maintain the status quo. In addressing these risks policymakers will need to consider policy options which provide opportunities for the risks to be minimised or the alternative to be made significantly attractive to incentivise action.

The involvement of industry input in this RDM approach has not only identified impacts and risks to the wider economy including society it has also identified impacts on the aviation industry within a single analytical paradigm. As outlined in section 3.1.2 asset stranding in aviation has not been developed previously, despite having industry characteristics which would suggest that it would be substantially exposed. One possible reason for this may be the lack of utilisation of exploratory tools such as RDM within research in both aviation decarbonisation and stranded asset corpus. This highlights the benefit of using an approach that exposes more of the decision space thereby intuitively bringing in a more interdisciplinary approach.

In summary there are three key findings:

- The most salient systemic risk facing the sector is substantial exposure of asset stranding;
- A continuation of existing policies is likely to lead to an undershooting of decarbonisation goals;
- Utilisation of sustainable aviation fuel (SAF) as the medium-term aviation fuel energy vector is the *"no regrets"* strategy for deep decarbonisation. It has many possible pathways drawing on a range of feedstocks allowing an element of robustness to be realised.

Though the approach is a substantive improvement on existing tools the analysis has not considered the role of (i) policy sequencing on

---

[9] Average of 1.8 %, maximum of 16.9 % of all asset value lost due to stranding

[10] 2050 UK narrowbody fleet – 1230, 2050 global narrowbody fleet – 40,855 (ATI fleet model). $1.9bn / 1230 × 40,855 = $63.6bn

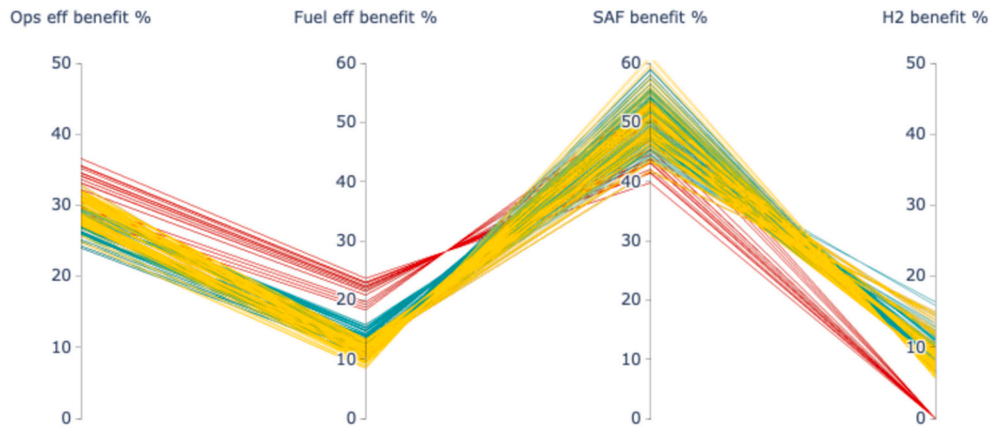

Fig. 6. RDM parallel coordinate plots displaying the proportion of category in total carbon reduction over period (red - Base Scenario, green - Net Zero Scenario, gold - Industry Scenario).

Table 7
a & b - Impact of scrappage scheme and cost-based price impact on market capitalisation of airlines (simplification of tables S7 and S8).

All Scenarios - Average of percent market cap			
Scrappage scheme	New tech impacts price		Total
	No	Yes	
No	4%	43%	**24%**
Yes	4%	34%	**19%**
Total	**4%**	**38%**	**21%**

Likely Scenario - Average of percent market cap			
Scrappage scheme	New tech impacts price		Total
	No	Yes	
No	0%	108%	**54%**
Yes	0%	87%	**43%**
Total	**0%**	**97%**	**49%**

Table 8
Stranded assets as a result of technology change impact acceleration.

Year of entry into service	Year of stranding	Value of stranding ($m) (discounted to 2024)
2026	2047	83
2026	2050	2
2027	2047	137
2027	2050	5
2028	2047	191
2028	2050	9
2029	2047	235
2030	2047	128
2031	2047	151
2032	2047	168
2033	2047	180
2034	2047	196
2035	2047	207
2036	2047	223
Total		**1915**
Current market capitalisation of UK fleet		7669

incentivising aviation sector as well as upstream and downstream actors in decarbonisation, the impacts of asset stranding, investment attractiveness to actors decarbonisation; and (ii) the implications of policy interaction at any point in time. The analysis therefore represents the start of a deliberative conversation on the needs of the broad range of actors within the aviation sector which requires the application of other aspects of exploratory modelling yet to be applied – see Fig. S1 in Supplementary Material.

5. Conclusion - need for more exploratory approaches and interdisciplinarity to aviation sector decarbonisation transitions analysis

This contribution highlights the need for the application of exploratory and interdisciplinary approaches to aviation decarbonisation transitions analysis to better inform aviation sector net zero strategies.

The study finds that there is a wide range of estimates of the key drivers for aviation decarbonisation, such as SAF cost and GHG reduction potential, cost of capital, speed of new technology development and diffusion, as well as the implications of these technologies on aviation sector company cost and revenue structures. There's a need to recognise the deep uncertainty in aviation sector decarbonisation analysis which is often more impactful on analysis than possible decarbonisation policies. In order to incorporate this uncertainty and unpack strategic investment insight from a firm perspective we applied an exploratory approach (RDM) to the aviation sector on an example of the UK narrow-bodied fleet.

The exploratory approach analysed a model that incorporated various scenarios into an existing industry fleet model to assess changes in passenger demand. It then integrated projected cost developments for new fuels and blended mandates to evaluate shifts in revenue and expenses, ultimately identifying potential stranded assets.

Based on industry stakeholder engagement, the metrics of electricity and land requirements, GHG emissions, and profitability allowed the vulnerability analysis to be more complete and identify both broader socio-economic factors and dysfunctional industry behaviour that the government needs to consider when developing policy. Addressing an industry with a series of oligopolies will require closer international and cross-departmental coordination.

The approach highlighted the following outputs relevant to policy within a single analytical paradigm:

- policies currently in place will ***not*** be enough to reach the decarbonisation goals of the UK;
- the main focus of aviation decarbonisation to 2050 needs to be the generation of SAF along with hydrogen production as a feedstock ***not*** the focus on hydrogen fuelled planes; and

- there is a risk of significant asset stranding which could impact on the financial stability of the UK aviation sector. Further analysis can be conducted to assess implications of this stranding on individual airlines and actors upstream of airlines to develop further fidelity, taking into account the particular nature of the aviation industry behaviours with respect to innovation.

The study has clearly demonstrated that the application of an exploratory approach can facilitate working with the extensive deep uncertainty and complexity of the aviation sector characteristics by: (i) its ability to decipher the pervasive extent of uncertainty across and along technology interventions – including upstream implications, financial fall-out and emissions – whilst facilitating deliberative engagement with stakeholders and market actors. That is the RDM approach provides a more flexible and comprehensive approach to understanding and addressing deep uncertainty in which modelling can exist in an iterative exchange with policy development rather than separate from it; (ii) the structuring of decisions as well as facilitating multi-sectoral decision making co-ordination both intra systemic within the aviation sector and inter systemic – i.e., beyond the sector; and (iii) intuitively encourages interdisciplinary approaches to identify systemic risks and the policy interventions that might be needed to mitigate those risks. This work concludes that cannot happen whilst the majority of aviation sector analysis applied relies on a limited suite of tools, limited in their ability to address the extent of complexity and deep uncertainty, generating inadequate net zero policy insight for the aviation sector.

It is hoped that this contribution will stimulate the application of a more diversified approach - incorporating exploratory and qualitative approaches - to better inform robust aviation sector decarbonisation policy design for possible net zero futures which is transparent and inclusive.

CRediT authorship contribution statement

A.C. Belcher: Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **M.H.W. Workman:** Supervision, Methodology, Conceptualization, Writing – original draft. **A. Ostrovnaya:** Supervision, Writing – review & editing. **Andy Jefferson:** Writing – review & editing.

Ethics approval

Approval for interviews with participants was granted by Imperial College Science, Engineering and Technology Research Ethics Committee (ID:7336877).

Declaration of competing interest

The authors report there are no competing interests to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2025.104158.

Data availability

Supplementary Information. The online version contains supplementary information on methods available and data available at: https://doi.org/10.1016/j.erss.2025.104158.

References

[1] Air Transport Action Group. Aviation Benefits Beyond Borders. Air Transport Action Group; 12/24.
[2] Air Transport Action Group Waypoint 2050. Air Transport Action Group; 9/21.
[3] International Energy Agency. Aviation. https://www.iea.org/energy-system/transport/aviation [Accessed 15th April 2025].
[4] IIASA, Chapter 16: transitions in energy systems. In: Global Energy Assessment. https://iiasa.ac.at/projects/gea, 2012.
[5] F.W. Geels, Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the multi-level perspective, Energy Res. Soc. Sci. 37 (2018) 224–231, https://doi.org/10.1016/j.erss.2017.10.010.
[6] T.J. Foxon, A coevolutionary framework for analysing a transition to a sustainable low carbon economy, Ecol. Econ. 70 (12) (2011) 2258–2267, https://doi.org/10.1016/j.ecolecon.2011.07.014.
[7] R. Bolton, T.J. Foxon, A socio-technical perspective on low carbon investment challenges – insights for UK energy policy, Environ. Innov. Soc. Trans. 14 (2015) 165–181, https://doi.org/10.1016/j.eist.2014.07.005.
[8] Sustainable Aviation Sustainable aviation net zero carbon road map. Sustainable Aviation; 2023.
[9] C. Bergero, G. Gosnell, D. Gielen, S. Kang, M. Bazilian, S.J. Davis, Pathways to net-zero emissions from aviation, Nat. Sustain. 6 (4) (2023) 404–414, https://doi.org/10.1038/s41893-022-01046-9.
[10] International Air Transport Association. Finance - Net Zero CO2 Emissions Roadmap. International Air Transport Association; 9/24.
[11] International energy agency. Technical note on the emissions and temperature implications of COP26 pledges. International Energy Agency; 2021.
[12] Lauerwald, M, Staudacher, S. The aircraft engine game - system dynamics of the aerospace industry. In: Deutscher Luft- und Raumfahrtkongress 2014. 2014.
[13] W. Spitz, F. Berardino, R. Golaszewski, J. Johnson, Development cycle time simulation for civil aircraft, NTRS Report number: NAS 1.26 (2001) 210658.
[14] M. Workman, G. Darch, K. Dooley, G. Lomax, J. Maltby, H. Pollitt, Climate policy decision making in contexts of deep uncertainty - from optimisation to robustness, Environ. Sci. Pol. 120 (2021) 127–137, https://doi.org/10.1016/j.envsci.2021.03.002.
[15] M. Workman, G. Darch, B. Denisart, D. Roberts, M. Wilkes, S. Brown, et al., A robust decision-making approach in climate policy design for possible net zero futures, Environ. Sci. Pol. 162 (2024) 103886, https://doi.org/10.1016/j.envsci.2024.103886.
[16] G. Semieniuk, P.B. Holden, J.F. Mercure, P. Salas, H. Pollitt, K. Jobson, et al., Stranded fossil-fuel assets translate to major losses for investors in advanced economies, Nat. Clim. Chang. 12 (6) (2022) 532–538, https://doi.org/10.1038/s41558-022-01356-y.
[17] N. Firdaus, A. Mori, Stranded assets and sustainable energy transition: a systematic and critical review of incumbents' response, Energy Sustain. Dev. 73 (2023) 76–86, https://doi.org/10.1016/j.esd.2023.01.014.
[18] M.A. Brown, J. Chandler, M.V. Lapsa, B.K. Sovacool, Carbon Lock-in: Barriers to Deploying Climate Change Mitigation Technologies, Oak Ridge National Laboratory, 2008, https://doi.org/10.2172/1424507. Report number: ORNL/TM-2007/124;.
[19] R. Lempert, Scenarios that illuminate vulnerabilities and robust responses, Clim. Chang. 117 (4) (2013) 627–646, https://doi.org/10.1007/s10584-012-0574-6.
[20] UK aviation commits to net zero carbon emissions by 2050. Sustainable Aviation. https://www.sustainableaviation.co.uk/news/uk-aviation-commits-to-net-zero-carbon-emissions-by-2050/ [Accessed 16th April 2025].
[21] Department of Transport Jet zero strategy: delivering net zero aviation by 2050. Department for Transport; 2022.
[22] NLR / SEO. Destination 2050. Destination 2050; 2021.
[23] International Civil Aviation Organisation. States adopt net-zero 2050 global aspirational goal for international flight operations. https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx [Accessed 16th April 2025].
[24] The Economist, What if aviation doesn't recover from covid-19, The Economist (2020). https://www.economist.com/the-world-if/2020/07/04/what-if-aviation-doesnt-recover-from-covid-19 (Accessed 15th November 2024).
[25] The Economist. Terminal conditions: air travels sudden collapse will reshape a trillion-dollar industry, The Economist (2020). https://www.economist.com/business/2020/08/01/air-travels-sudden-collapse-will-reshape-a-trillion-dollar-industry (Accessed 15th November 2024).
[26] D. Hirst, Aviation, decarbonisation and climate change. House of commons. Report number: 8826, 2021.
[27] CAA. Table 8.2 Aircraft type and utilisation - individual airlines. https://www.caa.co.uk/Documents/Download/12028/3fed8a79-482a-4ffd-96a9-f545f1ead82d/4084 [Accessed 15th September 2024].
[28] Oliver Wyman, Global Fleet and MRO Market Forecast 2023–2033. Oliver Wyman, 2023.
[29] NGFS. NGFS Scenarios Portal. NGFS Scenarios Portal. https://www.ngfs.net/ngfs-scenarios-portal/explore/ [Accessed 6th April 2024].
[30] IAG (Ed.), Annual Report, IAG 2023 (2024).
[31] Aerospace Technology Institute. ATI Tech Strategy 2022 Destination Zero, Aerospace Technology Institute, 2022.
[32] S. Gössling, A. Humpe, Net-zero aviation: transition barriers and radical climate policy design implications, Sci. Total Environ. 912 (2024) 169107, https://doi.org/10.1016/j.scitotenv.2023.169107.
[33] Airbus, GMF 20Global market forecast 2024, Airbus, 2024.
[34] Department of Transport, Jet Zero Strategy: One Year on, Department of Transport, 2023.

[35] Graver B, Mukhopadhaya J, Zheng XS, Rutherford D, Pronk E. Vision 2050 - Aligning aviation with the Paris agreement. The international council on clean Transportation; 6/22.
[36] Aerospace technology institute. Air Fleet model, Model data provided in July and (2024).
[37] Department of Transport. Transport and environment statistics: 2023. https://www.gov.uk/government/statistics/transport-and-environment-statistics-2023/transport-and-environment-statistics-2023 [Accessed 27th January 2025].
[38] D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, et al., The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmos. Environ. 244 (2021) 117834, https://doi.org/10.1016/j.atmosenv.2020.117834.
[39] L. Donceel, in: Airlines for Europe (Ed.), Non-CO2 emissions from the aviation sector: A4E perspectives, 2022.
[40] S. Wandelt, X. Sun, A. Zhang, Is the aircraft leasing industry on the way to a perfect storm? Finding answers through a literature review and a discussion of challenges, J. Air Transp. Manag. 111 (2023) 102426, https://doi.org/10.1016/j.jairtraman.2023.102426.
[41] B. Caldecott, N. Howarth, P. McSharry, Stranded assets in agriculture: protecting value from environment-related risks. Smith School of Enterprise and the, Environment (2013).
[42] J. Leaton, Unburnable Carbon - Are the World's Financial Markets Carrying a Carbon Bubble? Carbon Tracker, 2011.
[43] J.A. Schumpeter, Capitalism, socialism and democracy, Taylor & Francis Group, Oxford, UK, 2010. http://ebookcentral.proquest.com/lib/imperial/detail.action?docID=515353.
[44] V. Fisch-Romito, C. Guivarch, F. Creutzig, J.C. Minx, M.W. Callaghan, Systematic map of the literature on carbon lock-in induced by long-lived capital, Environ. Res. Lett. 16 (5) (2021) 053004, https://doi.org/10.1088/1748-9326/aba660.
[45] T.A. Hansen, Stranded assets and reduced profits: analyzing the economic underpinnings of the fossil fuel industry's resistance to climate stabilization, Renew. Sust. Energ. Rev. 158 (2022) 112144, https://doi.org/10.1016/j.rser.2022.112144.
[46] Federal Aviation Administration, Economic Values for Investment and Regulatory Decisions, Federal Aviation Administration, 2019.
[47] S. Holloway, Straight and level: practical airline economics, Routledge, 2014.
[48] McKinsey. Why rising fuel prices might not be as bad for the airline sector as it seems. https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/why-rising-fuel-prices-might-not-be-as-bad-for-the-airline-sector-as-it-seems [Accessed 23rd July 2024].
[49] IATA, McKinsey., Understanding the Pandemics Impact on the Aviation Value Chain, IATA, 2022.
[50] M. Dresner, J.S.C. Lin, R. Windle, The impact of low cost carriers on airport and route competition, JTEP 30 (3) (1996). https://jtep.org/wp-content/uploads/2021/02/Volume_XXX_No_3_309-328.pdf.
[51] ASTM. Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. https://www.astm.org/d7566-20a.html [Accessed 25th September 2024].
[52] S. Churchill, Narrowbody engine values as a proportion of aircraft values, Asset Valuations (2024).
[53] Aerospace Technology Institute Email sent to: Author 2024.
[54] findmeaplane.com. The Lifespan of a Jet Engine: Factors, Overhaul Cycles, and Costs. https://www.linkedin.com/pulse/lifespan-jet-engine-factors-overhaul-cycles-costs [Accessed 25th September 2024].
[55] Department of Transport Supporting the transition to jet zero: creating the UK SAF mandate. Department of Transport; 2024.
[56] G.A. Akerlof, The market for 'lemons': quality uncertainty and the market mechanism, Q. J. Econ. 84 (3) (1970) 488–500, https://doi.org/10.2307/1879431.
[57] ICOA, ICAO Environmental Report, ICOA, 2022.
[58] D.S. Lee, D.W. Fahey, P.M. Forster, P.J. Newton, R.C.N. Wit, L.L. Lim, et al., Aviation and global climate change in the 21st century, Atmos. Environ. 43 (22) (2009) 3520–3537, https://doi.org/10.1016/j.atmosenv.2009.04.024.
[59] Harris, L. China vs the west: the next phase in the hydrogen hype cycle. Fin. Times, 2024. https://www.ft.com/content/4b87d5ea-2801-4250-b521-0552b37a03d0 (Accessed 25th September 2024).
[60] J. Larsson, A. Elofsson, T. Sterner, J. Åkerman, International and national climate policies for aviation: a review, Clim. Pol. 19 (6) (2019) 787–799, https://doi.org/10.1080/14693062.2018.1562871.
[61] Bows-Larkin, A, Mander, SL, Traut, MB, Anderson, KL, Wood, FR. Aviation and climate change–the continuing challenge. Blockley, R, Shyy, W (eds.) Encyclopaedia of aerospace engineering. 1st ed. Wiley; 2016. 1–11. https://doi.org/10.1002/9780470686652.eae1031.
[62] European Union. Regulation - EU - 2023/2405 - EN - EUR-Lex. https://eur-lex.europa.eu/eli/reg/2023/2405/oj [Accessed 26th September 2024].
[63] J. Kantenbacher, P. Hanna, S. Cohen, G. Miller, C. Scarles, Public attitudes about climate policy options for aviation, Environ. Sci. Pol. 81 (2018) 46–53, https://doi.org/10.1016/j.envsci.2017.12.012.
[64] J. Thomä, F. Fischer, Challenges to NGFS scenarios and the way forward, Theia Finance Labs (2023).
[65] I. Monasterolo, M. Nieto, E. Schets, The good, the bad and the hot house world: conceptual underpinnings of the NGFS scenarios and suggestions for improvement, 2022, https://doi.org/10.2139/ssrn.4211384.
[66] F.G.N. Li, Actors behaving badly: exploring the modelling of non-optimal behaviour in energy transitions, Energ. Strat. Rev. 15 (2017) 57–71, https://doi.org/10.1016/j.esr.2017.01.002.
[67] C. Weber, D.L. McCollum, J. Edmonds, P. Faria, A. Pyanet, J. Rogelj, et al., Mitigation scenarios must cater to new users, Nat. Clim. Chang. 8 (10) (2018) 845–848, https://doi.org/10.1038/s41558-018-0293-8.
[68] E. Trutnevyte, Does cost optimization approximate the real-world energy transition? Energy 106 (2016) 182–193, https://doi.org/10.1016/j.energy.2016.03.038.
[69] S. Pye, O. Broad, C. Bataille, P. Brockway, H.E. Daly, R. Freeman, et al., Modelling net-zero emissions energy systems requires a change in approach, Clim. Pol. 21 (2) (2021) 222–231, https://doi.org/10.1080/14693062.2020.1824891.
[70] RAND. Robust Decision Making | RAND. https://www.rand.org/pubs/tools/TL320/tool/robust-decision-making.html [Accessed 10th September 2024].
[71] IRENA (Ed.), Stranded assets and renewables, IRENA (2017).
[72] A. Shimbar, Environment-related stranded assets: an agenda for research into value destruction within carbon-intensive sectors in response to environmental concerns, Renew. Sust. Energ. Rev. 144 (2021) 111010, https://doi.org/10.1016/j.rser.2021.111010.
[73] C. Zhao, K. Dong, S. Zheng, X. Fu, K. Wang, Can China's aviation network development alleviate carbon lock-in? Transp. Res. Part D Transp. Environ. 115 (2023) https://doi.org/10.1016/j.trd.2022.103578.
[74] B. Caldecott, A. Clark, K. Koskelo, E. Mulholland, C. Hickey, Stranded assets: environmental drivers, societal challenges, and supervisory responses, Annu. Rev. Environ. Resour. 46 (Volume 46, 2021) (2021) 417–447, https://doi.org/10.1146/annurev-environ-012220-101430.
[75] Aviva. Stranded! When assets become liabilities. https://www.avivainvestors.com/en-gb/views/aiq-investment-thinking/2020/02/the-future-of-the-energy-industry/ [Accessed 16th April 2024].
[76] PACE ESG. (7) COP26 – What all Aircraft Lessors should know | LinkedIn. https://www.linkedin.com/pulse/cop26-what-all-aircraft-lessors-should-know-pace-esg/ [Accessed 16th April 2024].
[77] Simms, A. Cars, aviation, steel … The stranded assets risk spreads far beyond fossil fuel firms. Guardian 2015. https://www.theguardian.com/environment/2015/oct/08/cars-aviation-steel-stranded-assets-risk-spreads-far-beyond-fossil-fuel-firms (Accessed 16th April 2024).
[78] Department for Energy Security and net Zero. Energy Trends: UK Renewables, DESNEZ, 2024.
[79] Department for Environment, Food & Rural Affairs. Bioenergy Crops in England and the UK: 2008–2023. https://www.gov.uk/government/statistics/bioenergy-crops-in-england-and-the-uk-2008-2023/bioenergy-crops-in-england-and-the-uk-2008-2023 [Accessed 13th August 2024].
[80] Easyjet., Annual Report and Accounts 2023, Easyjet, 2023.
[81] Bloomberg. UK Airline Market Capitalisation - 19/6/24. Bloomberg Terminal; 2024.
[82] A.J.L. Pfeiffer, The decarbonization identity and pathways to net-zero. [DPhil thesis] Oxford, 2018.
[83] Intergovernmental Panel on Climate Change (IPCC), Mitigation pathways compatible with 1.5°C in the context of sustainable development, in: IPCC (Ed.), Global warming of 1.5°C: IPCC special report on impacts of global warming of 1.5°C above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty, Cambridge University Press, Cambridge, 2022, pp. 93–174, https://doi.org/10.1017/9781009157940.004.
[84] V. Kadiyali, Entry, its deterrence, and its accommodation: a study of the U. S. photographic film industry, Rand J. Econ. 27 (3) (1996) 452–478, https://doi.org/10.2307/2555839.
[85] Jilani, H. Chinese solar panel boom threatens Pakistan's debt-ridden grid. Financial Times 2024. https://www.ft.com/content/69e4cb33-3615-4424-996d-5aee9d1afe19 (Accessed 25th September 2024).