National
Engineering
Policy Centre

Royal Academy
of Engineering

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Decarbonising Aviation Workshop

Summary Report

Contents

Introduction

This report summaries the findings of a workshop convened by the National Engineering Policy Centre (NEPC) on Tuesday 14 September 2021 to discuss how plans for a decarbonised aviation sector via ‘fuel switching’ may impact on wider energy, transport and environmental systems. By examining the implications of fuel switching in these wider systems, the aim was to assist officials and others considering options for decarbonising flight by identifying impacts, key interdependencies, systemic risks and potential opportunities for efficiency and speed in decarbonising aviation.

These low/zero-carbon fuels do not, and will not, exist in isolation from the energy, transport and environmental systems. Therefore, this workshop took a wider view of impacts on other systems to provide a broader understanding of the practical implications of large-scale use of those fuels.

The scale and pace of the ‘fuel switching’ necessary to decarbonise aviation in line with UK legal obligations[1] raises important questions about standards, safety, regulation, cost, transition process and timing. It also raises the potential for knock-on impacts on energy, land and transport systems, with the potential to increase the demand upon them or change what is required of them; for example in terms of energy supply, transport system integration, safety or logistical requirements, or new environmental risks.

Introduction to the National Engineering Policy Centre

The National Engineering Policy Centre’s (NEPC) Net Zero project applies a multi-disciplinary systems perspective to climate change policy. Our work draws on the expertise of diverse engineering disciplines as well as social sciences and systems science.

We explore key issues relating to the transition to a net zero future, such as infrastructure, governance, skills, and resilience, and do ‘deep-dives’ into specific sectors such as construction and aviation to explore the ways they are interconnected, and the actions required.

For more information on our net zero work please see www.raeng.org.uk/policy/policy-projects-and-issues/net-zero-a-systems-perspective-on-the-climate-chal

Background: aviation emissions and the challenge of decarbonising flight

Aviation emissions from 1990 to present and beyond

Aviation is responsible for 7% of the UK's greenhouse gas (GHG) emissions[2], 96% of which are from international flights[3] (see **Figure M8.1** from the Climate Change Committee's Sixth Carbon Budget[4]). The number of British flyers tripled between 1990 and 2019, with a corresponding near doubling (88%) of GHG emissions from the sector in that time[5] (see **Figure M8.2** from the Climate Change Committee's Sixth Carbon Budget[6]). Pre-COVID-19, Department for Transport projections estimated that the GHG emissions from aviation may double again by 2050 without artificial constraints.[7]

During 2020, as a result of the COVID-19 pandemic, UK aviation emissions fell by an estimated 60%[8], however without structural change in the industry, these emissions are projected to bounce back by 2024, and aviation is still expected to be the largest source of UK emissions in 2050.

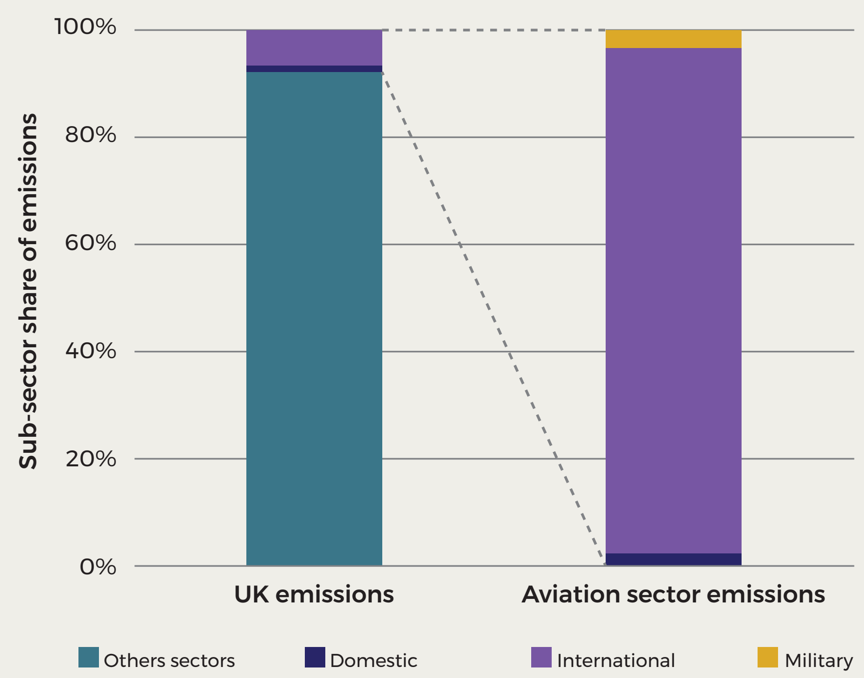
Globally, aviation contributes 2% of yearly GHG emissions.[9] The use of aviation is unevenly distributed globally and within populations. Globally, less than 5% of people take an international flight in any given year, and the most frequently flying 1% produce half of all commercial aviation emissions.[10]

Decarbonising flight

Aviation is generally considered to be the hardest transport sector to decarbonise due to the long lifetimes of aircraft and the lack of mature technology which can replicate the current scale of air travel without producing greenhouse gas emissions. The large mass of aircraft, long journey times and the high energy requirements pose additional obstacles not faced in other transport sectors.

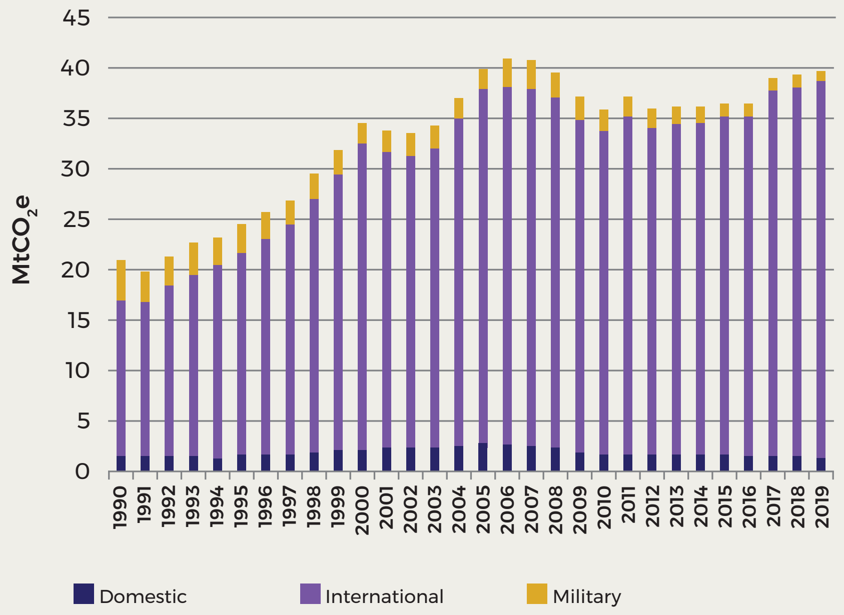
Alternative fuels such as 'drop-in' biofuels and synfuels, hydrogen or battery electricity are being considered alongside fuel efficiency gains from aircraft/engine design, changes to flight paths, demand management, reducing the number of 'ghost flights'[11] and changes to business models. It is thought that more efficient aircraft, flight routing and logistics, such as changes to fuel bunkering, could significantly reduce emissions in the short term, and in the long term a mix of new low/zero-carbon fuels could address different kinds of transport needs; for example, battery electric for short-haul flight and a mixture of sustainable aviation fuels, hydrogen and biofuels for medium- and long-haul flight.

Net zero aviation will require transformational change. No one alternative aviation fuel can be expected to act as a 'silver bullet' that will achieve



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018*.
Notes: Total UK emissions in 2018 were 359 $MlCO_2e/yr$ (AR5 basis, peatland revisions and IAS included). UK aviation sector emissions in 2018 were 39.3 $MtCO_2e/yr$.

Figure M8.1 | Breakdown of aviation sector emissions (2018)



Source: BEIS (2020) *Final UK greenhouse gas emissions national statistics 2018*: BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019*; BEIS (2020) *Energy Trends*: CCC estimates for 2019.

Figure M8.2 | Breakdown of aviation sector emissions (1990–2019) the dominance that fossil fuel-based flight has achieved. Transformation will require new enabling infrastructure, fuel supply chains, safety cases, new skills throughout the supply chain and operations, policy and regulatory frameworks, and business models. Transformation will also be significantly dependent on the nature of the transformations occurring in the wider energy and transport systems, as well as the physical and economic limitations that impact the availability and cost of fuels.

As a result of these technical and system limitations, and the pace of change required to meet the net zero target (and sixth carbon budget), decarbonising aviation requires an active transformation plan that is alive to the wider context in which aviation sits.

Workshop subject: Systemic impacts of aviation fuel switching

The workshop focused on the process of 'fuel switching' as the novel fuels analysed during the workshop are the basis of any plan for decarbonising the aviation sector by displacing the fossil fuels currently in use. It is important to note that 'fuel switching' alone is not the only means by which emission reductions can be achieved in the sector. Emission reductions can be achieved through, for example, aircraft design efficiency, flight routing and policies intended to shift consumer choice towards more sustainable modes of transport.

Some alternative aviation fuels, such as a number of biofuels and e-fuels/synfuels, are regarded as 'drop-in' fuels because they will work using existing engines and aircraft or with minor modifications. Other ways of powering flight such as hydrogen, battery electricity and hybrids thereof, will involve replacement designs or careful retrofit of existing air fleets for passenger and cargo flights.

The supply chain for aviation fuel is currently relatively simple and does not impact on many other energy supply chains; petrochemicals extracted from underground deposits are refined and a certain grade are used as aviation fuels. However, this process involves high levels of emissions before the fuel reaches an aircraft arising from the processes of oil and gas extraction and refinery, including from leakage and flaring.[12,13]

The potential new low/zero-carbon fuels examined in the workshop were:

a. **Battery electricity**. This can be drawn from a national or local power grid and its carbon intensity depends on how the electricity was generated. This means a reliable supply of zero-carbon electricity for charging is required to be net-zero compliant. The batteries can contain large quantities of critical raw materials.

b. **Hydrogen** can be produced through several methods outlined in the infographic in **Annex C**. The two most commonly considered methods are so-called 'green' and 'blue' hydrogen. Electrolytic 'green' hydrogen uses electricity and water, so requires an existing source of zero-carbon electricity'. Blue hydrogen is produced from fossil gas, producing CO_2 as a by-product which must then be abated using engineered geochemical carbon capture and storage to be considered low carbon.

c. **Biofuels** are hydrocarbon fuels that can be produced from a variety of feedstocks, including wastes such as forestry and agricultural residues or specially grown fuel crops that can be converted into biofuels. Like current aviation fuels, biofuel combustion in aircraft engines produces direct emissions of CO_2 and NOx into the atmosphere. The status of these as 'low carbon' fuels is dependent on the feedstock directly sequestering CO_2 (as in the case of crop biofuels) or diverting waste which would have otherwise produce GHG emissions from decomposition.

d. **E-fuels and synfuels** are hydrocarbon fuels that result from chemical engineering processes which combine hydrogen and CO_2, which must be captured either from a concentrated source or from the air. Like current aviation fuels, combustion of these fuels in aircraft engines produces direct emissions of CO_2 and NOx into the atmosphere. The status of these as 'low carbon' fuels is dependent on the source of, and emissions associated with, obtaining the feedstock CO_2.

Workshop structure

This workshop was structured around the following questions:

a. What are the energy, feedstock, and land requirements of powering the UK's aviation needs without high-carbon fuel?

b. What will the impact of the demand for new aviation fuels be on the wider energy system? (e.g., increased electricity demand for production of hydrogen or synfuels, and land use change for biofuels).

c. How do these requirements line up with expectations for the energy transition and other demands on electricity, land, and resources?

The workshop brought together policymakers, industry figures and academics. This included experts in aviation, energy and land systems, aircraft design and manufacture, airport design and management, and airline operations.[14]

Following a presentation from the responsible officials at the Department for Transport on the context and parameters of the upcoming Jet Zero Strategy, the workshop used structured and facilitated engagement to derive and check information across the questions detailed above. The engagement sessions included:

a. A Strength, Weakness, Opportunity and Threat (SWOT) Analysis

b. A session which discussed each fuel in-turn, looking at the timescales for deployment and potential outcomes and requirements for the UK's energy and transport systems and environmental impacts including greenhouse gas emissions, raw material sustainability and land use. Due to time constraints in the workshop, less information was gained on biofuels, and this is reflected in this report.

The findings of these sessions are summarised in the next section of the report where each fuel is examined in turn and informed the description of the aviation system and the relevant context introduced thus far and throughout this report.

Potential aviation fuels: Workshop discussion points

This section presents the key points from the discussion on each low/zero-carbon aviation fuel examined at the workshop.

Fuel analysis: Battery electricity

Background and impact on aviation sector

Currently, there are already some small commercial aircraft being test flown with retrofitted electric engines and it is hoped that, by the mid-2020s, there may be up to 19-seat electric aircraft and, by 2035, passengers may be able to purchase tickets for regional and short-haul battery electric-powered flights.[15]

For effective use of largescale battery electric technology in aviation, significant changes will be required. At ground level, there is a need for fast, battery charging infrastructure to meet demand.

In the air, flights will only be able to fly short-haul and aircraft design will have to change to accommodate the batteries. High energy density batteries do exist, but these are heavy which limits application to short-haul flights. Performance is negatively impacted by low temperatures at altitude which will further impact range. As a result of this, workshop attendees highlighted that many manufacturers are already moving away from pursuing batteries in aviation and, unless improvements happen quickly, they are likely to be overlooked as a potential technology and future investment will be limited.

Wider system impacts

What are the potential impacts of this fuel on the transport system?	The limited power achievable from batteries is not currently compatible with large commercial aircraft or long-haul travel, meaning the most realistic potential options are in short-haul flight only. There would be a need for fast battery charge infrastructure at ground level. While charging infrastructure is being developed to reduce charging time, operational changes to the aviation system will be needed to take account of this to ensure demand continues to be met.
What are the potential impacts of this fuel on the environment?	There is an environmental impact associated with battery production, particularly in the extraction, processing and use of the materials required for the batteries themselves. Lithium battery production also has an added environmental impact via water contamination. Largescale use of batteries may also lead to future environmental and social impacts and challenges from end-of-life batteries and waste.

Opportunities and risks

Opportunities (for UK)	There were thought to be IP opportunities from leading the development of battery technology. Workshop participants also noted that aviation was not currently one of the sectors at the cutting edge of battery technology development and that key breakthroughs, if they occurred, were likely to be driven by other sectors. There may be opportunities for the use of batteries in long-haul flights through hybrid systems which combine batteries with fuel-cells. However, this area requires investment, research, and development. Moving to more sustainable alternative raw materials like lithium sulphur can overcome some of the issues around materials use and supply chains.
Risks (for UK)	Materials manufacture in the UK is currently limited. Workshop attendees stressed that this create potential for a strong reliance on imports of raw materials and could expose sectors of the UK economy to vulnerability. China has very high industrial aspirations so constraints on the availability and affordability of materials may also increase.

Fuel analysis: Hydrogen

Background and impact on aviation sector

Hydrogen has been proposed as a fuel for aircraft via combustion in liquid form in hydrogen burning engines, such as the UK government-backed concept liquid hydrogen plane unveiled in December 2021[16], or when reacted in a fuel cell powering electric motors.

Hydrogen is an increasingly technically viable option for the aviation sector, but aircraft and engineering systems would need to be developed and in-air and ground-level storage would need to be progressed. Manufacturers may be required to complete safety and operational certification in completely new types of technology, as well as sell novel aircraft types to airlines. However, some workshop participants predicted that some hydrogen-fuelled planes could be in commercial use by 2026, with this starting with small aircraft, such as six-seater aircraft that will most likely be used on public service obligation routes (eg Scottish islands to Edinburgh or Glasgow) and then increasing in size and number up to 2050.

Despite having a gravimetric energy density[17] three times greater than kerosene, hydrogen's relatively higher volume requires larger fuel storage capacity on aircraft and adjusted aircraft designs. The size and weight of hydrogen storage tanks pose major limitations for long range flights with high energy requirements.

As raised by participants in the workshop, a potential advantage for the aviation sector of smaller aircraft powered by hydrogen fuel cells is that there can be a more distributed aviation sector where instead of requiring large amounts of power at one or two airports, the power requirements will be distributed at airports across the UK. This may alleviate some of the challenges around high demands for power and infrastructure at hub airports which will otherwise be faced.

Wider system impacts

What are the potential impacts of this fuel on the energy system?	Low carbon hydrogen would be required for aviation, which would likely require the production at scale of either green or blue hydrogen for aviation. **Green hydrogen** Green hydrogen requires significant amounts of low carbon electricity for its production. Workshop participants raised the following considerations: – A power source in the order of 10s of megawatts will be required to generate the hydrogen needed to fuel one large aircraft – Were green hydrogen used in aviation at largescale, this would require a significant uplift in UK grid generation – There is the added need for water and for the critical raw materials, such as precious metals, for the electrolysers needed to produce green hydrogen. To produce green hydrogen in the quantities needed to meet demand, this would require a significant amount of surrounding fresh water. **Blue hydrogen** The production of blue hydrogen is dependent on methane gas as a feedstock, requiring the resultant CO_2 to be captured and stored by geochemical carbon capture and storage (CCS) technologies. Therefore, any significant use of blue hydrogen in aviation (or elsewhere) would require a commensurate growth in CCS and continued dependency upon fossil fuels. The current UK CCS capacity is zero and the scale up of blue hydrogen must be proportionate with that of CCS to ensure there is the capacity to capture the carbon produced from blue hydrogen production.It is expected that the scale of CCS needed in the UK for blue hydrogen production in 2050 will be between 1–52 MtCO_2 per year,[18,19] compared to the current global geoengineered CCS capacity of 40 MtCO_2 per year.[20]
What are the potential impacts of this fuel on the transport system?	As discussed above, participants expected the UK to have hydrogen fuel cell planes by the mid-2020s, starting with small aircraft, carrying out public service obligation routes, and then increasing in size and number to 2050. Initially having smaller aircraft which are hydrogen fuel cell powered might enable a much more distributed aviation system which could help solve power and infrastructure problems. To put this into context, a more distributed future aviation system in the future could be supplied by a few hundred kilowatts at many sites distributed across the UK, rather than tens of hundreds of kilowatts at major hubs like Heathrow.
What are the potential impacts of this fuel on the environment?	The burning of hydrogen and ammonia would potentially add to the non-CO_2 environmental impact of the aviation sector, particularly from the production of NOx. The environmental concerns associated with NOx include the formation of smog, the formation of ground-level ozone and contributing to the problem of acid rain. NOx gases also have associated health risks as they can readily enter the lungs, where they can cause serious damage. Workshop participants also raised concerns over the climate impact of water vapour produced from hydrogen aircraft that leads to the formation of contrails in the stratosphere. When emitted into the atmosphere, these contrails form a 'cloud-like carpet', increasing solar radiation and thus increasing climate impact.[21] However, in the case of hydrogen aircraft, there will not be the emission of soot, which water vapour condenses around to form contrails in the case of fossil fuel-powered aircraft, so it is thought that the formation of contrails may be relatively reduced when hydrogen is burned. Workshop participants concluded that global warming effect of the contrails produced from hydrogen aircraft requires further study to provide clarity on their climate impact.

Wider system impacts continued…

Opportunities and risks

How might international factors (economic, infrastructural, metrics) influence the utility of this fuel?	One of the biggest challenges for hydrogen use in aviation is its worldwide availability at scale, the need to produce green hydrogen and the existence of appropriate supply chain infrastructure. This is both a constraint and an economic opportunity. Hydrogen will likely also be required in other hard-to-decarbonise sectors. This is also both a constraint as this may limit its availability to the aviation sector and also an opportunity in terms of economies of scale.

Fuel analysis: Biofuels from waste

As discussed previously in this report, time constraints in the workshop resulted in a reduced discussion on biofuels. To address this, much of the information discussed below is sourced from a 2017 Royal Academy of Engineering report on the sustainability of biofuels.

Background and impact on aviation sector

Biofuels are fuels produced from biomass. The two most common types of biofuels are bioethanol[22] and biodiesel[23]. Biofuels have commonly been distinguished by the type of feedstock from which they are produced as follows:

- **First generation biofuels**: Biofuels produced from food or animal feed crops. As reflected in workshop discussions, there is a clear and ongoing move in both the UK and EU away from the use of first generation of biofuels in aviation to those produced from waste streams.
- **Second generation biofuels**: Biofuels derived from dedicated energy crops, agricultural residues, forest and sawmill residues, wood wastes and other waste materials. In 2017, 57% of biofuel supplied in the UK is produced from second generation biofuels.[24]
- **Third generation biofuels**: Biodiesel produced from microalgae through conventional transesterification or hydro-treatment of algal oil.

Following a decade of steady growth, biofuel production fell by 5% in 2020 due to the overall decline in transport energy demand during the Covid-19 pandemic.[25] Nevertheless, they remained by far the largest contributor of renewable energy to the transport sector and some estimate that by 2050, as much as one-third of all transportation fuel could come from biofuels, while others predict more modest increases.[26,27,28] Biofuels play a role not only in aviation but also shipping and heavy goods vehicles where there are few alternatives to fossil fuels. However, as discussed in this workshop, the general industry view is that biofuels will not be a major solution to replacing fossil fuels in aviation. This is supported by conclusions of a Royal Academy of Engineering study of biofuels which found that industry would be reluctant to use biofuels unless government regulation enforced it.[29]

Wider system impacts

What are the potential impacts of this fuel on the transport system?	Aviation may face competition from shipping and heavy goods vehicles (HGVs) which also have few options for low-carbon fuels compared to passenger road transport. Analyses of the future energy system suggest that shipping and HGVs should be considered a priority for the development and use of biofuels over aviation, as aviation is considered to have more low/zero-carbon fuel options that HGVs and shipping.
What are the potential impacts of this fuel on the environment?	So-called 'first generation' biofuels (produced from dedicated food or energy crops) have complex environmental footprints due to links with deforestation, soil degradation and the greater potential carbon storage capacity of land without the harvesting of biomass. While so-called 'second generation' biofuels produced from wastes and residues do not necessarily share these properties, they still require full life-cycle assessment, monitoring and verification systems to provide assurance they are low-carbon and to protect against wider environmental impacts. The long-range transport of imported feedstocks for biofuels leads to additional GHG and other emissions, particularly those from shipping, including sulphur dioxide (SO_2), NOx and particulate matter. For example, transport of feedstocks or biofuels over a distance of 10,000 km can contribute 7% to 38% to the total carbon footprint of biofuels.[30,31]

Opportunities and risks

How might international factors (economic, infrastructural, metrics) influence the utility of this fuel?	**Competition with other sectors and applications** Biomass is already a subject of competition from a range of applications that are expected to increase in the future. This includes electricity and heat generation, which represent a more efficient use of biomass than its conversion to liquid transport fuels. In the transport sector, shipping and HGVs will also compete with aviation for liquid biofuels. **The politics of waste** The form and location of the waste used as a feedstock also needs to be considered. What is and what is not considered waste varies depending on economic, social and cultural contexts. If we are to use waste for biofuels, supply chain issues, questions of waste ownership, where it would be found and its availability all need to be considered. Such factors may impact the security and predictability of the supply chain and therefore fuel availability.

Fuel analysis: E-fuels and Synfuels

Background and impact on aviation sector

E-fuels and synfuels, otherwise referred to as 'sustainable aviation fuels' (SAFs), are hydrocarbon fuels which are synthesised from CO_2 and hydrogen gas feedstocks, so can be made low-carbon through the use of captured CO_2 and low-carbon hydrogen.[32] They are very similar in their chemistry to traditional fossil jet fuels. These are fuels produced for aviation by a process called "power to liquid" where hydrogen is combined with CO_2 to produce a fuel that can be used alone or blended with kerosene to power aircraft. These fuels are currently more costly than traditional jet fuels due to a combination of feedstock availability, development of production technologies and supply chains. This currently is limiting uptake by airlines.

These fuels have the benefit that they can be used in existing aircraft (so-called 'drop-in' fuels) so there would not be a need to replace existing aircraft and associated infrastructure. Since 2016 over 370,000 flights have used 'SAFs' in blended form with kerosene since 2016 and more than 45 airlines have now used them.[33] In 2021 the US government announced an ambition to produce 3 billion gallons of 'SAF' that has the potential to reduce US aviation emissions by 20% by 2030.[34] The EU have committed to 63% of aviation fuels supplied to EU airports being 'SAF's by 2050.[35]

Workshop participants stressed that these fuels are currently only being considered as transition fuels from fossil fuel powered aviation to liquid hydrogen, because they only reduce carbon emissions over the lifecycle of the fuel by a maximum of 80% compared to traditional jet fuels. The fact that they are being viewed as a transition fuel is advantageous to airlines not currently operating a hydrogen fleet. However, there are technology gaps that need to be considered if e-fuels and synfuels are to act as a 'steppingstone fuel'.

Wider system impacts

What are the potential impacts of this fuel on the energy system?	As e-fuels and synfuels are fuels that require hydrogen for their production, they share similar potential impacts on the energy system. If **green hydrogen** is used as a feedstock, there is a requirement for: – significant amounts of low carbon electricity for its production – a significant uplift in UK grid generation – supplies of fresh water and critical raw materials, such as precious metals, for the electrolysers needed in green hydrogen production If **blue hydrogen** is used as a feedstock, there is a requirement for the resultant CO_2 to be captured and stored by CCS technologies, which requires growth commensurate with the growth in use of blue hydrogen.
What are the potential impacts of this fuel on the transport system?	E-fuels and synfuels can be used as a 'drop-in' fuel in existing aircraft so existing fleets would not need to be replaced.
What are the potential impacts of this fuel on the environment?	Using e-fuels and synfuels can result in the reduction of up to 80% in carbon emissions over the lifecycle of the fuel compared to traditional jet fuels that they replace over the lifetime of the fuel, depending on the sustainability of the feedstock, production method and supply chain.[36]

Opportunities and risks

Risks associated with SAFs	Largescale capital investment is required to develop e-fuel and synfuel supply chains, and they are exclusively applicable to the aviation sector. This may hinder development as they may be out developed by other fuels which have cross-sector applications.

Workshop conclusions

Aviation is a critical sector of the economy which must be decarbonised as part of the wider transition to net zero. Discussions in this workshop demonstrated that decarbonising aviation will require transformational change, including: new enabling infrastructure, fuel supply chains, safety cases, new skills for engineers throughout the supply chain and operations, policy and regulatory frameworks, and business models.

Workshop discussions concluded that no one alternative aviation fuel will be a 'silver bullet' and it was not yet foreseen that any low-carbon fuel would achieve the dominance that fossil fuel-based flight has achieved previously. The transformation will also be significantly dependent on the nature of the transformations occurring in the wider energy and transport systems, as well as the physical, economic and environmental limitations that impact the availability and cost of fuels.

For alternative low/zero-carbon fuel options, workshop discussions raised some very significant implications for wider energy, transport and environmental systems and supply chains.

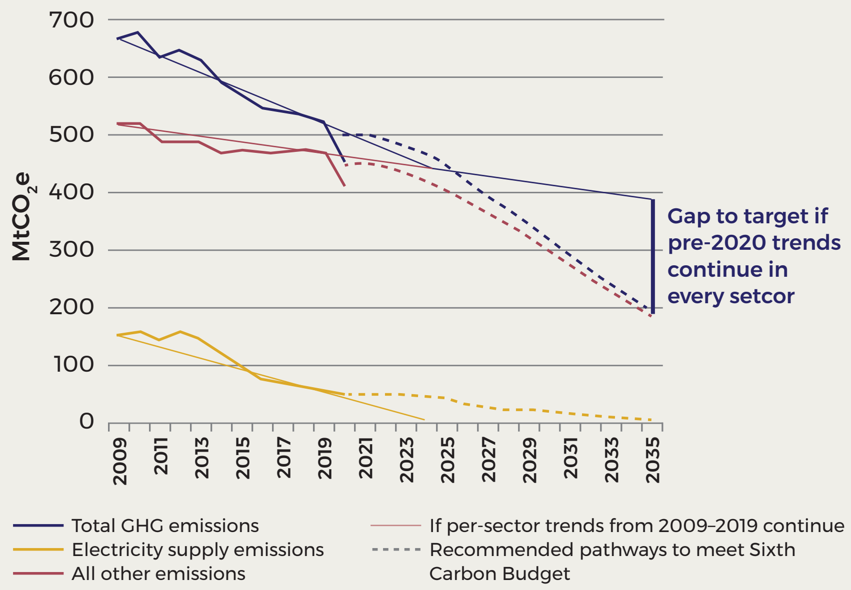
The significant demands which would be placed on these systems to power aviation at its current scale must be carefully considered, including as potential limiting factors.

While this workshop did not provide a roadmap to a carbon-free aviation sector, discussions did emphasise to policymakers and industry stakeholders setting out to decarbonise the sector that they will have to consider not just the advantages and disadvantages of different low/zero-carbon fuels options at the point of use, but the wider energy, transport and environmental system impacts of these fuels and the reciprocal impacts of these systems on alternative fuels.

Annex A
Workshop attendee list

Professor Iain Gray (Chair) | Cranfield University
Darryl Abelscroft | Department for Transport
Dr Jen Baxter | Protium Wales
Graham Beardwell | British Aviation Group
David Beare | Mott Macdonald
Philip Blagden | Civil Aviation Authority
Graham Bolton | British Aviation Group
Professor Harriet Bulkeley | Durham University
Andrew Clifton | Rolls Royce
Professor Serena Cussen | The University of Sheffield
Michael Duggan | Department for Business, Energy and Industrial Strategy
Annabel Estlin | Department for Transport
Paul Feely | BAE Systems
Dr Clive Ford | Department for Transport
Matt Finch | Transport & Environment
Abhilasha Fullonton | University of Manchester
Professor Stefan Gossling | Linneaus University, School of Business
Professor Mark Jolly | Cranfield University
Professor Roger Kemp | Lancaster University
Michael Laski | Connected Places Catapult
Angela Lynch | Civil Aviation Authority
Geoff Maynard | Royal Aeronautical Society
Ian McCluskey | Institute of Gas Engineers and Managers
Dervilla Mitchell | Arup
James Musisi | Royal Society
Professor Ian Poll | Cranfield University
Professor Bill Rutherford | Imperial College London
Professor Nilay Shah | Imperial College London
Professor Sarah Sharples | Department for Transport
Richard Toomer | Royal Aeronautical Society
Dr Zia Wadud | University of Leeds
Lisamarie Wood | Department for Transport
Dr Jem Woods | Imperial College London
Professor Graham Wren | University of Strathclyde

Annex B
The UK context: where are we on the road to net zero?

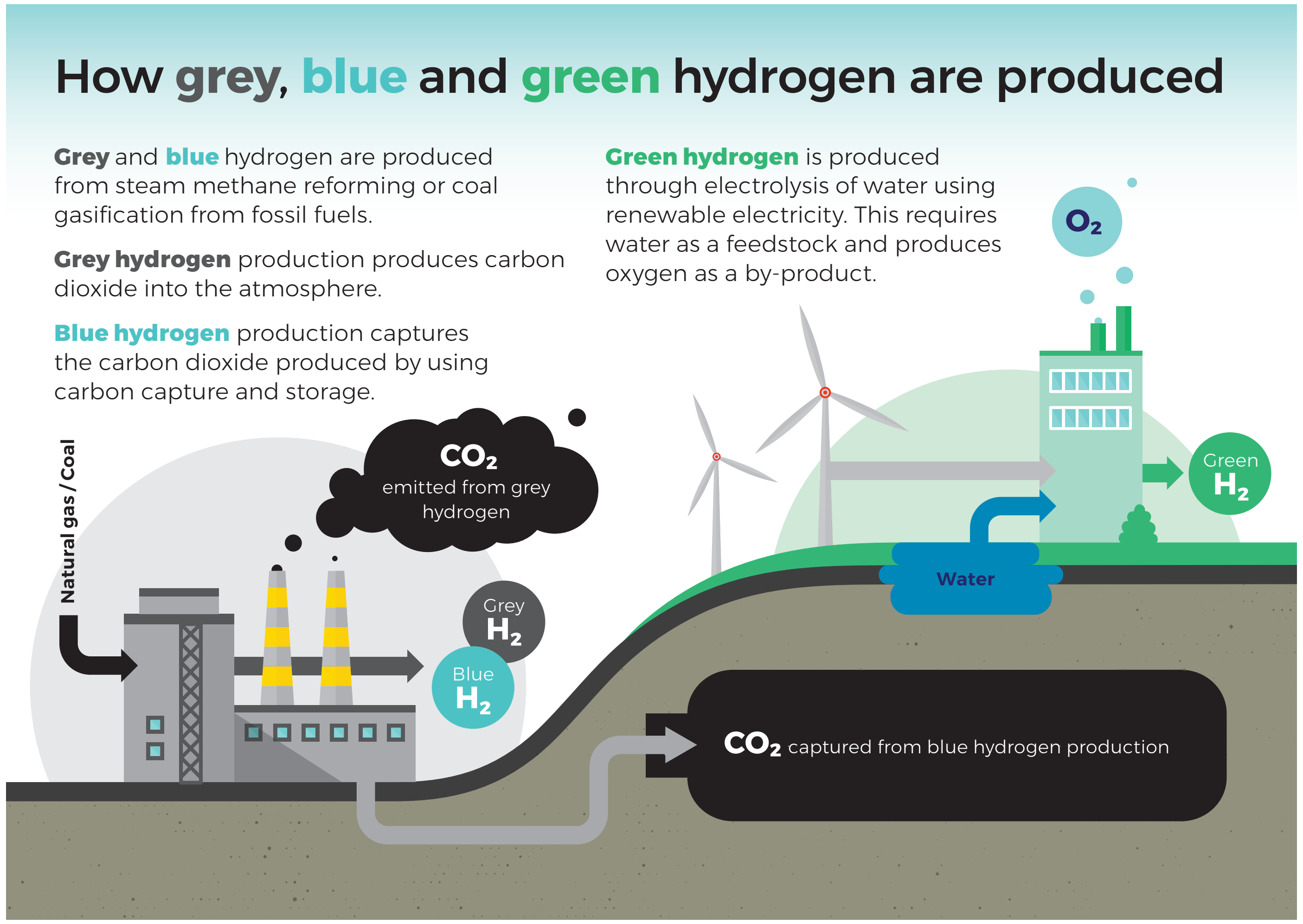


CCC: Progress in reducing emissions, 2021 report to parliament. Figure 2.3.

The UK has committed to reaching net zero greenhouse gas emissions by 2050, with interim targets of 68% reduction (compared to 1990 emissions) by 2030 and 75% by 2035. The 2035 target, formally called the Sixth Carbon Budget, is the first in which emissions from international aviation and shipping are included.[31]

Overall, while the UK has been relatively successful at reducing emissions compared to similar nations, the UK is significantly behind schedule of what is demanded by the Paris Agreement and the existential risks associated with climate change. Policies to which the UK government is committed are projected by the Climate Change Committee to fail to reach its net zero target, creating a 'policy gap'.

Annex C
Infographic on different hydrogen production methods



How grey, blue and green hydrogen are produced

Grey and **blue** hydrogen are produced from steam methane reforming or coal gasification from fossil fuels.

Grey hydrogen production produces carbon dioxide into the atmosphere.

Blue hydrogen production captures the carbon dioxide produced by using carbon capture and storage.

Green hydrogen is produced through electrolysis of water using renewable electricity. This requires water as a feedstock and produces oxygen as a by-product.

References

1 See **Annex B** for The UK context: where are we on the road to net zero?

2 See **Annex B** for the broader UK context: where are we on the road to net zero

3 Climate Change and Aviation, POST, 2021

4 The Sixth Carbon Budget: Aviation, Climate Change Committee, 2020

5 The Sixth Carbon Budget: Aviation, Climate Change Committee, 2020

6 The Sixth Carbon Budget: Aviation, Climate Change Committee, 2020

7 UK Aviation Forecasts, Department for Transport, 2017

8 The Sixth Carbon Budget: Aviation, Climate Change Committee, 2020

9 Climate change and flying: what share of global CO_2 emissions come from aviation, Ritchie, 2020

10 The global scale, distribution and growth of aviation: Implications for climate change, Gössling and Humpe, 2020

11 'Ghost flights' are those flown with no passengers or fewer than 10% of its passenger capacity. This is linked to landing slot use rules among other factors. More information: https://questions-statements.parliament.uk/written-questions/detail/2022-02-07/119801

12 Flaring Emissions, IEA, 2021

13 Assessment of Options to Reduce Emissions from Fossil Fuel Production and Fugitive Emissions, The Climate Change Committee, 2019

14 See **Annex A** for a full list of workshop attendees

15 Waypoint 2050, Air Transport Action Group, 2021

16 Government-backed liquid hydrogen plane paves way for zero emission flight, HM Government, 2021

17 Available energy per unit mass of the substance, typically expressed in watt-hours per kilogram (Wh/kg), or Megajoules per kilogram (MJ/kg)

18 The range shown above is deduced from the four exploratory scenarios in the Sixth Carbon Budget. In the recommended scenario, "Balanced Net Zero Pathway", 16 $MtCO_2$ from blue hydrogen production is estimated to be captured by CCS in 2050

19 Sixth Carbon Budget, The Climate Change Committee, 2020

20 Sixth Carbon Budget, The Climate Change Committee, 2020

21 Hydrogen-powered aviation, Clean Sky 2, 2020

22 An alcohol-based biofuel, typically produced from starch and sugar crops, such as wheat, corn, barley and sugar beet or cane, and blended with petrol for use in motor vehicles

23 An oil-based biofuel, typically produced from vegetable fats, such as rapeseed, sunflower seed, soya bean and palm oil, and blended with conventional diesel for use in motor vehicles

24 Advanced drop-in biofuels: UK production capacity outlook to 2030, HM Government Department for Transport, 2017

25 Renewable 2021: Global Status Report, REN21, 2021

26 Biofuels is the long run global energy supply mix for transportation, Timilsina, 2014

27 Technology Roadmap: Biofuels for Transport, International Energy Agency, 2011

28 A reassessment of global bioenergy potential in 2050, Searle and Malins, 2014

29 Sustainability of liquid biofuels, Royal Academy of Engineering, 2017

30 The BioGrace GHG calculation tool, BioGrace, 2015

31 Environmental life-cycle assessment of rapeseed-based biodiesel: Alternative cultivation systems and locations, Malça et al, 2014

32 Feedstocks include cooking oil, non-palm waste oils, packaging, paper, textiles and food scraps

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