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Original research article

# On a wing and hot air: Eco-modernisation, epistemic lock-in, and the barriers to greening aviation and ruminant farming

Ann Bruce\*, Graham Spinardi

Science, Technology &amp; Innovation Studies, The University of Edinburgh, Old Surgeons' Hall, High School Yards, Edinburgh, EH1 1LZ, UK



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## ABSTRACT

The aviation and livestock agriculture sectors are major producers of greenhouse gas emissions, and have been the subject of extensive examination to develop lower impact, more energy and resource efficient technologies. Yet little attention has been paid to the challenges faced in the adoption of these lower impact technologies in these industry sectors. In this paper we seek to understand the interactions between technological innovation and socio-behavioural contexts in the adoption of more environmentally sustainable practices. Focusing on the UK (although recognising the global context of aviation and agriculture) and using a combination of literature analysis and interview data we undertake a detailed examination of these interactions. We examine why the claims of eco-modernisation theory that argue that the drive for economic efficiency will lead also to improved energy and resource efficiency appear unfounded in our cases. We identify lock-in in both sectors, finding that the barriers to greener innovation hinge particularly on the knowledge practices that pertain in the two sectors. This 'epistemic lock-in', rather than simple inertia and resistance to unfamiliarity, appears crucial, and must be overcome to enable adoption of lower impact technologies.

## 1. Introduction

Towards the end of the twentieth century a scientific consensus emerged pointing towards a strong causal correlation between greenhouse gases (GHGs) and climate change, and in most countries this view is accepted by mainstream political opinion. In the United Kingdom (UK), policy responses to this challenge led to an ambitious target of reducing GHGs emissions by 80% by 2050 as compared to 1990 levels [1].

Achieving such challenging goals will require the transformation of many industrial sectors. Whether it be automobiles running on fossil fuels, poorly insulated houses, fuel-hungry aircraft, or meat consumption based on ruminant farm animals, it is clear that longstanding technological paradigms need to be displaced or drastically altered. Innovation can provide technologies with less climate change impact, but they must also be adopted into practice to produce this effect. Although 'eco-modernisation' has many conceptual strands, one key idea is that businesses seek to be efficient in order to make greater profits, and such efficiency should lead to less wasteful use of resources and greater energy-efficiency. This 'win-win' argument is also central to the claims made for 'clean technology' whereby innovative

restructuring of industrial processes can reduce waste production, thus reducing the need for end-of-pipe approaches to ameliorate pollution.

Here we focus specifically on the processes of innovation in two socio-technical systems – civil aviation and ruminant farming – and the barriers to change that need to be overcome to improve energy and resource efficiency in order to achieve substantial GHG reduction. These two sectors are chosen for their distinctive individual significance and the potential they afford for comparative analysis. To what extent, do these cases support or undermine the argument that eco-modernisation can lead to win-win outcomes by stimulating the adoption of more energy efficient processes? What factors limit the adoption of more efficiency due to the 'lock-in' of existing socio-technical systems? How do these factors differ between the two sectors under comparison here, and what policy measures can help overcome this lock-in?

## 2. Eco-modernisation, environmental transitions, and lock-in

In broad terms eco-modernisation theory (EMT) views 'the constant ecological restructuring of modernity' as sufficient to meet environmental challenges because of the inherent 'ecology-inspired and environment-induced processes of transformation and reform in the

*Abbreviations:* APD, Air Passenger Duty; EBV, Estimated Breeding Value; EU, European Union; ETS, Emissions Trading Scheme; FAA, Federal Aviation Administration; GHG, greenhouse gas; LFC, laminar flow control; MLP, multi-level perspective; UK, United Kingdom

\* Corresponding author.

E-mail address: [ann.bruce@ed.ac.uk](mailto:ann.bruce@ed.ac.uk) (A. Bruce).

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central institutions and social practices of modern society' [2,255]. There are a broad range of critiques of EMT (e.g. [3,4]). Here we focus on one particular aspect: the centrality of technological innovation to the achievement of more efficient and thus greener solutions. A core idea of EMT is that 'the only possible way out of the ecological crisis is by going further *into* the process of modernization' [5,42]. At the heart of this optimistic perspective is the belief that technological innovation can, and will, improve resource efficiency, and that in so doing economic gains and corporate profit will be aligned with reductions in environmental impacts. As Welford [6,3] puts it: 'Eco-modernism as a philosophy, with eco-efficiency as its flagship tool, represents a response to concern over the environment by those people and institutions who are committed to the traditional modernist growth trend. The tool of eco-efficiency, a broadly technological tool, sees no alternative to business setting the environmental agenda and business controlling the greening of development.'

Thus, according to EMT, technology is the solution, not the problem, and 'clean(er) technology' offers 'win-win' solutions [7]. In this perspective, so long as environmental costs over the whole life cycle are internalised, the profit maximising nature of capitalist economies will drive down environmental damage whilst increasing profits. EMT thus seeks to 'solve environmental problems by making capitalism less wasteful and thus more sustainable, while retaining the basic system of capitalist production and consumption. The approach to environmental problems is therefore efficiency-oriented' [8,pp. 3–4].

However, such a benign view of market-driven innovation rests on a neo-classical view of economics in which technological substitution relies simply on straightforward cost-benefit analysis, and where new technology can be readily accessed and exploited by companies. In reality, certain aspects of innovation do not follow this idealised model. Rather than constantly seeking to maximise efficiency (and profits), companies instead 'satisfice' by following routines that usually provide adequate financial returns [9,10]. Moreover, technologies are not readily and smoothly substitutable: in some cases because of the high R&D costs needed to develop new technologies to the point where they can out-perform existing technologies that have benefitted from years of incremental improvement, but more generally because technologies are embedded in broader 'socio-technical regimes'. Moreover, as we will outline in both our case studies, environmental impacts can be multiple, complex, and not directly related to energy or resource efficiency.

A particular barrier for efficiency incentives to drive radical improvements in environmental performance is that socio-technical regimes are typically persistent, and characterised by 'technological trajectories' in which paradigmatic technologies are gradually improved. As Dosi [11,153] noted, 'a technological paradigm has a powerful exclusion effect: the efforts and the technological imagination of engineers and of the organisations they are in are focused in rather precise directions while they are, so to speak, "blind" with respect of other technological possibilities.'

Dosi's emphasis on technical exemplars and engineers' practices was too narrow, and later thinking on regimes emphasises 'the embedding of existing technologies in broader technical systems, in production practices and routines, consumption patterns, engineering and management belief systems, and cultural values' [12,182]. In recent years, the dominant framework applied to understanding the persistence of such regimes has focussed on 'technological transitions', typically through application of the multi-level perspective (MLP) approach (e.g. [13,14]).

Many interesting historical case studies have been produced using the MLP framework, but this approach has also attracted a range of critiques (e.g. [15,16]). Our concerns about the MLP approach to transitions centre on two issues. First, many of these studies are limited by a tendency to focus on the development of technology more than on its use, on the supply-side rather than the demand-side [17]. Second, MLP transition case studies are dominated by accounts of successful

transitions (for an exception, see [18]). Because MLP accounts of transitions 'have a tendency to focus on "winning" technologies' [15:1444] they suffer from a lack of methodological symmetry as regards explaining success and failure [19].

While the MLP has dominated recent work on transitions, studies of lock-in have been relatively neglected, and yet they offer a useful corrective to this focus on successful transitions. Understanding lock-in is a key step towards overcoming barriers to more sustainable systems [20]. The concept of lock-in theorises two specific mechanisms – 'increasing returns' and 'network externalities' – that account for the persistence of socio-technical regimes.

'Increasing returns' draws on the idea of 'learning by doing' [21] whereby chosen technologies get locked in because 'the more they are adopted, the more experience is gained with them, and the more they are improved' [22,116]. Arthur [22,116] thus argues that 'a technology that by chance gains an early lead in adoption may eventually "corner the market" of potential adopters, with the other technologies becoming locked out.' The significance for environmental transitions is clear, as Unruh [23,817], for example, claims that 'industrial economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale.'

The second concept underpinning lock-in hinges on the role of network externalities and has been developed by David – though he did not use this term in his 1985 paper – with his iconic case of the QWERTY keyboard. David [24,334] argues that the history of QWERTY shows that what is now considered an inferior technology remains locked in because of '*technical interrelatedness, economies of scale, and quasi-irreversibility of investment*' (his italics). In other words, there was a strong linkage between the choice of typewriter keyboard and the expertise to type on it quickly, the more that one keyboard design dominated, the more it paid to be skilful in its use, and once such a large stock of keyboards and of people skilled in their use existed, it became increasingly hard for a competitor to gain traction.

Together, these two concepts provide a framework for understanding path-dependence, explaining how a particular technological approach can be locked-in, and others locked-out. Accounts of lock-in include the light water nuclear reactor [25], the gasoline car [26], and, of particular relevance to our case of ruminant farming, pest control in agriculture [27].

However, the classic economic explanations of lock-in take a black-boxed view of technology, neglecting the specific technological practices of the 'epistemic cultures' [28] involved. In particular, the catch-all term of 'increasing returns' (which [29] later disaggregated into 'scale economies', 'learning effects', and 'adaptive expectations') covers a range of kinds of investment, but does not sufficiently un-pick the crucial role of knowledge in socio-technical lock-in.

Shove and Walker [17] argue that practices play an important role in transitions in creating demand, but our contention is that knowledge practices are also key to the adoption of technology. We therefore propose a category of lock-in focussed on the knowledge involved in the development, diffusion and enactment of the technological practices that constrain innovation. We argue that fully understanding lock-in requires us to look at the socio-technical practices involved in *both* development and implementation. In particular, we will investigate the extent to which knowledge-intensive practices constrain technological choice, producing what we call *epistemic lock-in*.

Our central hypothesis is that lock-in happens in ways that are specific to the knowledge practices that prevail in a particular socio-technical regime. According to Knorr-Cetina [30,362] 'epistemic cultures can be seen as a structural feature of knowledge societies' in which knowledge can develop and be applied in local contexts rather than being universal in nature. This means that there can be 'divides between global knowledge and its expert cultures and social groups, and those areas of practice and mentality that remain local' [30,372]. Although Knorr-Cetina focuses on scientists and their practices (for

example, in laboratories), we argue that the creation and utilisation of knowledge throughout society is also crucial to environmental transitions. This means that there are no universal, generic solutions to lock-in; each case must be addressed separately to understand the role played by knowledge in embedding and sustaining path-dependence. We demonstrate this phenomenon through two distinct case studies that also show the limitations of eco-modernisation in driving environmental improvement through profit-driven efficiency gains.

### 3. Methods

This paper draws on research from two separate UK Economic and Social Research Council funded projects, providing case studies of lock-in in two distinct sectors – aviation and ruminant agriculture – conducted by Spinardi and Bruce respectively. These case studies and their comparative analysis draw on 57 semi-structured interviews,<sup>1</sup> and extensive literature reviews, including specialist technical documents. Further details on methods can be found in [31–33].

The focus of each study was on technology adoption and involved detailed accounts of existing socio-technical arrangements in each sector as well as of alternative greener approaches. In what follows we describe for each case study: the key characteristics of the socio-technical system as regards its environmental impacts: potential solutions for mitigation; and the barriers to these solutions. After setting out our two case studies, we then compare the two, particularly in respect of lock-in mechanisms.

## 4. Case study 1: aviation

### 4.1. Environmental impacts

Historically, environmental concerns with aviation focussed on local impacts (emissions and especially noise), and on the impact of airport building on amenity. Such local environmental concerns are now overshadowed by the much greater global consequences attributed to climate change. Many see air travel as an unnecessary activity that causes great environmental damage. However, it is also a popular, substantive part of the economy, and there seems little prospect that environmental angst alone will curb, never mind reverse, its growth. Official 2012 figures show UK aviation carrying around 235 million passengers per year, along with 2.3 million tonnes of freight.<sup>2</sup> UK aviation CO<sub>2</sub> emissions are expected to grow from 37.5 Mt CO<sub>2</sub> in 2005 to between 40 and 59 Mt CO<sub>2</sub> in 2050 (with a central estimate of 49 Mt CO<sub>2</sub>) [34,10], though UK policy is aimed at ‘reducing CO<sub>2</sub> emissions from UK aviation down to, or below, 2005 levels by 2050’ [34,3].

Carbon dioxide is not aviation’s only contributor to climate change. Contrails (condensation trails) and contrail-induced clouds are also thought to produce warming (there is uncertainty about how much, but it is generally thought to be at least as much as that produced by aircraft CO<sub>2</sub> emissions), but these only last for hours in the troposphere. It should be noted that while most environmental impacts of air travel are directly related to energy (fuel) efficiency, this is not the case for the production of contrails, and in some cases routes chosen to reduce contrail formation would use more fuel than otherwise [35].

Despite fluctuations in the oil price, fuel is a significant operating cost and this means that ‘airlines have an enormous built-in incentive to

reduce consumption’ [36,1]. Fuel efficiency has improved considerably over the years, with, for example, US airlines tripling their fuel efficiency (in terms of passenger-miles per gallon) between 1971 and 2005 [36,2]. Some of this improvement has come from better operational practices (e.g. cruising longer at higher altitudes with short, steep approaches), but the replacement of older aircraft with newer more efficient designs has made the biggest contribution.

### 4.2. Potential solutions

Aviation’s environmental impacts could be lowered if demand for flying was reduced, either by making it more expensive (through taxation) and/or by making alternatives (e.g. high-speed rail) cheaper and/or more available. However, building high-speed rail can be politically difficult and expensive, and the environmental benefits may be marginal for some routes – especially if there are significant physical obstacles involved [37]. Using taxation to increase the cost of flying can be problematic because of the international nature of aviation. Where an airport is simply a transit point then local taxation may simply lead to pollution (and business) being transferred elsewhere with no global environmental benefit. The UK taxes departures from UK airports through Air Passenger Duty (APD) levied on individual passengers according to flight distance bands. Clearly, as UK air travel has continued to grow since the introduction of APD in 1994, current levels of taxation have a limited effect on behaviour.

Apart from reducing the number of flights, the potential ways of reducing aviation’s climate change impact fall into three categories: more efficient aircraft designs to reduce fuel usage and therefore GHG emissions; switching to the use of biofuels, if sources could be found that did not produce damaging environmental or social side-effects; and more efficient aircraft operation, particularly through the use of air traffic management (ATM) to reduce the conflicts that cause delays and inhibit fuel-efficient trajectories [32]. For reasons of brevity, we will focus here on the potential for, and obstacles to, radical innovation in airliner design.

Airliners have become much more fuel-efficient over the last fifty years – although the first ‘jet’ airliners such as the Boeing 707 were vastly less efficient than the propeller-engined airliners they replaced. Over this period technological advances have reduced emissions by around 70% per passenger/mile, though overall emissions have risen as many more people fly. Over the decade up to 2011 an increase in aviation traffic of 45% was managed with only a 3% increase in fuel use [38]. However, incremental improvements in the classic airliner design ‘are rapidly nearing the limits of what conventional technology can do’ [38]. About 40% of airliners currently in service were built in the previous century [39]. Some progress can be made by replacing them with fuel-efficient designs, but achieving the UK targets for GHG reductions will require new, greener aircraft.

Improvements in airliner fuel efficiency can be achieved in three ways: by making aircraft lighter, by adopting more aerodynamic designs, and by making engines more efficient. The most obvious approach to trim excess weight is to use lighter-weight materials such as carbon fibre rather than aluminium. Although carbon fibre has been used in military aircraft since the 1970s, it is only now finding substantive structural use in airliners, notably in the Boeing 787 [33]. Additive manufacturing processes may also hold potential for reducing emissions [40].

‘Dead’ weight can also be removed by the use of designs that minimise structure that does not provide lift. The ultimate expression of this is a ‘flying wing’ design in which the whole aircraft structure provides lift, maximising the lift-to-drag ratio by eliminating the fuselage. Aerodynamic performance could also be enhanced, for flying wing designs as well as conventional ones, by using laminar flow control (LFC) to minimise drag. As air flows over a wing it quickly becomes turbulent, and this turbulence greatly increases drag. However, it has long been known that it is possible to maintain laminar flow, and thus

<sup>1</sup> These interviews were conducted on the basis of anonymity but the aviation interviewees comprised engineers and managers from both NASA and major aerospace companies, while the agriculture interviewees were 30 sheep and beef cattle farmers and 12 industry actors (e.g. veterinarians, meat processors, breeding advisors). The differing numbers of interviewees for the two cases reflect the differing methodologies of the original projects, with the aviation project focusing on key participants to trace the development of greener aviation technology, while the agriculture project adopted a purposive sampling approach. Furthermore, as farmers are very heterogeneous, larger numbers of interviewees were needed to reach thematic saturation.

<sup>2</sup> <http://www.dft.gov.uk/aviation>. (Accessed 4 December 2012).

reduce drag, through suction from within the wing surface. Together with the use of a flying wing type design, it is thought that LFC could reduce fuel use by 50% [41,51].

Finally, fuel efficiency can be enhanced through the use of more efficient engines. Current turbofan engines are more efficient than earlier designs (and much more efficient than the first turbojet engines), but turboprop engines offer even greater efficiency. Increased fuel prices resulting from the 1973 oil crisis led NASA to carry out an R&D programme (the Advanced Turboprop Project) that ran from 1978 to 1987. However, although turboprops capable of speeds suitable for intercontinental airliners were developed by General Electric and Pratt & Whitney, commercial uptake did not follow [42,43].

#### 4.3. Lock-in and barriers to transition

There is thus a history of greener aviation technologies that have only been used partly (turboprop engines in some short-haul airliners), belatedly (carbon fibre), or hardly at all (flying wings and LFC). To what extent are these potentially greener aviation technologies held back by lock-in? Given the potential for radical technological improvement, why is airliner innovation mainly incremental?

The key challenge is to bring radically greener airliner technology to market in a commercially-viable form. In one regard, this is a simple innovation system. There are few producers (Boeing and Airbus for large airliners), and if they produced a much greener airliner then its 'diffusion' would be straightforward if the customers (airline companies and ultimately passengers) were prepared to use the final product. As largely 'black-boxed' technologies, airliners do not depend on user-implementation to achieve most of their performance (though environmental impact per passenger-mile depends on the numbers of passengers packed in).

However, the airliner innovation system discourages radical innovation because developing a new airliner is expensive and a significant product failure (particularly as regards customer acceptance) would be commercially disastrous. As a former Boeing engineer put it, there is an initial cost to design or 'draw' a new airliner that 'you cannot overcome because of all of the data requirements to certify an aircraft' so that 'once you draw this aeroplane you've incurred this cost, and ... you're locked in.' Airliner development is thus risk-averse for commercial reasons, and this is reinforced by the particular safety culture of civil aviation. Accidents are bad for business, and all participants have a shared interest in avoiding them [44].

The new Boeing 787 airliner is estimated to have cost around \$15 billion to develop, and with such high development costs, it is crucial that a new airliner is both technically and commercially successful. Making a technology that works, at a reasonable cost, is not the only concern facing aircraft manufacturers. Every new aircraft must not only be acceptable to the customers – airline operators and the travelling public – it must also be certified as safe by the regulatory authorities.

American aircraft certification is carried out by the Federal Aviation Administration (FAA) (working with its European counterpart). The FAA's certification process seeks to promote innovation and so its 'regulations do not constrain designers a priori by specifying details such as material properties or the design of individual structures. Instead, designers are given a free hand to incorporate new materials, structural concepts, etc., so long as they accept the responsibility for showing that systems with innovative design features meet the FAA's stringent reliability requirements' [45,12].

However, this certification process has become increasingly challenging as the complexity of aircraft design has increased. A comprehensive account of the process [43,38] noted that:

... a major airframe manufacturer may employ as many as 8000 engineers, flight test pilots and inspectors to design, develop, and certificate a new wide-body passenger jet. ... The number of labor hours invested by a manufacturer in designing a large new jet may

be several hundred times greater than the number of labor hours the FAA has available to verify the safety of the aircraft design.

The FAA gets round this problem by co-opting aircraft engineers to self-regulate, and by drawing on the past record of the aircraft manufacturers and their aircraft [44]. Certification rests crucially on knowledge and expertise built up over many decades, and several generations of aircraft. This cumulative knowledge base facilitates certification because incremental innovation allows extrapolation from earlier knowledge claims (either empirical, say, from wind tunnel testing or theoretical), and from the proven track record of aircraft that have been in operation for decades:

Reliability assessments of new civil aircraft lean very heavily on inferences from the – statistically well-established – data from earlier, different, aircraft designs. ... Large civil aircraft change only very incrementally between generations. Innovations are extremely modest, with new technologies being withheld until their reliability has been well-established in other contexts (in military aircraft, for instance) [46,27].

If new designs diverged radically from this knowledge base, certification would be more problematic, and riskier for the airliner developer. This conservative innovation process is the main barrier to radically greener airliner technology. However, the case of carbon fibre composites shows that more radical change is possible [33]. Following its invention in the 1960s, high-strength carbon fibre was taken up for use in military aircraft first, and then in small non-structural roles in civil aircraft.

Despite this history of use, the high levels of structural composites found in the Boeing 787 (about 50% by weight) have raised concerns. In a 2007 letter<sup>3</sup> to the FAA, former Boeing engineer Vincent Weldon noted that aluminium has 'far fewer failure modes' than carbon fibre and that a particular concern about the latter was that 'there is far less proven knowledge than for aluminium structure'. Weldon argued that 'the less mature composite structure data base, compared to that of aluminium, is of concern'. A 2011 investigation by the US General Accountability Office concurred:

These concerns are partly attributable to the limited in-service experience with composite materials used in the airframe structures of commercial airplanes and, therefore, less information is available on the behaviour of these materials than on the behaviour of metal [47,28].

Nevertheless, the GAO report concluded that the FAA's certification process had been satisfactory, citing expert opinion 'that while not every risk can be known, the use of composites is not revolutionary; rather, it is a new application of technology that has a history in military and general aviation applications' [47,28].

As this example shows, knowledge about reliability is at the heart of airliner innovation. The conservative culture of airliner manufacturers is shaped by their relationships with customers and regulators, but the crucial factor limiting radical innovation is concern about the reliability (and commercial appeal) of technology that lacks a track-record and accumulated knowledge base. According to a former Boeing engineer, the design process for a new airliner is 'very dependent on who you have. So if you have somebody who can do a flying wing then, yeh, you'll look at a flying wing because you've got somebody who knows enough about it to draw one that you can analyse. If you don't, you never look at it.' As he put it, 'the fact that we have the aircraft configurations today is not necessarily because they are the smartest things in the world to build, but because of a long series of historical accidents.'

Airliner technology is thus locked in by lack of knowledge,

<sup>3</sup> <http://seattletimes.nwsourc.com/ABPub/2007/09/17/2003889769.pdf>. (Accessed 5 December 2012).

especially as regards the reliability of ‘unproven’ approaches. Describing this simply as lock-in due to increasing returns fails to capture fully the role of knowledge. What is important is not simply the accumulation of a body of knowledge about reliability, but also the reliability of this knowledge, and the social relations that inform it. It is thus epistemic lock-in that constitutes a barrier to radical innovation in airliner technology. As the histories of laminar flow control and the advanced turbojet show (see [16]), further R&D alone cannot fill this knowledge gap because what is lacking is operational experience.

## 5. Case study 2: ruminant farming

### 5.1. Environmental impacts

The environmental, and in particular climate change impact, of cattle and sheep production has been widely recognised [48]. UK estimates are that agricultural emissions account for some 48 MtCO<sub>2</sub>e (carbon dioxide equivalents) or 8% of UK total GHG emissions [49], making the sector broadly comparable with aviation (at 37.5 MtCO<sub>2</sub>). The main sources of GHGs are nitrous oxide from fertilisers and manure, and methane from digestive systems of cattle and sheep.

About 2.1 million cattle and 14 million sheep were slaughtered in the UK in 2010, to provide over 1.1 million tonnes of meat for human consumption, at a farm gate value of over £3 billion [50]. The industry sector is very heterogeneous with a range of different production systems. For example, a simplified breakdown includes three beef production categories (lowland suckler beef, hill and upland suckler beef, and dairy beef), and three sheep production categories (hill flocks, upland flocks and lowland flocks) with baseline climate change impacts associated with them ranging from 11 kg CO<sub>2</sub>e/kg meat (dairy beef) to 18 kg CO<sub>2</sub>e/kg meat (hill flocks of sheep) [51].

The UK agricultural industry has been challenged to reduce emissions as part of the overall reductions in GHG emissions [1], and is furthermore strongly influenced by Government policy via the European Union’s Common Agricultural Policy. For example, the shift from subsidies based on the number of animals to a Single Farm Payment is claimed to have contributed to a drop in the total number of livestock [48], and coincidentally facilitated reductions in agricultural GHG emissions by 21% between 1990 and 2008 [49].

### 5.2. Potential solutions

Ruminant farming differs from aviation in that there is no vision of a radical technical paradigm-shift that could significantly reduce GHG emissions. Instead the potential solutions envisioned are piecemeal and incremental in nature. Four types of action could reduce GHG emissions from ruminant livestock: i) reduce the amount of meat produced and consumed; ii) improve the efficiency of the food chain; iii) manipulate the processes of methane production; iv) increase the meat produced for a given amount of GHG emissions.

Reducing demand by urging consumers to eat less meat relies on voluntary action by many individual consumers. Taxation at the point of consumption could reduce UK demand, but because meat is traded globally, UK producers could sell to other jurisdictions. Similarly, taxing production could simply export the emissions. The worldwide production of meat and milk is projected to more than double due to increasing population size and increasing wealth [52]. Reduction in UK meat consumption is therefore unlikely to be a panacea, though there are opportunities to reduce food wastage.

The second approach involves addressing food chain efficiency. The value chain from farm to plate is extremely complex [53], involving multiple agents and different configurations. For example, around 50% of UK beef is produced as a by-product of the dairy industry (dairy cows need to have a calf each year in order to produce milk), the remainder coming from specialist producers. However, dairy cattle breeds produce much less meat than those used for beef production. Some have

suggested a return to dual-purpose cattle (i.e. producing meat and milk from the same animals which reduces the methane output for each ‘product’) – a radical change in production system – but many interviewees perceived such an approach would be economically uncompetitive and have infrastructural implications that are challenging, if not infeasible.

The third potential way to reduce ruminant GHG emissions focuses on the methane produced by the rumen (or stomach) bacteria needed to break down grass for digestion. Manipulating the amount of methane produced by these bacteria could reduce GHG emissions. A range of methods have been suggested, from using different grass varieties, to using feed additives, to vaccination to modify the bacterial population. Different methods may be appropriate in different circumstances. For example, interviewees noted that sheep are only given supplementary feeds a few weeks per year and therefore feed additives may be ineffective. Similarly, some grassland is unsuitable for re-seeding due to topography or because it is being managed to maintain biodiversity. It is also important to note that although the above three methods for methane reduction would be environmentally beneficial, they are not directly related to the efficiency of meat production, and so, like the impact of aircraft contrails, could not be driven by eco-modernisation.

Finally, there is the potential to increase the efficiency of meat production relative to GHG emissions. Options include faster growing animals, converting feed to meat more efficiently, managing feed sources and manure better, and reducing wastage due to disease and fertility problems. Improved efficiency means that many of the measures currently suggested to reduce GHG emission from cattle and sheep are viewed as benefitting both emissions reductions and improved economic performance, as would be argued by advocates of eco-modernisation. Calculation of Marginal Abatement Cost Curves [54] show that genetic change in beef cattle aimed at greater growth rate and efficiency is beneficial both in reducing methane emissions and providing economic benefits to farmers. Likewise, Jones et al. [55] calculated carbon footprints for sheep and concluded that measures to improve productivity (e.g. lamb growth rate, number of lambs produced) had the best potential for reducing carbon footprints. Both genetic change in beef cattle and improved lamb growth rate can be promoted by selective breeding, and we now focus specifically on the role of genetic change in increasing resource efficiency.

Traditionally, selective breeding involved selecting animals for future reproduction by their appearance. However, considerable technological innovation has transformed selection based on appearance to selection on genetic merit, drawing on advances in computing power, statistical analysis, understanding of genetics, and increasingly, use of gene sequencing and diagnostic devices to measure characteristics that have hitherto been impossible to measure. The current approach uses Estimated Breeding Values (EBVs) to provide year-on-year incremental improvements in efficiency and consequent reductions in GHG emissions.

EBVs make use of sophisticated statistical analyses combined with information on pedigree and measures of performance in specific characteristics, such as growth rate. Rather than comprising a discrete radical innovation, EBVs work at the level of small incremental changes that gradually accumulate to large differences. For example, estimates suggest that selection informed by EBVs in pork production led to GHG emission reductions of 15% between 1988 and 2007 [56], although the changes so far in beef and sheep have been estimated to be much smaller.

Within the UK sheep and beef sectors, there are three major suppliers of EBVs linked with individual breed societies that act as gatekeepers for which animals are to be included in their books. Farmers buy the animals associated with specific EBVs. In this way, the breed societies act in analogous ways to regulators in aviation but with less power; it is still possible to produce meat without involving breed societies. While an individual farmer may obtain quick improvements by changing breed, producing genetic change requires decades of

consistent action. The use of EBVs requires ongoing attention rather than a one-off purchase, and is usually achieved by repeated purchase of high EBV animals (analogous to updating computer software). However, the purchase comprises an animal and the EBV can thus be considered a ‘black-box’ that requires no special user implementation.

### 5.3. Lock-in and barriers to transition

The barriers to lower GHG producing ruminant farming stem not from difficulties with the development of commercially-viable greener technology, but rather from failure to use existing solutions. For example, farmers experience different barriers to the use of EBVs depending on their circumstances. Key barriers include: i) limited human resources on small farms; ii) structural issues; iii) failure to give credibility to the problem being tackled; iv) conflicting objectives; v) lack of trust of external expertise.

First, unlike aircraft manufacturers, farms are often small family enterprises with limited ability to adopt new technologies and practices. For example, several interviewees indicated that they were not in principle against using EBVs, but simply did not have the time to engage with the issue. Similarly, as one farmer noted, the methane challenges went straight into the ‘too difficult’ box. In the context of family farms, the lack of a clear successor to take on the farm also inhibited engagement with EBVs.

Second, there are features of livestock marketing and production that constrain the ability of an individual farmer to act in isolation. Livestock for meat production are frequently sold from one farm to another (often moving from upland regions to lowland regions) reflecting the availability of grass during the year, and information is lost during this process. Furthermore, the demands of different actors in the chain can vary. The breeding priorities of farmers in upland regions may differ from those of lowland farmers, who in turn may have different priorities from meat processors. Some information is more readily available and therefore given greater weight (e.g. the price received for slaughtered animals as compared to profit per breeding animal). Economic benefits of faster growth rate are difficult to demonstrate if records are not kept and if prices at auction markets vary unpredictably from week to week, as is often the case. Farmers’ perceptions of being treated unfairly by meat processors are also a barrier to collaboration [57], as exemplified by a quote from a sheep breeder in our research: ‘There is an instinctive distrust by the farming industry of the major retailers’. This kind of complexity and interrelatedness leads to the conclusion that effective change to improve sustainability would require reform of the entire production chain.

The third barrier lies in farmers’ acceptance of the problem. Methane was not perceived as a pollutant by most beef and sheep farmers interviewed, but rather a natural and inevitable part of livestock agriculture [31]. As one farmer put it, ‘my sheep... they don’t get fed anything that makes them more gaseous, they’re just eating what’s naturally here.’ Based on the interview sample, farmers tend to conceive their activities as environmentally beneficial due to the absorption of carbon dioxide by the grass eaten by sheep and cattle, and many question whether this carbon fixing is fully taken into account when emissions are calculated.

Fourthly, potential mitigation actions may be difficult to implement because they conflict with other key objectives. For example, farmers selling direct to consumers (e.g. through farm shops) see their customers as valuing local, high quality production. The traditional, often slower-growing, breeds preferred perform well on a grass-fed diet and in the environmental conditions prevailing in the area, but slower growth means greater GHG emissions for a given amount of meat produced. In the context of livestock there are factors other than EBVs to take into account, such as the aesthetic value of an animal [58] and the way in which the identity of a ‘good’ farmer is tied up with how their peers evaluate the appearance of their livestock [59]. Thus a sheep and beef farmer interviewed noted that: ‘The sheep industry is a very

strange industry, there’s all sorts of traits in breeds that have nothing to do with economics...But when you’re involved in it, it’s not easy to change it’.

Finally, contestation of both the issue, and of mitigation methods, is related to distrust of expert knowledge claims. Many farmers distrusted scientific expertise because of its perceived poor track-record (for example in dealing with animal disease outbreaks) and the apparent lack of appreciation of practical constraints faced by farmers (see also [60]). Thus, one farmer noted that: ‘Agriculture has always been pretty quick to take on board new things that were deemed to be good, but we’ve had quite a lot of stuff come at us that’s ... turned out to be bad.’

This distrust of expertise is particularly significant in limiting the uptake of EBVs. Although widely adopted in some areas of the industry, many farmers doubt the applicability of EBVs to their situation. The gains from EBVs were frequently perceived to be only achievable in intensive and favourable lowland conditions. Farmers in upland and hill conditions require their stock to thrive in harsh environments, surviving with poor grass growth, rain, wind and lower temperatures, and they did not think EBVs would be useful in such challenging conditions. As one farmer put it: ‘For me, on this type of land, it’s not going to be appropriate because if I go and buy statistically the very best bull or sheep from a mart and I bring it here, it’s just not going to perform’. Another sheep farmer had experience of using EBVs, but found them wanting: ‘For several years I did go and select [sheep] slightly on the look of them but it was mainly on performance. I brought them here [to this hill environment] and thought they did really badly’. It should perhaps be noted that the farmer’s evaluation was on the basis of visual assessment as they did not weigh any animals.

There are potential risks associated with investing in ‘new’ strains of livestock with higher EBVs, and little incentive to experiment with something that might be ‘less than the best’ [27,523]. These animals may not be able to thrive or even survive in the prevailing conditions as well as the farmers’ current animals. However, our interviews suggest that farmers are willing to experiment with different breeds (not always successfully) and appear attracted to buying-in clearly identified attributes associated with the new breed. While the reasons for this cannot be assessed with any certainty, it may be that breeds provide innovation in a single, identifiable packet that fits in with traditions of herd improvements, whereas the incremental change promised by EBVs is undervalued, perhaps because it incorporates disembodied scientific knowledge.

Although ruminant farming is quite different from aviation in its characteristics, both sectors have knowledge-laden activities at their core. The way in which farmers and farming communities gain knowledge predisposes them towards particular forms of livestock management. In particular, the example of EBV uptake (or the lack of it) shows that farmers’ existing knowledge-practices do not easily admit knowledge from different domains. In farmers’ reluctance to adopt EBVs we also see innovation held back by ‘epistemic lock-in’. The uncertainty about whether EBVs will provide benefits in all conditions, along with doubts over whether scientific advice is correct, result in what Cowan and Gunby [27,523] term lock-in due to ‘uncertainty reduction’. If farmers are unsure whether a real problem exists and whether the actions suggested to mitigate the problem are likely to be effective, then there are few incentives to change current practices.

## 6. Discussion

Both the aviation and ruminant agriculture sectors produce significant levels of GHG emissions, yet they vary enormously in their characteristics as highlighted in Table 1.

The two sectors are very different with high-tech artifice and few producers of aircraft in the one case, and low-tech ‘natural’ production undertaken by a large number of small independent producers in widely varying environments in the other. Despite these differences, a detailed analysis of potential pathways to sustainability demonstrates

**Table 1**  
Characteristics of aviation and ruminant agriculture industry sectors.

Aviation	Ruminant agriculture
High tech	Low tech, but informed by relatively high tech processes (e.g. EBVs)
Concentrated in a few companies	Dispersed with many different producers
Science-based: high levels of R&D, funded by industry and government	Most research funding from government, low priority until food price spike in 2007
Same technology can be applied globally	Global industry but production influenced by local considerations
Alternative markets exist in the military sphere.	Niche markets exist for local and organic production in particular
Product (travel) is delivered by a combination of technology (aeroplanes) and infrastructure of flying	Product (meat) is delivered by a combination of animal, farmer knowhow, technological input (e.g. genetics) and a complex infrastructure of markets.
New aeroplane requires considerable capital investment	Investment in replacements can be considerable relative to size of organisation. Animals can be 'produced' on farm.
Risk averseness due to safety and regulatory concerns	Risk averseness due to climatic challenges and historically low levels of return
Public perceptions of safety important in attitudes to commercialisation of technology	Public perceptions of 'quality' relate to emphasis on aesthetics by part of the industry, and forms a high-value market sector.

some similarities, with the following characteristics in both cases:

- Not all of the environmental impacts are directly related to energy or resource efficiency, as would be necessary for eco-modernisation to address climate change.
- It is unlikely that constraining consumption will restrict emissions adequately. Indeed both sectors are expected to grow rapidly globally due to increasing demand, and taxation to moderate demand may result in movement of activity to other jurisdictions rather than reducing demand *per se*.
- Perceived consumer acceptability limits the range of actions possible.
- Significant improvements in efficiency could be made with existing cutting-edge technology, but there are complex barriers to adoption.

Our focus in both these cases is to what extent these barriers can be understood in terms of the lock-in mechanisms of increasing returns and network externalities, or whether knowledge flows are so central as to cause what we term epistemic lock-in. Although the sectors are very different in many regards, it is these knowledge practices that are key to environmental transitions in our case studies. In aviation, with its high-tech centralised and highly regulated innovation system, the key knowledge practices are those surrounding the safety certification process. In ruminant agriculture, with a more dispersed and localised production process, it is the relationships between farmers and sources of knowledge that are key. A focus on 'epistemic lock-in' highlights the importance of knowledge practices and relationships, and goes beyond the classic 'increasing returns' approach to lock-in.

Thus, airliner innovation is characterised by a conservative approach that prioritises reliability (and hence passenger safety) and limits the commercial risk involved in the expensive process of developing new aircraft. Although other factors are involved, the central issue is that safety certification rests on a cumulative knowledge base – built up over decades of testing and use – that enables extrapolation from past to future designs. The airliner innovation system is thus locked-in at the development stage, with radical, greener technologies not reaching commercial production because there is insufficient knowledge about their reliability [16].

There are network externalities effects (e.g. existing airports are designed for aircraft of a particular shape and weight and may be unsuitable for heavy, flying wing designs), and also lock-in resulting from increasing returns as the incremental improvement of the paradigmatic airliner design (a fuselage with swept wings powered by turbofan engines) has gained from decades of investment and operation. The recent introduction of carbon fibre as a structural material shows that this lock-in can be overcome when sufficient knowledge exists to facilitate the certification of new airliner technology. However, this is not straightforward as what counts as 'sufficient' knowledge depends as much on the relationship between the regulator (the FAA) and the aircraft manufacturers, as it does on 'hard' data [44,46]. What matters

is not just the accumulation of knowledge relating to reliability, but also the practices and relationships that link this knowledge to regulators such as the FAA. The challenge for overcoming this 'epistemic lock-in' of aviation technology thus lies not just in supporting potentially greener technologies, but also in enhancing the knowledge flows surrounding such radical innovations. Policies aimed at 'pump-priming' innovation through R&D will thus be insufficient to drive environmental improvements unless they are accompanied by measures to acquire and transfer the appropriate reliability information for regulatory approval.

Our account of ruminant farming likewise shows epistemic lock-in, but manifested in a different way. In the livestock agriculture sector, farmers have strong motivations for retaining practices they personally trust to work, and there is inertia against approaches involving high levels of uncertainty. Local knowledge gained over generations tends to trump scientific advice with farmers sceptical of claims about farming's GHG contribution, and about the practical efficacy of EBVs.

Adoption of scientific breeding techniques based on EBVs requires beef and sheep farmers to trust external evaluations. However, given the varied nature of the UK natural environment, the predominance of beef and sheep rearing in some of the more demanding areas, and the strong emphasis given by farmers to the capability of their stock to thrive under specific environmental conditions, this trust in externally evaluated animals is often lacking. The epistemic lock-in of ruminant farming thus hinges on the locally-embedded practices of farmers and their complex relationships with different types and sources of knowledge claims. Overcoming this epistemic lock-in again requires enhanced knowledge flows from innovative niches (in this case, farmers who have adopted innovative practices and who can demonstrate their practical application and impact). The mechanisms for these knowledge flows may require a range of different actions, for example extension services, demonstration farms, facilitation of movement of farmers between different livestock sectors and countries.

Our comparative analysis of the commercial aviation and livestock agriculture sectors suggests that transformations to more sustainable practices cannot be driven purely by 'green' innovation, even when this is successfully supported in niches. Rather wider adoption of these technologies depends on knowledge practices and the reduction of risks of adoption. This suggests that in both cases, policies to enable 'safe' spaces to explore new methods of production will be effective in enabling change only if knowledge thus gained is effectively transferred to key actors. Such policies need to go beyond traditional R&D support in order to ensure that experience is gained under realistic conditions, without the full risks implicit in widespread adoption of technologies, and that this experience generates knowledge in a form that is useful for the specific needs of the sector in question.

Our cases also indicate that we cannot rely on eco-modernisation to reduce environmental impacts through efficiency gains. Not only so some climate change effects (such as contrails in aviation) not have a direct relationship to efficiency, but also the complex path dependence



phenomena of lock-in show that the drivers (and inhibitors) of innovation do not conform to the neo-classical economic model. Even if all environmental costs were internalised (which is still rarely the case), a profit-orientated approach to the environment is only likely to achieve patchy, and mainly incremental, improvements at best.

Instead, we need policy initiatives targeted towards the knowledge practices of specific sectors. In the case of aviation, funding basic R&D seems futile unless it is accompanied by support for operational implementation that addresses the risk-adverse nature of the industry by building a knowledge base with regard to commercial viability and reliability. In the case of carbon fibre this operational experience was gained through military sponsorship, but other greener aviation technologies could be supported either by programmes to build on what has already been learnt in military applications (such as with the B2 ‘flying wing’ bomber) or with specific environmental and efficiency-orientated programmes.

With regards to ruminant agriculture, and agriculture more generally, co-design of research with stakeholders is increasingly being promoted as a way of overcoming barriers to uptake of innovations (e.g. [61,62]). Similarly, Barbier and Elzen [62,14] advocate an approach that ‘articulates a co-research relationship between all relevant knowledge producers, including farmers’. This approach, drawing on development studies, is not without criticism [64], with ensuring that appropriate stakeholders are engaged in the best ways being a major challenge [65]. A key aspect is to develop networks of practitioners that enable innovation [66] and facilitate the participation of smaller and remoter farmers, while recognising that a focus on resource efficiency may not be the best way forward for everyone. Alternative approaches, such as planting trees or changing management of grassland, may also have substantial impacts on greenhouse gas emissions.

In summary, our key conclusion is that epistemic lock-in presents a barrier to the uptake of greener technology in aviation and ruminant agriculture, and that given the diverse nature of these two industries, this is likely to be the case in other sectors. For this reason, if not others, eco-modernisation alone cannot be relied upon to bring about environmental transformations of industries. Instead, we need policy measures tailored to the specific knowledge practices of each sector.

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## References

- [1] Climate Change Act, (2008) <http://www.legislation.gov.uk/ukpga/2008/27/contents>. (Accessed 2 November 2015).
- [2] A. Mol, G. Spaargaren, et al., Ecological modernisation and industrial transformation, in: Noel Castree (Ed.), *A Companion to Environmental Geography*, Wiley-Blackwell, Malden and Oxford, 2009.
- [3] R. York, E.A. Rosa, Key challenges to ecological modernization theory, *Organ. Environ.* 16 (3) (2003) 273–288.
- [4] P. McLaughlin, Ecological modernization in evolutionary perspective, *Organ. Environ.* 25 (2) (2012) 178–196.
- [5] A. Mol, *The Refinement of Production: Ecological Modernization Theory and the Chemical Industry*, International Books, Utrecht, 1995.
- [6] R. Welford, Corporate environmental management, technology and sustainable development: postmodern perspectives and the need for a critical research agenda, *Bus. Strategy Environ.* 7 (1) (1998) 1–12.
- [7] M.E. Porter, C. van der Linde, Green and competitive: ending the stalemate, *Harv. Bus. Rev.* (1995) 120–134.
- [8] C. Hunold, J.S. Dryzek, Greening the State? Ecological modernization between state and movement in the USA, UK, Germany and Norway, Paper Prepared for the Joint Sessions of the European Consortium for Political Research, Grenoble, 6–11 April 2001, 2001 workshop on the Nation-State and the Ecological Crisis: Sovereignty, Economy and Ecology <https://ecpr.eu/Filestore/PaperProposal/daeb29dc-230c-4c4b-94ed-e2c18516d1c8.pdf>.
- [9] H.A. Simon, *Models of Bounded Rationality*, MIT Press, 1982.
- [10] D. MacKenzie, *Economic and sociological explanations of technological change, Knowing Machines: Essays on Technical Change*, MIT Press, Cambridge MA, 1996, pp. 49–65.
- [11] G. Dosi, Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technological change, *Res. Policy* 11 (1982) 147–162.
- [12] R. Kemp, J. Schot, R. Hoogma, Regimes shifts to sustainability through processes of niche formation: the approach of strategic niche management, *Technol. Anal. Strategic Manage.* 10 (2) (1998) 175–195.
- [13] F.W. Geels, Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case study, *Res. Policy* 31 (2002) 1257–1274.
- [14] H. Van Driel, J. Schot, Radical innovation as a multilevel process: introducing floating grain elevators in the port of Rotterdam, *Technol. Cult.* 46 (2005) 51–76.
- [15] A. Genus, A.-M. Coles, Rethinking the multi-level perspective of technological transitions, *Res. Policy* 37 (9) (2008) 1436–1445.
- [16] G. Spinardi, R. Slayton, Greener aviation take-off (delayed): analysing environmental transitions with the multi-level perspective, *Sci. Technol. Stud.* 28 (1) (2015) 28–51.
- [17] E. Shove, G. Walker, Governing transitions in the sustainability of everyday life, *Res. Policy* 39 (4) (2010) 471–476.
- [18] P. Wells, P. Nieuwenhuis, Transition failure: understanding continuity in the automotive industry, *Technol. Forecast. Soc. Change* 79 (9) (2012) 1681–1692.
- [19] T.J. Pinch, W.E. Bijker, The social construction of facts and artefacts: or how the sociology of science and the sociology of technology might benefit each other, *Soc. Stud. Sci.* 14 (3) (1984) 399–441.
- [20] H. Corvellec, M.J. Z.Campos, P. Zapata, Infrastructures, lock-in, and sustainable urban development: the case of waste incineration in the Göteborg Metropolitan Area, *J. Clean. Prod.* 50 (2013) 32–39.
- [21] K.J. Arrow, The economic implications of learning by doing, *Rev. Econ. Stud.* 29 (3) (1962) 155–173.
- [22] W.B. Arthur, Competing technologies increasing returns, and lock-in by historical events, *Econ. J.* 99 (1989) 116–131.
- [23] G.C. Unruh, Understanding carbon lock-in, *Energy Policy* 28 (2000) 817–830.
- [24] P.A. David, Clio and the economics of QWERTY, *Am. Econ. Rev.* 75 (2) (1985) 332–337.
- [25] R. Cowan, Nuclear power reactors a study in technological lock-in, *J. Econ. Hist.* 50 (3) (1990) 541–567.
- [26] R. Cowan, S. Hulten, Escaping lock-in: the case of the electric vehicle, *Technol. Forecast. Soc. Change* 3 (1996) 61–79.
- [27] R. Cowan, P. Gunby, Sprayed to death: path dependence, lock-in and pest control strategies, *Econ. J.* 106 (436) (1996) 521–542.
- [28] K. Knorr-Cetina, *Epistemic Cultures: How Sciences Make Knowledge*, Harvard University Press, Cambridge, MA, 1999.
- [29] W.B. Arthur, *Increasing Returns and Path Dependence in the Economy*, University of Michigan Press, Ann Arbor, MI, 1994.
- [30] K. Knorr-Cetina, Culture in global knowledge societies: knowledge cultures and epistemic cultures, *Interdiscip. Sci. Rev.* 32 (4) (2007) 361–375.
- [31] A. Bruce, The lore of low methane livestock: co-producing technology and animals for reduced climate change impact, *Life Sci. Soc. Policy* 10 (2013) 10–31, <http://dx.doi.org/10.1186/2195-7819-9-10>.
- [32] G. Spinardi, Up in the air: barriers to greener air traffic control and infrastructure lock-in in a complex socio-technical system, *Energy Res. Soc. Sci.* 6 (2015) 41–49.
- [33] R. Slayton, G. Spinardi, Radical innovation in scaling up: Boeing’s dreamliner and the challenge of socio-technical transitions, *Technovation* 47 (2015) 47–58, <http://dx.doi.org/10.1016/j.technovation.2015.08.004>.
- [34] Department of Transport, Government Response to the Committee on Climate Change Report on Reducing CO2 Emissions from UK Aviation to 2050, (2011) August.
- [35] B. Sridhar, N.Y. Chen, Fuel efficient strategies for reducing contrail formations in United States airspace, 29th Digital Systems Avionics Conference, Oct 3–7, 2010.
- [36] J.P. Heimlich, Commercial jet fuel supply: impact on US airlines, Vice President and Chief Economist of the Air Transport Association of America, Statement Before the Aviation Subcommittee of the Committee on Transportation and Infrastructure of the House of Representatives, (2006) February 15. [http://www.airmeth.com/index.php/doc\\_download/713-heimlich-jp-2006-commercial-jet-fuel-supply-impact-on-us-airlines-heimlich-jp-2006-commercial-jet-fuel-supply-impact-on-us-airlines.html](http://www.airmeth.com/index.php/doc_download/713-heimlich-jp-2006-commercial-jet-fuel-supply-impact-on-us-airlines-heimlich-jp-2006-commercial-jet-fuel-supply-impact-on-us-airlines.html). (Accessed 2 November 2015).
- [37] R. Kemp, Short-haul aviation—under what conditions is it more environmentally benign than the alternatives? *Technol. Anal. Strategic Manage.* 21 (1) (2009) 115–127.
- [38] M. Watson, Aviation & climate change: a global response to a global challenge, Paper Presented at Greener by Design Conference, October 18, London, 2011.
- [39] C. Seymour, Aircraft life cycles and fleet turnover, Paper Presented at Greener by Design Conference, October 18, London, 2011.
- [40] R.M. Huang, D. Riddle, J. Graziano, S. Warren, S. Das, J. Nimbalkar, J. Cresko, E. Masanet, Energy and emission saving potential of additive manufacturing: the case of lightweight aircraft components, *J. Clean. Prod.* 135 (2015) 1559–1570, <http://dx.doi.org/10.1016/j.clepro.2015.04.109>.
- [41] J.E. Green, The potential for reducing the impact of aviation on climate, *Technol. Anal. Strategic Manage.* 21 (1) (2009) 39–59.
- [42] M.D. Bowles, V.P. Dawson, The advanced turboprop project: radical innovation in a

- conservative environment, in: P.E. Mack (Ed.), *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners, 1998* <http://history.nasa.gov/SP-4219/Chapter14.html>.
- [43] M.D. Bowles, *The Apollo of Aeronautics: NASA's Aircraft Energy Efficiency Program 1973–1987*, NASA, Washington DC, 2010.
- [44] J. Downer, Trust and technology: the social foundations of aviation regulation, *Br. J. Sociol.* 61 (1) (2010) 83–106.
- [45] National Research Council, Committee on aircraft certification safety management, *Improving the Continued Airworthiness of Civil Aircraft: A Strategy for the FAA's Aircraft Certification Service*, National Academy Press, Washington DC, 1998.
- [46] J. Downer, On audits and airplanes: redundancy and reliability-assessment in high technologies, *Account. Organ. Soc.* 36 (2011) 269–283.
- [47] GAO [General Accountability Office], *Aviation Safety: Status of FAA's Actions to Oversee the Safety of Composite Airplanes*, (2011) GAO-11-849, September.
- [48] M. Gill, P. Smith, J.M. Wilkinson, Mitigating climate change: the role of domestic livestock, *Animal* 4 (3) (2010) 323–333.
- [49] Committee on Climate Change, *The Fourth Carbon Budget. Reducing Emissions Through the 2020's*, (2010) <http://www.theccc.org.uk/reports/fourth-carbon-budget/>. (Accessed 2 November 2015).
- [50] EBLEX, *Beef, Sheep and Climate Change: the Facts*, (2015) <http://beefandlamb.ahdb.org.uk/news/livestock-and-the-environment/livestock-and-climate-change-the-facts/>. (Accessed 31 October 2015).
- [51] EBLEX, *Change in the Air. The English Beef and Sheep Production Roadmap—Phase 1*, EBLEX, Kenilworth, 2009 November. [http://www.eblex.org.uk/documents/content/publications/p\\_cp\\_changeintheairtheenglishbeefandsheepproductionroadmap.pdf](http://www.eblex.org.uk/documents/content/publications/p_cp_changeintheairtheenglishbeefandsheepproductionroadmap.pdf). (Accessed 2 November 2015).
- [52] FAO, *The State of Food and Agriculture – Livestock in the Balance*, Food and Agriculture Organization of the United Nations, Rome, 2009.
- [53] D. Simons, M. Francis, M. Bourlakis, A. Fearn, Identifying the determinants of value in the U.K. red meat industry: a value chain analysis approach, *J. Chain Netw. Sci.* 3 (2) (2008) 109–121, <http://dx.doi.org/10.3920/JCNS2003.x034>.
- [54] D. Moran, M. Macleod, E. Wall, V. Eory, A. McVittie, A. Barnes, R. Rees, C.F.E. Topp, A. Moxey, Marginal abatement cost curves for UK agricultural greenhouse gas emissions, *J. Agric. Econ.* 62 (1) (2011) 93–118.
- [55] A.K. Jones, D.L. Jones, P. Cross, The carbon footprint of lamb: sources of variation and opportunities for mitigation, *Agric. Syst.* 123 (2014) 97–107.
- [56] Genesis Faraday Partnership, *A Study of the Scope for the Application of Research in Animal Genomics and Breeding to Reduce Nitrogen and Methane Emissions from Livestock Based Food Chain*, (2008) Defra research project AC204, Final Report.
- [57] A. Cox, D. Chicksand, M. Palmer, Stairways to heaven or treadmills to oblivion? *Br. Food J.* 109 (9) (2007) 689–720.
- [58] L. Holloway, C. Morris, B. Gilna, D. Gibbs, Choosing and rejecting cattle and sheep: changing discourses of practices of (de)selection in pedigree livestock breeding, *Agric. Hum. Values* 28 (4) (2011) 533–547.
- [59] R. Yarwood, N. Evans, A Lleyn sweep for local sheep? Breed societies and the geographies of Welsh livestock, *Environ. Plann. A* 38 (2006) 1307–1326.
- [60] B. Wynne, Misunderstood misunderstandings: social identities and public uptake of science, in: A. Irwin, B. Wynne (Eds.), *Misunderstanding Science? The Public Reconstruction of Science and Technology*, Cambridge University Press, Cambridge, 1996, pp. 19–46.
- [61] T. MacMillan, T.G. Benton, Engaging farmers in research, *Nature* 509 (2014) 25–27.
- [62] F. Hermans, L. Klerkx, D. Roep, Structural conditions for collaborating and learning in innovation networks: using an innovation systems performance lens to analyse Agricultural Knowledge Systems, *J. Agric. Educ. Ext.* 25 (1) (2015) 35–54.
- [63] M. Barbier, B. Elzen (Eds.), *Systems Innovations, Knowledge Regimes, and Design Practices Towards Transitions for Sustainable Agriculture*, Inra, 2012, [http://www4.inra.fr/sad\\_eng/Publications2/Free-e-books/System-Innovations-for-Sustainable-Agriculture](http://www4.inra.fr/sad_eng/Publications2/Free-e-books/System-Innovations-for-Sustainable-Agriculture).
- [64] A. Neef, D. Neubert, Stakeholder participation in agricultural research projects: a conceptual framework for reflection and decision-making, *Agric. Hum. Values* 28 (2) (2011) 179–194.
- [65] M.S. Reed, Stakeholder participation for environmental management: a literature review, *Biol. Conserv.* 141 (10) (2008) 2417–2431.
- [66] C. Lamprinopoulou, A. Renwick, L. Klerkx, F. Hermans, D. Roep, Application of an integrated systemic framework for analysing agricultural innovation systems and informing innovation policies: comparing the Dutch and Scottish agrifood sectors, *Agric. Syst.* 129 (2014) 40–54.