BAAN/W2/5

TOWN AND COUNTRY PLANNING ACT 1990

Appeal by Bristol Airport Limited concerning land at North Side Road, Felton, Bristol, BS48 3DY

DEVELOPMENT OF BRISTOL AIRPORT TO ACCOMMODATE 12 MILLION PASSENGERS PER ANNUM

Appeal Reference APP/D0121/W/20/3259234

SUPPLEMENTARY PROOF OF EVIDENCE

of

Finlay Asher (MEng)

Founder at Green Sky Thinking

20 AUGUST 2021

CONTENTS

Appendices to BAAN/W2/5

1. Introduction

1.1. This is my supplementary proof of evidence addressing the following:

1. UK Department for Transport, July 2021: “Decarbonising Transport: A Better, Greener Britain” [**CD 9.134**] (“**Decarbonising Transport**”);
2. UK Department for Transport, July 2021: “Jet Zero Consultation: A consultation on our strategy for net zero aviation” [**CD 9.135**] (“**the Jet Zero Consultation**”);
3. UK Department for Transport, July 2021: “Jet Zero Consultation: Evidence and Analysis” [**CD 9.136**].
4. UK Department for Transport, July 2021: “Sustainable aviation fuels mandate: “A consultation on reducing the greenhouse gas emissions of aviation fuels in the UK” [**INQ/040**].
5. UK Department for Transport, Aug 2021: “Response dated 13 August 2021 to NSC letter regarding Aviation Decarbonisation” [**INQ/042**]
6. UK Department for Business, Energy & Industrial Strategy, Aug 2021: “UK Hydrogen Strategy” [**INQ/043**]

1.2. This supplementary evidence should be read together with my proof of evidence [**BAAN/W2/1**] and my rebuttal [**BAAN/W2/4**]. I can confirm that these documents do not cause me to withdraw any of that evidence, apart from noting that the Sustainable Aviation Fuel mandate consultation, to which I referred in para 7.5.2 of my main proof was published on 23 July 2021.

1.3. I have seen the supplementary proof of evidence of Sam Hunter Jones [**BAAN/W3/4**] and understand from his evidence that Decarbonising Transport and the Jet Zero Consultation do not alter the planning framework for the assessment of airport expansion proposals or change the central relevance of the Net Zero target and the Climate Change Committee’s analysis to the inquiry.

1.4. Except where I indicate to the contrary, the facts and matters contained in this proof of evidence are within my own knowledge. Where facts and matters are not within my own knowledge, I have identified my sources of information or belief.

2. Summary

2.1. In para 1.1 of the Jet Zero Evidence and Analysis document [**CD 9.136**] the Department for Transport ("**DfT**") states: "*many of the technologies needed to achieve net zero aviation are in the early stages of development and there is significant uncertainty regarding the expected cost, availability and uptake of these technologies over the coming decades*." I agree. Uncertainty is the absolute watchword of "sustainable" aviation. This is why the CCC has advised (and I agree) that demand management is crucial to achieving a Balanced Net Zero Pathway [**CD 9.66** pgs 11 and 21].

2.2. Decarbonising Transport [**CD 9.134**] emphasises the "*wide range of uncertainty*" around the DfT projections and states: "*Over time we will continue to develop and refine the range of policies and proposals set out in this plan to ensure that the transport sector fulfils its contribution to our legally binding climate targets.*" (pg. 44)

2.3. As I point out in paras 2.2-2.4 of my main proof of evidence, there is much rhetoric around the false hope that technological innovation alone will lead to decarbonisation. The Government's Decarbonising Transport document and the Jet Zero Consultation, while expressing high ambition for technology and thereby being very reliant on innovation, fully recognise the uncertainty around that approach and the need to review the framework for aviation decarbonisation within the next five years, as suggested in para 3.43 of the Jet Zero Consultation [**CD 9.135**].

2.4. This is presumably why neither Decarbonising Transport nor the Jet Zero Consultation rule out demand management when progress is reviewed. I set out below the reasons why I consider it highly likely that demand management will be required, as some of the suggested approaches in the Jet Zero consultation are highly aspirational, not evidence-based, and are in my view extremely likely to either directly require or indirectly result in demand management as a consequence of their application.

2.5. I also agree with the evidence of Sam Hunter Jones that the proposals in the Jet Zero Consultation, which are in turn referred to in Decarbonising Transport, are overtly based on "aspirational" scenarios rather than the "feasible" pathway informing the CCC's advice [**BAAN/W3/5** paras 3.6 and 3.9]. It should be remembered that the CCC's Balanced Net Zero pathway itself assumes that technological progress (sometimes ambitious progress) will be achieved. This is another reason why I consider it highly likely that demand management will soon be required.

2.6. I refer in paras 5.5 and 6.13 of my main proof to statements and publications from the Chief Technology Officer of Airbus and the Chief Executive Officers of Airbus and Boeing, showing that they do not consider that either electric or hydrogen aircraft will be available by 2050 for the types of aircraft for which Bristol Airport is predominantly configured. While the Jet Zero consultation is designed to boost ambition and accelerate technological development, the obvious uncertainty about the timeline is whether that could succeed in bringing these developments forward, at scale, before 2050.

2.7. Given that Decarbonising Transport, the Jet Zero Consultation and the Jet Zero Evidence and Analysis documents all acknowledge the uncertainties in this area, they cannot safely be relied on as justifying BAL's airport expansion plans.

2.8. The Jet Zero Consultation proposes to consult on a target for UK domestic aviation to reach net zero by 2040 and contains ambition to scale-up the use of hydrogen- or battery-electric "zero emissions" aircraft. It is important to note that combustion engines burning hydrogen or alternative jet fuels such as biofuel or synthetic e-fuel are not zero emissions. Therefore, due to the adverse energy density (volume and mass) of hydrogen and batteries – these proposals would rely on aircraft with severely restricted payload and range capability vs. conventional aircraft operated by airlines today. This would have a number of significant consequences for infrastructure design, as future airports would likely require:

2.8.1. different airline operations due to significant differences in aircraft capability (speed, range, payload), aircraft changeover times, and aircraft maintenance requirements;

2.8.2. different number of flight movements (number of aircraft taking-off/landing) for an equivalent number of passengers using the airport;

2.8.3. different aircraft gate sizing and layout, due to substantially different aircraft shapes, sizes, and/or passenger numbers;

2.8.4. different airport layout and configuration due to changes to the flow of passengers through the airport to different sized and spaced gates with different passenger numbers and timings at each one

2.8.5. different fuelling and/or charging infrastructure for aircraft

2.9. All of these points add further doubt and uncertainty to the suitability of the expansion plans currently proposed by BAL, as while BAL mention these technologies at several points, they do not address how their infrastructure proposal aligns with a significant uptake of such aircraft.

2.10. Finally, Decarbonising Transport and the Jet Zero Consultation propose the use of carbon pricing, alternative jet fuel mandates and greenhouse gas removals, all of which will substantially increase the cost of flying and thus limit aviation growth. While it is a point of semantics whether these are “direct” or “indirect” measures, the overall point for this appeal is that the Decarbonising Transport plan and the measures in the Jet Zero Consultation do not support the case for expansion of Bristol Airport.

3. The Jet Zero Consultation and Underlying Evidence

3.1. There are a number of areas where the Jet Zero Consultation [**CD 9.135**] and the Evidence and Analysis Document [**CD 9.136**] support the evidence in my main proof and rebuttal. I will set these out first. I will then go onto areas where I disagree with the approach suggested in the consultation – it is, of course, not surprising that there will be such areas, given it is a consultation document designed to elicit views.

<u>Areas Where the Jet Zero Consultation [**CD 9.135**] Supports My Evidence</u>

3.2. For ease, I will set these out in a table:

	Jet Zero Consultation	**My Evidence**
1.	<u>Alternative Jet Fuel</u>	
a.	Para 3.16: "*currently the costs of SAF are high and uncertain, ranging from 2-3 times compared to the price of the fossil counterfactual, and potentially up to 8 times more for certain technology pathways*"	This acknowledges the current high costs of alternative jet fuels, as per para 7.3.9 in my main proof.
b.	Para 3.19: "*there is currently no comprehensive global regulatory standard for SAF sustainability*	I addressed this in the context of CORSIA in para 8.3.7 of my main proof. CORSIA is the only existing policy mechanism for international aviation emissions, which account for the majority of aviation emissions with respect to Bristol Airport. CORSIA was developed by the UN ICAO Council. Their rules only require that any alternative jet fuels used deliver a minimum emission reduction of 10% compared to kerosene. Other sustainability criteria such as criteria on water rights, biodiversity and food security, were rejected by

		the ICAO Council, and only criteria linked to GHG reduction remains. The ICAO Council have also approved the crediting of 'lower carbon aviation fuel'. This is fossil kerosene produced in a manner which is supposed to deliver emission savings relative to the average measures of producing kerosene, but it is still a fossil fuel.
2.	Zero Emissions Aircraft	
a.	Para 3.28: "*For zero emission aircraft to be able to operate in the UK, we need to ensure that our airports and airfields have the infrastructure to fuel, take-off and land those planes*"	This acknowledges that both hydrogen and electric planes would require modification to airport infrastructure for compatibility with these new and novel aircraft configurations, as in para 5.6, 6.7 and 9.2.1 of my main proof
3.	Market Measures and Removals	
a.	Para 3.35: "*By pricing CO2 emissions, market-based measures can drive cost-effective and technology-agnostic emissions reductions, making system efficiencies, SAF and zero emission flight more economically attractive, and influencing the travel choices of consumers. They also implement the 'polluter pays' principle – that those who engage in activity that has an environmental impact should bear the cost of that impact*."	This is a **very important point** with which I strongly agree – proper carbon pricing is a **demand management tool**, and as I set out at para 9.1(13) on pg 45 of my main proof, the "*most effective way to reduce emissions is to limit air traffic demand and growth by limiting airport capacity and applying a high price to aviation emissions, via an emissions-based levy or increased aviation fuel taxation.*"

	Policy Proposal (pg. 37): "*We will strengthen carbon pricing for aviation to ensure we continue to apply the 'polluter pays' principle and consider incentives for greenhouse gas removal methods.*"	Currently, the price of CO2 emissions does not do this – see para 8.3.6 of my main proof of evidence.
b.	Para 3.37: "*we expect schemes that rely on offsetting through avoided emissions to shift to employing greenhouse gas removal methods. These take an equivalent amount of CO2 out of the atmosphere in a verifiable and additional manner*".	This admits offsetting is time-limited and that it is difficult to verify and prove "additionality" i.e., that the emissions reductions would not have taken place anyway. Greenhouse gas removals (GGR) do not have these difficulties, which is why at para 9.1(13) on pg 45 of my main proof I refer to the CCC's advice that scalable GGR technology will be required. There is, however, difficulty with GGR, which the Jet Zero consultation acknowledges. This includes issues of technological uncertainty, very high resource consumption (biomass, renewable energy, water, land, and even fossil fuels), competition for resource with other applications, and very high costs e.g. £/tCO2.
c.	The box on "Greenhouse gas removal (GGR) and aviation" (pg. 36): "*GGRs are not yet implemented at commercial scale, either in the UK or globally, and forecasts of costs and scale-up potential are highly uncertain.*"	I agree, and in para 9.1(13) on pg 45 of my main proof, and in Section 8, I set out that the price for such removals is in the multiples of £100 per tCO2.

4.	Influencing Customers	
a.	Para 3.44: "*We expect the approach set out in this draft strategy could impact demand for aviation indirectly. Where new fuels and technologies are more expensive than their fossil-fuel equivalents, and where the cost of CO2 emissions are correctly priced into business models, we expect, as with any price rise, a moderation of demand growth*.".	This strongly suggests that the Government is considering demand reduction measures, although they are indirect: demand/growth will be indirectly reduced by the increased price of their carbon abatement options. In my main proof I make the point at para 6.10 that hydrogen aircraft will be more expensive, at paras 7.3.9, 7.4.2 and 7.6 that new fuels will be more expensive, and at para 8.4 that negative emissions technologies (GGRs) will increase the costs of aviation emissions and thus "*undermine the case for airport expansion*".

<u>Areas Where the Jet Zero "Evidence and Analysis" [**CD 9.136**] Supports My Evidence</u>

3.3. There are a considerable number of areas where the Evidence and Analysis document supports my evidence:

	Jet Zero Evidence and Analysis	**My Evidence**
1.	<u>Alternative Jet Fuel</u>	
a.	Para 2.5: "*Current SAF use in UK aviation is negligible and there is significant uncertainty around the availability and cost of SAF in the future.*" "*While certain SAF production pathways from waste oils and fatty acids are already commercial, the vast majority of SAF technologies have been*	This acknowledges the uncertainty around future availability and costs, and that Hydroprocessed Esters and Fatty Acids (HEFA), is the only commercially scaled pathway, yet has a limited feedstock, is susceptible to supply fraud, and is already being fully-utilised by the

	certified and proven at demonstration stage but have yet to be rolled out at commercial scale.”	road transport sector as per para 7.3.5 in my main proof.
b.	Para 2.6: “*not all SAF is necessarily sustainable, for example, due to the emissions, or direct and indirect land use change potentially arising from the production, cultivation and transportation of the feedstocks.*”	This acknowledges that not everything called “Sustainable Aviation Fuel” is actually sustainable, a point I make in detail at paras 7.3.2-7.3.5 of my main proof and with regards to CORSIA eligible fuels (the only standard for international aviation) in para 8.3.7 of my main proof.
c.	Para 2.7: “*There are likely to be competing demands for these feedstocks from other sectors, so high uptake rates in aviation are likely to be as dependent on cross-economy prioritisation decisions as on the total availability and use of feedstocks*”.	This acknowledges competing demands and need for use prioritisation, per para 7.3.3 and 7.3.5 of my main proof.
d.	Para 2.8: “*The ICCT has found that used cooking oil-derived HEFA is currently the most cost-effective SAF pathway, at an abatement cost of €200/tCO2e (or around £170/tCO2e), followed by gasification of municipal solid waste and lignocellulosic feedstocks, at around €400-500/tCO2e (or £350-430/tCO2e).*”	Ignoring the HEFA pathway which cannot be scaled and is already more effectively utilised by road transport, the next most cost-effective pathway costs £350-430/tCO2e which is significantly higher than the carbon price assumed in the modelled scenarios (discussed below) and fits with my conclusion in para 7.6 of my main proof that *“Even where they are used, they will be more expensive than conventional jet fuel and will*

		undermine the case for airport expansion."
e.	Para 3.11: "*analysis suggests that use of biomass would need to be prioritised in aviation over other sectors in order to support this level of SAF uptake*".	This admits that even for a 30% use of SAF, it would divert limited biomass from other sectors. This is a <u>very important point</u>, which I make in detail at para 7.3.3 and 7.3.5 of my main proof.
f.	Para 3.14: "*the costs of SAF will need to fall significantly, or the cost of kerosene (inclusive of a carbon price) will need to increase significantly"* *"Achieving such a high proportion of SAF would require a high share of more advanced SAF pathways in particular (such as power-to-liquids), which are currently much more expensive than others."*	This admits the cost of fossil jet fuel needs to increase unless the cost of SAF drops significantly. This reduction in cost will only be possible eventually through economies of scale which can only be achieved by paying for SAF earlier while at higher prices. So, this demonstrates the overall cost of fuel will need to significantly increase, particularly in the near-term (see para 7.3.9 and 7.4.2 of my main proof). Power-to-liquids are currently estimated at eight times the price of others, per para 7.3.9 and 7.4.2 of my main proof.
g.	Para 3.14 "*the lack of secure and sustainable supply chains for feedstocks, competition for feedstocks with other sectors (such as biomass used in road fuels)*".	I refer in para 7.3.5 of my main proof to the concerns with illicit markets, and the fact that scaling HEFA aviation biofuels will likely only divert fuel already being used by road transport. Scaling non-HEFA aviation biofuels will be competing with very large Bioenergy Carbon

		Capture and Storage (BECCS) requirements as I detail in para 7.3.3 of my main proof.
2.	<u>Zero Emissions Aircraft</u>	
a.	Para 2.11: "*the timelines for zero emission flight are still uncertain*".	I address the uncertain timelines in my main proof in paras 5.5-5.6 concerning electric flight and para 6.13 concerning hydrogen flight. These paragraphs show that airline industry insiders do not consider that either electric or hydrogen aircraft will be available by 2050 for the types of aircraft for which Bristol Airport is predominantly configured. While the Jet Zero consultation is designed to boost ambition and accelerate technological development, the obvious uncertainty about the timeline is whether that could succeed to bring these developments forward, at scale, before 2050.
b.	Para 2.11: "*There is currently limited available evidence on the costs of these technologies*". Abatement costs are quoted as £30-55/tCO2e for regional aircraft, £110-250/tCO2e for long-range aircraft, or £195/tCO2 in general. "*These costs assume hydrogen will be widely adopted and the*	I address the costs of hydrogen in paras 6.10 of my main proof, citing similar figures to those in the Evidence document (I site costs in $). Regarding infrastructure: I detail why airport infrastructure and airline operations would require significant re-configuration to support these hydrogen aircraft in para 6.7 of my main proof and in

	necessary infrastructure and fuel supply systems will be available. Any substantial difference in capex costs of hydrogen aircraft or longer refuelling times would increase these abatement cost estimates. In the initial years, as the technology first begins rolling out on commercial aircraft, it is likely that the abatement costs will be considerably higher than these estimates."	para 2.8 above of this supplementary proof. It should therefore be concluded that near-term (next few decades) costs will be even higher again than the abatement costs quoted here. These indicate high abatement costs by 2050, and even higher costs earlier on – far higher costs than the carbon pricing levels assumed in the scenario models.
c.	Para 3.12: even assuming "*zero emission aircraft enter the fleet in 2035, these have a minimal impact on total emissions in 2050. This is because these only enter into service on the shortest routes*".	I address the fact that zero emission aircraft will only enter service on the shortest routes in paras 5.6 and 6.2 of my main proof; and their limited scope to decarbonise UK aviation emissions in para 5.7 and 6.2.
d.	Para 3.17: "*airport infrastructure (e.g. re-fuelling infrastructure for hydrogen and electricity supply for charging electric aircraft) will need a coordinated change to facilitate the use of new aircraft types, and airlines will need to be able to quickly incorporate new aircraft types into their fleets*."	This confirms that airport infrastructure and airline operations would require significant re-configuration to support these aircraft types, as per para 6.7 of my main proof and as per para 2.8 above of this supplementary proof.
e.	Para 3.18 "*Class 3 (150-250 seat) zero emission aircraft enter into service from 2040, at accelerated replacement rates. These aircraft still operate mainly on domestic and short-haul routes, meaning that although 53% of ATMs are zero*	This shows that, even assuming success of the highly ambitious intention to replace current aircraft with zero emissions aircraft, with 53% of flights made zero emission by 2050, there is a limited ability for hydrogen or battery-electric aircraft

	emission by 2050, only 34% of ATM-kms are zero emission."	to contribute significantly towards decarbonisation. If 34% of kms travelled are zero-emissions, this only results in 12.8% of emissions being reduced (Figure 11: Scenario 4). I address the limited ability of zero emissions aircraft to reduce emissions in paras 5.6, 5.7 and 6.2 of my main proof.
3.	Market Measures and Removals	
a.	Para 2.12: "*Airlines are likely to pass at least some of these costs on to consumers in the form of increased ticket prices and this may reduce demand for air travel*"	I agree and make the point in para 10.9 of my main proof that these increased costs of flying undermine the industry's expansion plans.
b.	Para 2.15 "*the first UK ETS auction took place on the 19th of May. The first auction fully cleared at a price of £43.99*".	This shows the UK ETS price is below even the 'central' carbon price used in the modelled scenarios (£70/tCO2 in 2021). This, along with the fact that UK ETS does not apply to most emissions due to airline free allowances, supports my conclusion in paras 8.1 and 8.4 of my main proof that the current carbon pricing schemes will not be effective in reducing emissions.
c.	Para 2.16: "*Future prices of CORSIA eligible emission units are also uncertain. In 2016, estimates for 2020 used in ICAO analysis ranged from $6/tCO2e to $20/tCO2e. However, these estimates are*	Exactly the same point applies – this shows that, even if much higher prices for CORSIA are adopted than have thus far been used in the pilot stage, the price is far below the 'central' carbon price used in the

	considerably higher than the prices of CORSIA eligible emission units in recent years".	modelled scenarios (£70/tCO2 in 2021). The same point applies about free emissions, and that this supports my point in para 8.3.6 and my conclusion in para 8.4 of my main proof of evidence.
4.	<u>Influencing Customers</u>	
a.	Para 1.1: "*many of the technologies needed to achieve net zero aviation are in the early stages of development and there is significant uncertainty regarding the expected cost, availability and uptake of these technologies over the coming decades*."	As I set out above, uncertainty is the absolute watchword of "sustainable" aviation. This is a theme that runs throughout my evidence.

<u>Non-CO2 Emissions</u>

3.4. I address non-CO2 emissions in particular in paras 3.4 – 3.5 and 7.5.1 in my main proof of evidence and section 5 of my rebuttal proof [BAAN/W2/4]. They are dealt with in Section 4 of the Jet Zero Consultation [**CD 9.135**]. First, this shows that, contrary to BAL's approach, non-CO2 emissions cannot be ignored.

3.5. Para 4.5 of the Jet Zero Consultation states: "*Many of the measures to improve efficiencies, rollout SAF, and accelerate zero emission flight are expected to have a positive impact on reducing non-CO2 impacts. Where there is evidence to the contrary, we will carefully consider the overall impact on the climate*." This indicates that the DfT recognises it will need to consider the fact fuel efficiency improvements may make non-CO2 emissions increase, as I set out in para 5.7 of my rebuttal proof, referring to the research by Klöwer et al that jet engine efficiency gains may be overcompensated by the greater non-CO2 effects they cause (see Appendix R2 to my rebuttal proof and Appendix S3 of this supplementary proof of evidence).

3.6. Para 4.5 also states: "*We will ensure that the latest scientific understanding of aviation non-CO2 impacts is used to inform our policy*." This indicates that, when setting the Jet Zero strategy after receipt of the consultation responses and then updating Decarbonising Transport in the next five years, the DfT will carefully consider both the estimate that non-CO2 cause approximately two thirds of aviation's total climate impact [**CD 9.60** pg. 2] and that these effects may be exacerbated by the technologies covered in the consultation.

4. Areas Where the Jet Zero Consultation is Unevidenced or Appears in Error

Alternative Jet Fuels – Stage of Development

4.1. Para 2.5 of the Jet Zero Consultation includes "sustainable aviation fuels" in the suggestion that "*many of the technologies we need to achieve Jet Zero are at an early stage of development or commercialisation*". That is not correct. Alternative jet fuels such as advanced biofuels have been in development for more than a decade, with promises of scale-up that have not materialised (per para 10.7.3 of my main proof).

4.2. The DfT's consultation "Sustainable aviation fuels mandate: A consultation on reducing the greenhouse gas emissions of aviation fuels in the UK", July 2021 (the SAF Consultation) [**INQ/040**] addresses the Government's "ambition to go further and faster and develop a strong SAF sector in the UK as quickly as possible" (para 4.21). But it immediately sounds two important notes of caution, both of which are evidence-based:

4.2.1. It states that "we acknowledge such a level of ambition may be achievable under certain circumstances but may be very optimistic at this stage" (para 4.21), and

4.2.2. " While acknowledging the urgency of climate change and the role SAF can play, we understand the implications of setting too high a target at this stage in the short term as it could encourage use of unsustainable feedstocks, either in the UK or replacing the fuel diverted to the UK. Should SAF not develop as quickly as expected and should penalties or buy-out be introduced (see paragraphs 6.3-6.6), there is also a risk that high, undeliverable targets could translate to high costs passed on to the aviation supply chain to cover the cost of those penalties or buy-out, without delivering additional fuel volumes or GHG emissions savings. We are keen not to set targets that would have to be revised down at a later stage should they prove unfeasible." (para 4.22)

4.3. This all suggests that the targets that will eventually be set by the SAF mandate consultation will be below the targets (e.g., 30% or 75% alternative jet fuels by 2050) assumed in the Jet Zero consultation scenarios.

Alternative Jet Fuels - Hydroprocessed Esters and Fatty Acids

4.4. A Rolls-Royce case study appears on page 28 of the consultation document: "*supported with a £16m government grant, Rolls-Royce have undertaken engine ground tests using 100% SAF*". I am aware of this project from the time when I was employed at Rolls-Royce and can confirm that these tests were using HEFA jet fuel from animal fat – a process which cannot be scaled sustainably to any significant quantity. I note that, even in the "High Ambition" and "Fast Industry development" scenarios in the SAF consultation, HEFA does not feature, as it is acknowledged that its "*availability in the long term will likely be limited by feedstock constraints*" (paras 4.7–4.8).

4.5. The SAF Consultation [**INQ/040**] recognises that HEFA is the only commercial SAF currently in production. Nevertheless, the DfT is consulting on the potential for HEFA use in SAF to be capped (paras 4.27-4.29), recognising (correctly) that HEFA is <u>not sustainable</u> at scale. As I state in para 7.3.5 of my main proof, the scaling-up of HEFA for aviation is likely to result in negative environmental impact because it could encourage fraudulent markets, and would incentivise the diversion of waste oils from existing uses in the road sector, where it is already being used to replace fossil fuel.

4.6. Para 4.8 of the SAF Consultation acknowledges that "Relying on this fuel could also divert used cooking oil (the feedstock primarily used to produce HEFA) away from the renewable diesel (HVO) production process. When plants increase the product slate of HEFA over HVO, their overall fuel yield decreases and production costs increase. This means pivoting this feedstock away from use in road transport at this stage will make economy-wide decarbonisation more expensive". This demonstrates that limited waste oil feedstocks are better utilised in the road transport sector on both an environmental and economic basis. Scaling aviation HEFA would only result in shifting of emissions savings from one sector to another, whilst reducing total emissions saved, and increasing tax payer costs.

4.7. It is worth pointing out that BAL acknowledges e.g., in para 3.7.5 of Matt Osund-Ireland's proof of evidence [BAL/6/2] that the proposed expansion of Bristol Airport should "not have a material impact on the government's ability to meet its carbon reduction targets". Given it is clear that scaling aviation HEFA would reduce emissions saving when considering the transport industry as a whole, and thus negatively impact the government's ability to meet its carbon reduction targets, it would not be right to grant permission for the expansion on the assumption that "sustainable" aviation fuels would make the climate change impact of the expansion acceptable.

4.8. It is also noted in para 4.30 of the SAF consultation that a limit on HEFA use would "accelerate the deployment of non-HEFA technologies, especially those least developed to date" which demonstrates a preference for aviation not to rely on HEFA and instead focusing on other, more-expensive and uncertain pathways. This undermines BAL's ability to rely on any significant quantities of alternative jet fuel in the near future, because the commercial development of these pathways is still uncertain, and even if developed, they would cause substantial additional costs to passengers and this would significantly undermine the planned growth.

<u>Alternative Jet Fuels – Emissions Reduction Potential</u>

4.9. In Annex A.10 it is stated that "We assume 100% CO2 emission savings for the aviation sector for these fuels" when referring to alternative jet fuels or "SAF". This is very misleading as many "low carbon fuels" may only reduce emissions by a small %. The UK SAF mandate consultation proposes a minimum threshold of 60% emissions reduction, and CORSIA eligible fuels only require an emissions reduction of 10% relative to fossil fuels [**INQ/040** pg. 37]. Even if using synthetic e-fuel, no fuel is zero emissions: they all produce CO2 emissions and non-CO2 emissions as I detail in para 7.5.1 of my main proof.

Fuel Efficiency Assumptions

4.10. Para 3.7 of the Jet Zero Consultation expects aircraft "fuel efficiency improvements of 1.5%-2% per annum". This assumption is very optimistic. All evidence points to fuel efficiency improvements slowing with time, as we have reached the stage of marginal gains with existing conventional tube-and-wing aircraft configurations, and more radical configurations would require development and certification timelines of 15 years or more, meaning they will not achieve significant fleet penetration prior to 2050. 1.5% per annum efficiency improvements are very optimistic, yet are presented in the Jet Zero consultation as the worst-case scenario.

4.11. In a recent ICAO report, their most optimistic scenario projected a long-term fuel efficiency of 1.37% per annum [**Appendix S1**, attached to this proof, pg. 18]. According to a recent review requested by ICAO using independent experts, targets deemed challenging were annual improvements of between 1.22 and 1.28 per cent [**Appendix S2**, attached to this proof, pg. 56]. This demonstrates that the range of efficiencies assumed within the scenarios used by the Jet Zero Consultation are overly optimistic and unlikely to be achieved – resulting in more stringent policy measures being required.

4.12. Para 2.3 of the Jet Zero Evidence and Analysis [**CD 9.136**] states that the CCC/ATA: "suggested that efficiency improvements such as these could reduce the fuel burn of aircraft coming into service in the mid-2040s by 40-50% compared to types entering service in the early 2000s. Over the period from 2017-2050 this translates to a fuel efficiency improvement of between 1.5 and 2.0% per annum". However, even if such a radical step-change in aircraft efficiency is achieved, such aircraft entering service in 2045 will only account for a tiny fraction of the fleet composition in 2050. The fleet will predominantly be composed of aircraft entering service in the 2020s and early 2030s, which will predominantly be aircraft designed and certified in the 2010s.

4.13. Para 2.3 of the Jet Zero Evidence and Analysis also states that "1960-2008 saw 1.5% annual fuel efficiency improvement on average" however, it is misguided to assume that this efficiency improvement will either continue at the same rate, or accelerate.

In fact, aircraft efficiency improvements are becoming more difficult to achieve each year. This is due to the marginal gains possible from continued incremental improvements to the current conventional "tube-and-wing" aircraft design. With a relatively constant aircraft design, the majority of the efficiency improvements have historically been achieved by the engines: improving thermal and propulsive efficiency.

4.14. Thermal efficiency can be improved by increasing the operating temperatures and pressures within the engine cores but these have already been highly optimised and further gains are very difficult. Propulsive efficiency can be improved by increasing the engine diameter but limits to the extent of diameter possible under the wings of current aircraft are already being reached.

4.15. The other issue with increasing engine diameter is that the aerodynamic efficiency improves, but the weight and drag increases, which cancels out the aerodynamic improvement. As such, the rate of improvement is more likely to slow with time unless airframe manufacturers switch to novel aircraft configurations (for example, aircraft where the engines are integrated into the structure of the airframe fuselage or wings), which they have so far been reluctant to do. My experience working in Rolls-Royce future programmes for 3 years, as well as chairing the Civil Aerospace Chief Engineer's 'highspots' for almost two years, is that both Airbus and Boeing are very reticent to develop a new aircraft configuration due to the large technical and economic risk, as well as the safety risk (which I address below). Development costs are huge, timescales are long (around 15 years), commercial success is uncertain, and there is the engineering risk of potential technical failures e.g., performance targets being missed and unforeseen reliability issues occurring.

4.16. The aviation industry is also very safety orientated, and that often results in a hesitancy to change their design too much because of the confidence of 50 years' experience of using the exact same, predictable, tested and safe design. It is not clear to me that the Jet Zero Consultation appreciates this. Instead, it assumes, very optimistically and without evidence, that an aspirational Government policy and a very small (comparatively) level of investment will overcome this strong safety-based hesitancy in the industry.

4.17. Furthermore, costs associated with the Covid-19 pandemic have slashed R&D budgets and pushed technology development back several years. I do consider that there are policy levers that could encourage airframe manufacturers to take the leap and accelerate technological developments – a high carbon or emissions price, properly in line with the polluter pays principle (i.e. not borne by the taxpayer) and applied in the near-term (i.e. the 2020s and 2030s). However, no plan for that yet exists in the UK or internationally. Even with high ambition, it will take time for the Government to influence the implementation of high carbon prices internationally.

4.18. In any event, it would in my experience take around 15 years to develop and certify a more novel aircraft configuration that is capable of another step-change in aircraft efficiency, even if the airframe manufacturers started working, with speed, determination and sufficient funding, now. It is therefore my estimation that we will not see such an aircraft certified, for the type and size of aircraft that predominantly operate from Bristol Airport, before 2035.

4.19. In that regard, it is concerning that a lot of funding appears to be going towards eye-catching hydrogen and battery-electric concepts for small aircraft but these are of very little use for decarbonising the predominant types of commercial aircraft which produce most aviation emissions. This is concerning because hydrogen, batteries and electrical systems do not scale well due to physical constraints and material properties. Both Airbus and Boeing acknowledge this, as per my main proof (paras 5.5 and 6.13).

4.20. Para 2.3 of the Jet Zero Evidence and Analysis [CD 9.136] also states that "The International Civil Aviation Organisation (ICAO) has set a goal of 2% annual fuel efficiency improvement through to 2050". However, ICAO's own report from 2019 details a "low" scenario of 0.57%, "moderate" of 0.96%, advanced of 1.16%, and "optimistic" of 1.5%/year [**Appendix S1**, pg. 17, Table 1]. Therefore, I consider the 'goal' to be unreasonably optimistic.

4.21. It is also well understood that higher aircraft/engine fuel efficiency causes contrails at higher ambient temperatures and over a larger range of flight altitudes such that "Aircraft with more efficient propulsion cause contrails more frequently" [**Appendix S3** to this proof, pg 1] (see also Appendix R2 to my rebuttal proof). This means that reductions in CO2 from a given flight, due to improved fuel efficiency, may be at least partly counteracted by the non-CO2 warming effect of contrails. Without assessing the effect of non-CO2 emissions, it would be uncertain whether the climate impact per passenger-mile had even reduced.

<u>Hidden Costs in the Jet Zero Scenarios</u>

4.22. Throughout the Jet Zero Consultation there is a pattern of disguising the actual cost increases, and thus the resulting demand reduction which will be caused by the approaches proposed (i.e., the increased fares which will necessarily result from the aircraft technology, aviation fuel and airline operation measures which the Jet Zero consultation promotes). The Jet Zero Evidence and Analysis document [**CD 9.136**] details all of the costs of the various options which they openly admit are very high e.g., in para 2.8 for alternative jet fuels or "SAF", para 2.11 for hydrogen aircraft, and para 2.20 for greenhouse gas removal (GGR). These emissions abatement costs are all in the multiples of £100/tCO2. This is far higher than ETS or CORSIA carbon offset prices (which do not even apply to most emissions), and far higher than the assumed carbon price that is used within the modelled scenarios and was taken from the Department for Business, Energy and Industrial Strategy (BEIS) (para 2.18 of Jet Zero Evidence and Analysis).

4.23. However, in A.3. of the Evidence Annex A [**CD 9.136** pg 21] the DfT states that its modelling "implicitly assumes that the cost of the measures (/tCO2e) are less than the carbon price assumed in each scenario". This carbon price is then applied <u>in isolation</u>, despite being far lower than the cost of the various abatement measures proposed (I have illustrated this in Fig. 1). Put simply, the options for decarbonisation proposed in the Jet Zero Consultation ("zero emissions" aircraft such as hydrogen; alternative jet fuel such as biofuel from waste and greenhouse gas removals such as BECCS or Direct Air Carbon Capture and Sequestration, DACCS) all cost more than the BEIS carbon prices used in the consultation (certainly prior to 2050). They also cost much more than current existing policies of the UK ETS and CORSIA (which in any event only apply to a limited set of emissions).

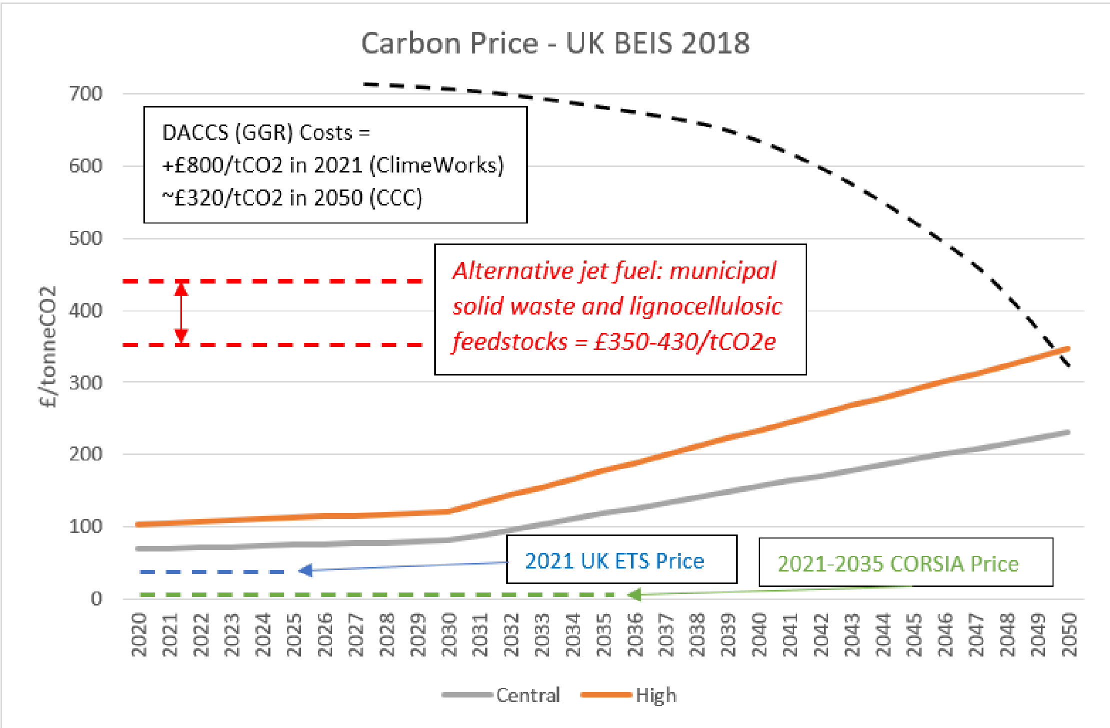


Figure 1: Comparison of UK BEIS Carbon Prices Modelled in Jet Zero Scenarios vs. UK ETS, CORSIA, and mitigation options such as alternative jet fuel produced from waste and Direct Air Carbon Capture and Storage (DACCS)

4.24. The DfT also claims that a changing carbon price has an almost insignificant impact on air traffic demand in the modelled results. This is unrealistic, and means that the high costs discussed in the text of the Evidence document do not materialise in the scenarios in either the Evidence document or the Consultation document – a major flaw in the models.

4.25. There are further obvious flaws in the model assumptions:

4.25.1. As can be seen on pages 13 and 14 of the Jet Zero Consultation [**CB 9.135**] in the figures for Scenario 1 and Scenario 2, the major difference between

Scenario 1 “Continuation of current trends” and Scenario 2 “High ambition” is that “Fuel efficiency improvements” change from delivering 14 $MtCO_2$ to 21 $MtCO_2$ in 2050 – an increased reduction of 50% more. The model is flawed, as the carbon price has remained constant, yet this efficiency improvement would reduce the cost of flying (without an increased emissions price), and this would lead to a change in demand – i.e., air miles and total emissions would increase (this is known as a “rebound effect”). This ‘rebound effect’ does not appear to be modelled (despite the claim in claim made in Annex A.9), as demand appears to remain constant.

4.25.2. Scenario 2 and 3 also have different levels of SAF use, as Scenario 3 models “High Ambition with a breakthrough on SAF” [**CB 9.135** pg 14]. However, such a high SAF uptake would also have greatly increased the cost of flying (as SAF would at best be at least twice the cost of fossil fuel and likely in the range of 3-8 times the cost) and reduced the total demand. However, when the scenarios switch from low- to medium- to high- uptake of “SAF”, this does not affect the modelled air traffic demand – so this effect does not appear to be modelled either.

4.25.3. All scenarios require “Abatement outside aviation sector” – it would be expected that this value would also impact the demand for flying due to the high cost of Greenhouse Gas Removal technologies – again this does not appear to be modelled.

<u>“Zero” Emission Flight</u>

4.26. Para 3.21 of the Jet Zero Consultation claims: “Zero emission flight technologies such as hydrogen-electric and battery-electric aircraft have already been demonstrated in the UK. Continued investment in these technologies could support a significant reduction in global aviation emissions”. This is misleading, as the demonstrations have been of very small aircraft with very limited range and payload capability. As yet nothing has been demonstrated that would give any confidence that these technologies could be commercialised soon or could be used for the longer-range flights with commercial airline size aircraft that are responsible for the majority of the UK's and Bristol Airport's aviation emissions. As set out in my main proof of evidence (paras 5.5-5.8 and 6.8 and 6.12), it is highly unlikely that hydrogen-electric and battery-electric aircraft will be able to contribute to a significant reduction in global aviation emissions prior to 2050, and certainly not across the next two crucial decades.

4.27. Para 3.22 of the Jet Zero Consultation refers to the ambition of "*zero emission flight across the Atlantic*", which it describes as a "*challenging technological endeavour*". This considerably downplays the position. Given the physics of flying long distances, it is very difficult to see how, even with very ambitious improvements in battery technology, it would be possible to see trans-Atlantic aircraft of any reasonable commercial size and number of passengers e.g., over 100. While this is an interesting and important goal, it should not serve as a distraction from the steps needed to reduce aviation emissions now, from the vast majority of the sector where these technologies are not viable in the necessary timescales.

Conclusion – Demand Management

4.28. Para 3.39 of the Jet Zero Consultation states that, "*even if the sector returns to a pre-COVID-19 demand trajectory, as we have assumed in our analysis, we currently believe the sector can achieve Jet Zero without the Government needing to intervene directly to limit aviation growth*" (emphasis added). I have set out above the acknowledged uncertainties, as well as areas where the Jet Zero Consultation is unevidenced. In my view, either in response to the consultation responses due by 8 September 2021; or in the review which will take place within the next five years, it will be clear that it is implausible that the aviation sector will achieve zero emissions without government intervention that limits aviation growth.

4.29. Furthermore, the use of carbon pricing, hydrogen powered aircraft, alternative jet fuel mandates and GGR will all substantially increase the cost of flying and limit aviation growth, so the Government is already proposing measures that limit aviation growth. While it is a point of semantics whether these are “direct” or “indirect” measures, the overall point for this appeal is that the measures in the Jet Zero Consultation do not support the case for expansion of Bristol Airport and do not change any of the conclusions I reach in my original proof of evidence.

5. Response dated 13 August 2021 to NSC letter regarding Aviation Decarbonisation

Carbon Pricing

5.1. The DfT "Response dated 13 August 2021 to NSC letter regarding Aviation Decarbonisation" [**INQ/042**] states that within the Jet Zero Consultation "No analysis has been undertaken examining the likely scale and nature of uncertainty surrounding future carbon values" and that instead the consultation relies on values from BEIS (responses to Qs 4.1 and 4.2, pg 4). It should be noted that the "Evidence and Analysis" document [**CD 9.136**] acknowledges issues with these BEIS values being outdated and undervaluing GHG emissions in para 2.18. This is a very significant issue when reviewing the modelled scenarios as it is patently obvious that each of the various abatement options proposed within the consultation for decarbonising aviation must rely on a carbon price far exceeding the BEIS values (see Fig.1 of this document), including the "high" values which were apparently used to explore the "potential impact of placing a higher value on GHG emissions".

5.2. It is thus a serious weakness of the Jet Zero Consultation that this uncertainty was not explored in order to provide an evidential basis for the consultation. For example, an analysis should have modelled introducing higher carbon prices, earlier in the 2020 and 2030s, in order to simulate the cost of scaling the various abatement options considered.

5.3. The DfT asserts that the BEIS "high" carbon price has a minimal impact on overall emissions reductions compared to the "central" carbon price (response to Q 4.6, pg 6). This is unexpected because the "high" carbon price is 50% higher than the "central" carbon price in 2050, indicating that fuel costs would be 50% higher. I would expect this to have a far larger impact on long-haul aviation, whereas the "Evidence and Analysis" document in para 3.15 states that the small reduction in demand is "diverted away mostly from flights in the domestic and short-haul markets". This claim cannot be interrogated as these modelling details have not been provided.

5.3.1. However, taking this outcome at face value, it implies that the short-haul market, which Bristol Airport predominantly services, would be most affected by a carbon price – this adds further uncertainty to Bristol Airport's expansion plans due to the uncertainty of a far higher carbon price than currently applied within the UK ETS and CORSIA (see Fig. 1 of this document) being introduced in the future.

5.3.2. On the flip-side, if the BEIS carbon price (which is higher than both the UK ETS and international CORSIA carbon price – which are meant to be the main "mechanisms to control aviation emissions" over the next crucial decades) fails to significantly affect demand, then this demonstrates the clear need to <u>constrain demand</u> i.e., by limiting airport expansion, in order to ensure aviation emissions are limited. This is another reason why, on DfT's own approach, it is highly likely that demand management will be required.

5.4. The DfT also asserts that the assumed carbon price has been used as an input to the demand module of the aviation model used for the different scenarios, so that the scenarios reflect the likely impact of the assumed carbon price on passenger demand (response to Q6, pg 7). The issue is that the BEIS carbon price remains very low for the next decade (when most of their assumed UK airport expansion occurs), then rises gradually to 2050. There is no doubt also an assumption that travellers in future decades are wealthier than today, so absorb the increased costs as carbon price rises slowly. However, if for instance the BEIS carbon price targets for 2050 need to be achieved in 2030, that could greatly impact near-term demand and undermine expansion. Given that even the BEIS 2050 prices are still far lower than the current cost of proposed abatement measures or GGR today, I judge this to be a significant risk to airport expansion.

<u>Fuel Efficiency</u>

5.5. I have addressed from para 4.10ff above that the Jet Zero Consultation expects aircraft fuel efficiency improvements of 1.5%-2% per annum. In NSC's Q11.2, the DfT was asked to provide information to explain "why it is considered appropriate to reject the approach recommended by the CCC of 1.4% efficiency growth." [**INQ/042** pg 13). The DfT stated it does not reject the CCC's approach (pg 13).

5.6. The DfT's response references the ATA research (see para 2.3 of "Evidence and Analysis" **CD 9.136**). It attempts to explain that the CCC used the same ATA research as a basis for 1.4% average annual efficiency growth, but in some "exploratory scenarios" the CCC used 2.1% efficiency growth (response to Q11.2, pg 13). However, while the CCC did use such values e.g., in their "tailwinds" scenarios, they did not judge this a "feasible" "balanced" pathway to use within the 6th Carbon Budget. This shows again that the DfT's approach is overtly based on aspirational scenarios.

5.7. Furthermore, as I detail above in paras 4.8-4.18 of this supplementary proof, I judge even an efficiency growth of 1.4% to be highly optimistic. It is worth noting that the ATA research itself concludes that "likely" fuel improvements from aircraft entering service in the 2030-2035 period would be achieved of nominally -30% or less, relative to a year 2000 aircraft (Fig. 2 below). This would amount to an improvement of less than 1%/year for each "Class" (1, 2, 3 or 4) of aircraft. I do not judge the 2040-2045 improvements to be relevant as they make use of very speculative, unproven technology and in any case, aircraft entering service between 2040-45 will not have time to make any significant impact on the fleet composition and thus aviation emissions. As I state in para 4.10 above: even in 2050, the fleet will predominantly be composed of aircraft entering service in the 2020s and early 2030s, which will predominantly be aircraft designed and certified in the 2010s.

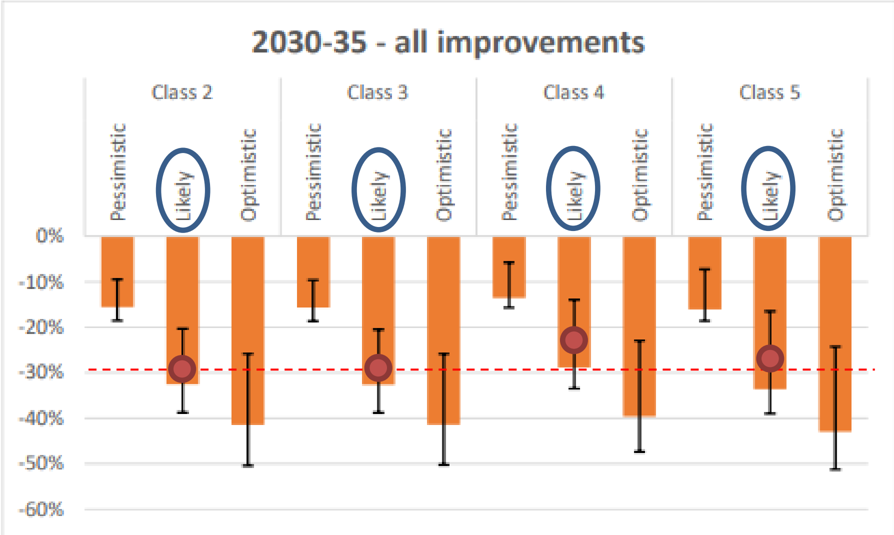


Figure 2: Potential combined block fuel improvement between 2030-2035 from ATA (pg 26)

Alternative Jet Fuels

5.8. The DfT confirms that they did not undertake any detailed appraisal of the likelihood and/or risks associated with an assumption of 30% fuel demand met by SAF (response to Q13, pg 15). This is a clear issue for the many reasons detailed above and summarised in para 7.6 of my main proof of evidence.

5.9. The DfT states that it "did not undertake an internal assessment of the abatement costs of SAF for the Jet Zero Consultation" (response to Q15.2, pg 17) and that it purely relying on other sources of information as detailed in the response to Q15.1 (pgs 16-17). However, it should be noted that none of the costs in those sources are utilised in the models at all, as they are simply replaced by the BEIS carbon price. This means that none of the assumptions for cost of abatement via these fuels with time can be inspected as they are not in the model. This is a crucial flaw, as the evidence suggests that the abatement cost of these fuels would be far higher than the BEIS carbon price used instead.

Demand Management

5.10. The DfT states that "We haven't undertaken any analysis looking at capping demand in anyway other than the application of a carbon price. We also haven't included any analysis incorporating different costs of GGRs" (response to Q22.2, pg 21) Again, this admits that neither the in-sector abatement measures (alternative fuels) or out-of-sector abatement measures (GGR) have been priced in and the BEIS carbon price has been applied instead, which remains far lower than the implied price of these throughout the crucial next two decades (see Fig. 1 above).

6. Decarbonising Transport

6.1. The Decarbonising Transport plan [**CD 9.134**] recognises that: "*[d]ecarbonising aviation is one of the biggest challenges across the global economy. The technological requirements to provide the power to propel aircraft the distances required far outstrip those for equivalent land-based transport.*" (pg 118). I agree.

6.2. Furthermore, it accepts that "*a projected increase in passenger numbers, and the need for global coordination, means that decarbonization will require a consistent, long-term effort from government and industry, both in the UK and internationally*." (pg 118). I also agree with this and note that it acknowledges that increasing passenger numbers poses a challenge to decarbonisation.

6.3. The Decarbonising Transport Plan confirms its intention to include international aviation in the Sixth Carbon Budget (pg 8) and asserts the Government's commitment to achieving net zero by 2050 (pg 118).

6.4. It goes on to set out a high-level "start" (pg 119) to aviation decarbonisation, by supporting initiatives to fast-track research and development and by strengthening carbon pricing mechanisms (pg 118), with the strategy for achieving this left to be settled through the Jet Zero Consultation process (pg 119). I have addressed this in detail above, so will not repeat the points made.

6.5. Pages 121-125 set out a list of commitments:

6.5.1. Consultations on the Jet Zero Strategy; on a target for UK domestic aviation to reach net zero by 2040 and a target for decarbonising emissions from UK airports operations in England by 2040 (pg 121) – I have addressed the Jet Zero Consultation above. The other commitments to consult do not provide much detail. The consultation on decarbonising airport emissions does not share the ambition of other aspects of the plan, given the urgent need for swift decarbonisation in this decade;

6.5.2. Supporting the development of new and zero carbon UK aircraft technology through the Aerospace Technology Institute (ATI) programme (pg 121) and working with industry to accelerate the adoption of innovative zero emission aircraft (pg 125) – I have addressed new and zero aircraft technology above and note this commitment entails reconfiguring how we fly, meaning it does not support current airport expansion.

6.5.3. Funding zero emission flight infrastructure R&D at UK airports (pg 122) – a £3 million investment is proposed in 2021-2022. Given the scale of the task this is a fairly limited investment. I address further below the implications for airport infrastructure and their relevant to BAL's application;

6.5.4. Kick-starting commercialisation of UK SAF via the "*recently launched the £15 million Green Fuels, Green Skies competition*" and a £3 million SAF clearing house (pgs 122-123). I have already addressed SAF in detail. As to the investment, it is a relatively insignificant amount compared to the industry investment required;

6.5.5. Consultation on a UK sustainable aviation fuel mandate (pg 123) – I have also addressed this, pointing out how it contradicts a number of elements of the Jet Zero Consultation. I note that the SAF Mandate Consultation recognises the need for a SAF mandate as an additional intervention to "*accelerate the roll-out of this technology in the UK and ensure its use can meaningfully contribute to delivering net zero emissions*" (para 1.21). This echoes the point I made at para 9.1(10) on pg 43 of my main proof of evidence, that little weight could be put on the Ten Point Plan [**CD 8.8**] as it did not set requirements for SAF quantity or impose sustainability criteria, which is what the SAF Mandate seeks to do. At this point, there remains no SAF Mandate. The consultation runs until 19 September 2021 and the Government will then publish a summary of responses and next steps, although no commitment is given as to when that will happen;

6.5.6. Supporting UK airspace modernisation – this should be happening as a matter of business-as-usual. As I state in para 9.1(7) of my main proof of evidence on pgs 41-42, airport expansion and the potential for more aircraft in the sky does not facilitate airspace modernisation. Furthermore, the increased emissions from increased flights would be likely to wipe out any savings achievable via airspace modernisation in my view.

6.5.7. Working to further develop the UK ETS and increase the ambition of CORSIA – I have addressed the UK ETS above and address carbon offsetting in more detail below.

7. UK Hydrogen Strategy "Analytical Annex"

7.1. On 17 August 2021, BEIS published the UK Hydrogen Strategy [**INQ/043**], which was supported by the “Hydrogen Analytical Annex”. The Annex notes that "No hydrogen use is modelled in aviation due to the relative immaturity of technology and lack of modelling to date. Illustrative estimates of hydrogen demand for an airport are based on the Clean Sky 2 report." [Appendix S4, pg 18]. This adds weight to the conclusion in para 6.15 of my main proof of evidence that “Hydrogen flight is as yet unproven, and its continued development is speculative and very uncertain, meaning that no weight can be given to claims that hydrogen flight will help to meet sustainability targets by Bristol Airport in their expansion plans.”

7.2. The Analytical Annex also notes on page 20 that “the constraints on availability of biomass and low-cost electricity limit the amount of low-cost and low carbon hydrogen that can be produced by BECCS and electrolysis, so additional demand above this level is likely to be met by hydrogen production via CCUS-enabled methane reformation. Scenarios with very high hydrogen demand could therefore have a higher proportion of CCUS-enabled methane reformation.” This echoes my points around limited availability of global sustainable biomass resource (para 7.3.3 of my main proof of evidence) and of global renewable electricity for producing green hydrogen (para 6.11 of my main proof of evidence) or synthetic e-fuel (para 7.4.4 of my main proof of evidence).

7.3. The implication here is a reliance on “CCUS-enabled methane reformation” which is “Blue Hydrogen” produced from methane, a fossil fuel (explained in para 6.9 of my main proof of evidence). However, a recent study has shown that the “greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas”, a fossil fuel [**Appendix S5**, pg 1]. This underscores the issues of relying on large quantities of hydrogen within aviation: for hydrogen aircraft or for producing biofuels or synthetic e-fuels for conventional aircraft.

7.4. The Analytical Annex also notes on page 27 that "The lack of a fully developed market, imperfect information and the presence of a negative externality linked to carbon" … "all contribute to the lack of cost competitiveness" and that "the high carbon alternatives have a cost advantage as their price does not capture the full societal cost of carbon they generate. UK carbon pricing policy (primarily the UK Emissions Trading Scheme (ETS)) addresses this by requiring businesses within scope to pay a price for every tonne of CO_2 equivalent emitted. However, the scope of the UK ETS does not currently include all sectors of the economy where low carbon hydrogen potentially has value; and for sectors within scope, low carbon hydrogen is not yet competitive as an abatement option in the ETS market". This underscores the issue of a non-existent or significantly low carbon prices as illustrated by Fig. 1 above. It also reinforces the conclusion I made about the inadequacy of the UK ETS market in paras 8.1 and 8.4 of my main proof of evidence.

8. Implications for Airport Infrastructure

8.1. Bristol Airport's application includes extensions to the terminal building on its west and southern sides and enhancement to airside infrastructure [**CD 2.18** BAL's Statement of Case]. In my main proof of evidence, I stated that technology such as hydrogen aircraft would require modification to airport infrastructure [para 6.7] and I noted that BAL's Draft Carbon and Climate Change Action Plan only contained a vague reference to "exploring" the infrastructure change needed to provide SAF infrastructure, without any reference to quantity or sustainability criteria [pg 39].

8.2. Decarbonising Transport (pg 118) and the Jet Zero Consultation (paras 3.28-3.30) both refer to the need for research and development into airport infrastructure upgrades for zero emission flight, and refer to the fact that investment has been, and will be, made into the research and development needed.

8.3. Electric/hydrogen aircraft will require a complete re-configuration of aviation infrastructure and airline operations. This very fact undermines the case for airport expansion now. Rather, airport expansion should only be considered once we fully understand this future configuration of air transport.

8.4. As I set out in Section 2 of my main proof, with regards to hydrogen-electric or battery-electric aircraft, we currently know that airports would need:

8.4.1. different airline operations due to significant differences in aircraft capability (speed, range, payload), aircraft changeover times, and aircraft maintenance requirements;

8.4.2. different number of flight movements (number of aircraft taking-off/landing) for an equivalent number of passengers using the airport;

8.4.3. different aircraft gate sizing and layout, due to substantially different aircraft shapes, sizes, and/or passenger numbers;

8.4.4. different airport layout and configuration due to changes to the flow of passengers through the airport to different sized and spaced gates with different passenger numbers and timings at each one

8.4.5. different fuelling and/or charging infrastructure for aircraft

8.5. Furthermore, current proposed airport expansion, including BAL's proposal, is based on business-as-usual growth of existing aircraft. If, however, BAL's case is that in future it anticipates that a significant number of hydrogen-electric or battery-electric aircraft will be flying from the airport (assuming for this purpose that such aircraft have been developed and are commercially available), then that would significantly alter the way the airport operates and its customer mix.

8.6. As set out in my main proof of evidence in Section 5, battery-electric aircraft are anticipated to be feasible for short-haul flights in small aircraft. The Jet Zero Consultation reflects this, as it expresses the hope that battery-electric aircraft "could enter the sub-regional and General Aviation markets this decade" (para 3.24). Bristol Airport is not predominantly configured for such aircraft. If in future Bristol Airport plans to be an airport with predominantly small electric or hydrogen powered aircraft that fly short hops e.g. to other parts of the UK or to connect to a larger hub like Heathrow for larger aircraft / longer flights - then the airport will function and look very different. For example, it would significantly alter the number of passengers at each gate and the flow of passengers through the airport (e.g. relatively high number of aircraft, carrying fewer than 50 passengers, less than 500km).

8.7. If the future of aviation is indeed to rely on relatively small and short-range hydrogen and battery-electric aircraft, then this would affect the airport's growth as the number of take-off and landing slots within one day are limited, and would be consumed by aircraft carrying relatively few passengers compared to the aircraft predominantly operating from Bristol Airport currently.

8.8. Finally, as I pointed out in para 5.7 of my main proof, where infrastructure allows, lower energy- and emissions-intensity ground-based public transport options such as rail, coach, or ferry services should generally be favoured over hydrogen or electric aircraft for short distance travel, given the urgent need to cut emissions.

9. Carbon Offset Schemes

9.1. I have already set out above where the Jet Zero Consultation and Evidence documents concur with my evidence on this topic. I addressed the EU or UK ETS and CORSIA in Section 8 of my main proof and Section 4 of my rebuttal.

9.2. Decarbonising Transport and the Jet Zero Consultation do not change the position. They reiterate what the Government has previously said about supporting these schemes, but do not change the Government's approach that it will meet the Net Zero target without relying on use of international offset credits, which the Government confirmed to Parliament is its approach [**CD 9.93**].

9.3. I note that the Jet Zero Consultation recognises that the Government needs to negotiate "*for the strengthening of the CORSIA offsetting scheme*" to align it with the temperature goal in the Paris Agreement (para 2.14). This recognises the CCC's advice in the Sixth Carbon Budget Report that "*The current level of ambition under CORSIA is an insufficient contribution to the goals of the Paris Agreement*" [**CD 9.34** pg 425]. I set out in para 8.3 of my main proof and para 4.5-4.8 of my rebuttal why CORSIA is weak.

Finlay Asher
20 August 2021

APPENDICES INDEX

Appendix S1

ICAO ENVIRONMENT

2019 Environmental Report

Aviation and Environment

Environmental Trends in Aviation to 2050

By Gregg G. Fleming (US DOT Volpe) and Ivan de Lépinay (EASA)

BACKGROUND

At the end of each three-year work cycle, the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) conducts an assessment of future environmental trends in aviation that includes:

- Aircraft engine Greenhouse Gas (GHG) emissions that affect the global climate,
- Aircraft noise, and
- Aircraft engine emissions that affect Local Air Quality (LAQ).

The environmental trends discussed in this section are based on the latest CAEP/11 air travel demand forecast data, using a base year of 2015. Forecast years were 2025, 2035, and 2045, and results were then extrapolated to 2050. The passenger and freighter forecasts were derived from ICAO's Long-Term Traffic Forecast, while the business jet forecast was developed by CAEP. Data presented for years earlier than 2015 are reproduced from prior CAEP trends assessments. Fuel burn and emissions results are for international aviation only, while noise trends include both domestic and international operations. In 2015, approximately 65 per cent of global aviation fuel consumption was from international aviation. This proportion is expected to remain relatively stable out to 2050.

The trends presented here were developed in the context of a longer-term view, and assume that there would be no airport infrastructure or airspace operational constraints. Such trends can be affected substantially by a wide range of factors such as fluctuations in fuel prices, and global economic conditions.

Three environmental models contributed results to the fuel burn and emissions trends assessment: US Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT), EUROCONTROL's IMPACT, and Manchester Metropolitan University's Future Civil Aviation Scenario Software Tool (FAST). Three models contributed results to the noise trends assessment: US FAA's AEDT, EC / EASA / EUROCONTROL's SysTem for AirPort noise Exposure Studies (STAPES), and UK Civil Aviation Authority's (CAA) Aircraft Noise Contour Model (ANCON).

Key databases utilized in this assessment included: CAEP's Global Operations, Fleet, and Airports Databases.

TRENDS IN EMISSIONS THAT AFFECT GLOBAL CLIMATE

Table 1 below summarizes the aircraft technology and operational scenarios developed for the assessment of trends for fuel burn and aircraft emissions that affect the global climate.

TABLE 1: Fuel Burn and GHG Emissions - Technology and Operational Improvement Scenarios

Scenario	Aircraft Technology: per annum fuel burn improvements for fleet entering after base year	Aircraft Technology: Emissions Improvements against CAEP/7 IE NOx Goal	Additional Fleet-Wide OP Improvements by Route Group from CAEP/9 IE
Fuel 1 - Baseline	NA: use only base-year in-production fleet	NA	NA: maintain baseline meet-demand efficiency
Fuel 2 - Low Aircraft Technology and CAEP/9 IE Operational Improvements	Low: 0.96% to 2015 then 0.57% to 2050	NA	Apply added fleet-wide improvements
Fuel 3 - Moderate Aircraft Technology and CAEP/9 IE Operational Improvements	Moderate: 0.96% to 2050	NA	Apply added fleet-wide improvements
Fuel 4 - Advanced Aircraft Technology and CAEP/9 IE Operational Improvements	Advanced: 1.16% to 2050	NA	Apply added fleet-wide improvements
Fuel 5 - Optimistic Aircraft Technology and CAEP/9 IE Operational Improvements	Optimistic: 1.5% to 2050	NA	Apply added fleet-wide improvements
NOx 1 - Baseline	NA	NA	NA
NOx 2 - Moderate Aircraft Technology, CAEP/9 IE Operational, and 50% CAEP/7 IE Emissions Improvements	Moderate: 0.96% to 2050	50% by 2026 nothing thereafter	Apply added fleet-wide improvements
NOx 3 - Advanced Aircraft Technology, CAEP/9 IE Operational, and 100% CAEP/7 IE Emissions Improvements	Advanced: 1.16% to 2050	100% by 2026 nothing thereafter	Apply added fleet-wide improvements

Trends in Full-Flight Fuel Burn and CO_2 Emissions

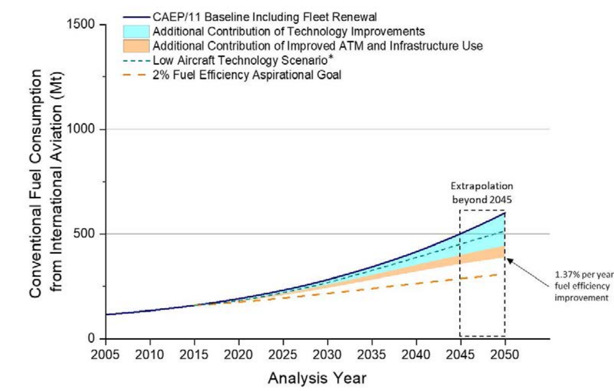
Figure 1 shows results for global full-flight (i.e., from departure gate to arrival gate) fuel burn for international aviation from 2005 to 2045, and then extrapolated to 2050. The fuel burn analysis considers the contribution of aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements) to reduce fuel consumption. The Figure also illustrates the fuel burn that would be expected if ICAO's 2% annual fuel efficiency aspirational goal were to be achieved.

Even under the most optimistic scenario, the projected long-term fuel efficiency of 1.37% per annum falls short of ICAO's aspirational goal of 2% per annum. The long-term forecast fuel burn from international aviation is lower by about 25% compared with prior CAEP trend projections. This decrease can be attributed to a combination of more fuel efficient aircraft entering the fleet, as well as a reduction in the forecast long-term traffic demand. The computed 1.37% per annum long-term fuel efficiency includes the combined improvements associated with both technology and operations. The individual contributions from technology and operations is .98% and .39%, respectively. The .98% is slightly lower than the 1.3% cited in the latest CAEP/11 Independent Experts (IE) Review for single aisle aircraft.

Figure 2 depicts these contributions in the context of the uncertainties associated with the forecast demand, which is notably larger than the range of potential contributions from technological and operational improvements. Despite these uncertainties, the CAEP/11 forecast traffic trends are broadly consistent with other published aviation forecasts. The forecast commercial market trend, which is for available tonne kilometres (ATK), shows a 20 year (2015-2035) compound average annual growth rate (CAGR) of 4.3%. By way of comparison, using revenue passenger kilometres (RPK) for all traffic as the forecast measurement, forecasts of Boeing, Airbus and Embraer for 2015 have 20-year (2015-2035) CAGRs of 4.8%, 4.5%, and 4.7%, respectively. The CAEP/11 RPK 20-year forecast (2015-2035) has a CAGR of 4.4%.

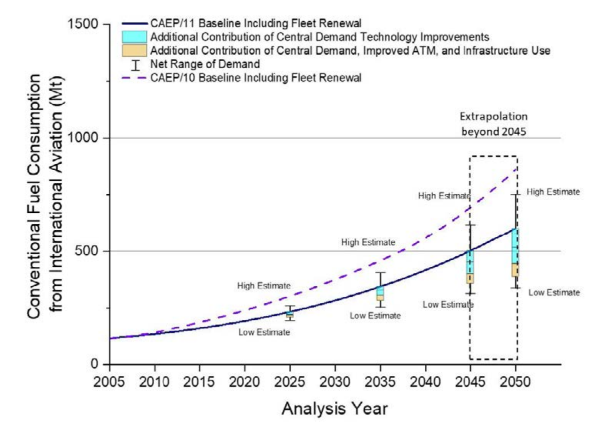
Figure 3 presents full-flight CO_2 emissions for international aviation from 2005 to 2045, and then extrapolated to 2050. This Figure only considers the CO_2 emissions associated with the combustion of jet fuel, assuming that 1 kg of jet

FIGURE 1: Fuel Burn from International Aviation, 2005 to 2050



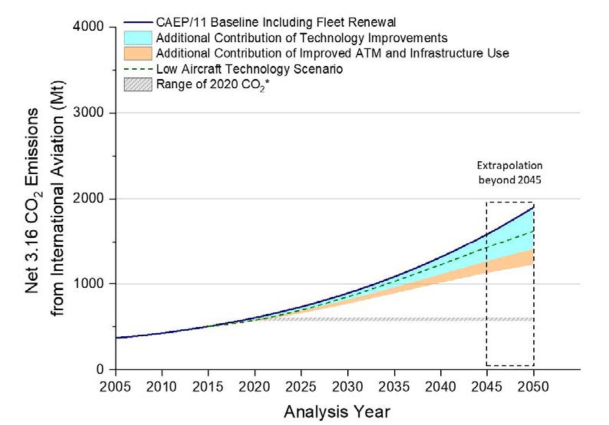
*Dashed line in technology contribution sliver represents the "Low Aircraft Technology Scenario."
Note: Results were modelled for 2005, 2006, 2015, 2025, 2035, and 2045 then extrapolated to 2050.

FIGURE 2: Range of Uncertainties Associated with Demand Forecast, 2005 to 2050



Note: Fuel burn was only modelled for the central demand forecast. The effects of the high and low demand sensitivities shown are based on the ratio of forecasted revenue passenger kilometres for high/low demand relative to central demand.

FIGURE 3: CO_2 Emissions from International Aviation, 2005 to 2050



*Actual carbon neutral line is within this range
Dashed line in technology contribution sliver represents the "Low Aircraft Technology Scenario."
Note: Results were modelled for 2005, 2006, 2010, 2015, 2025, 2035, and 2045 then extrapolated to 2050.

fuel burned generates 3.16 kg of CO_2. As with the previous fuel burn analyses, this analysis considers the contribution of: aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements). In addition, the range of possible CO_2 emissions in 2020 is displayed relative to the global aspirational goal of keeping the net CO_2 emissions at this level.

Although not displayed in a separate figure, the demand uncertainty effect on the fuel burn calculations shown in Figure 3 has a similar effect on the CO_2 results. With reference to the fuel consumption scenarios in Table 1; the highest anticipated fuel consumption in 2020 (Scenario 1), and the lowest anticipated fuel consumption in 2045 (Scenario 5), a minimum CO_2 emission gap of 517 million metric tonnes (Mt, 1kg × 10^9) is projected for 2045. Extrapolating Scenario 5 to 2050, results in a minimum gap of 612 Mt.

Contribution of Alternative Fuels to Fuel Consumption and CO_2 Trends

CAEP's Alternative Fuels Task Force (AFTF) was charged with calculating estimates of sustainable aviation fuel (SAF) contributions to fuel replacement and life cycle GHG emissions reductions in conducting its trends assessment out to 2050. Analyses were performed for 2020 and 2050. The short-term scenarios for SAF availability were established from announcements made by fuel producers regarding their production plans from State-sponsored production plans. For the long-term scenarios, CAEP assessed future jet fuel availability in three ways: by estimating the primary bioenergy potential constrained by selected environmental and socio-economic factors, by estimating the proportion of bioenergy potential that could actually be achieved or produced, and by exploring the quantity of SAF that could be produced from the available bioenergy. SAF availability calculations included 9 different groups of feasible feedstocks: starchy crops, sugary crops, lignocellulosic crops, oily crops, agricultural residues, forestry residues, microalgae, municipal solid waste, and waste fats, oils and greases. The final values provided by AFTF to the Modelling and Databases Group (MDG) include potential total global production, and an average Life Cycle Assessment (LCA) value based on the share of different fuel types that contribute to each scenario. The LCA values are not intended to be applied separately to regional forecasts.

For 2020, there were six production estimates and two GHG LCA estimates (low and high), resulting in 12 possible GHG emissions scenarios. The 2020 scenarios result in up to 2.6% petroleum-based fuel replacement and up to 1.2% GHG emissions reductions.

For 2050, CAEP calculated 60 production achievement scenarios and two GHG emissions scenarios, resulting in a total of 120 scenarios. Certain global conditions, economic investments, and policy decisions are assumed as part of each scenario definition, and would be necessary to reach the associated outcome of alternative fuel production and GHG reductions.

The trend assessment figures for international aviation shown below include the range of CAEP results, and an "illustrative" scenario that achieves 19% net CO_2 emissions reduction, assuming significant policy incentives and high biomass availability. Fuel replacement results for international aviation can be found in Figure 4, and Net CO_2 emissions results are shown in Figure 5. The amount of SAF, and the associated CO_2 emission reductions were allocated proportionally between international use and domestic use, based on projected fuel demand (65% and 35% in 2015, respectively).

For 2020 and 2050, total petroleum-based fuel amounts for the different fuel demand scenarios were multiplied by the specific CO_2 combustion emissions factor of 3.16 to get the baseline GHG emissions shown in Figure 5. Calculations of GHG emissions reduction were performed according to the following formula provided by the CAEP Market-Based Measures Task Group:

Total Emissions = 3.16 × (CJF + SAF*(LCA_SAF/LCA_CJF))

Where CJF = conventional jet fuel, SAF = sustainable aviation fuel, and LCA_X = life cycle CO_2 equivalent emissions of fuel X.[1]

1 This calculation provides an "in-flight" equivalent of CO_2 emissions reduction based on the life cycle values of the alternative fuels, which are used because reductions in atmospheric carbon from aviation biofuel use occur from feedstock production and fuel conversion and not from fuel combustion.

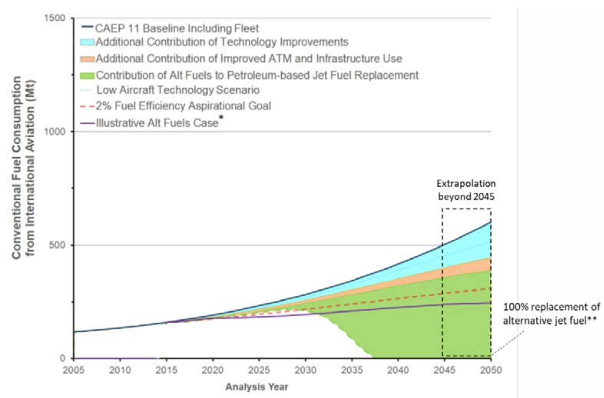
The green GHG reduction "wedge" was created by connecting the least contribution scenario values to each other and the greatest contribution values to each other. The 2020 "medium scenario without green diesel" was connected to the 2050 value for the illustrative scenario. CAEP elected to assume a linear growth for intermediate and high GHG reduction scenarios.[2]

Several of the 2050 scenarios that CAEP evaluated resulted in zero alternative jet fuel production and therefore no contribution to GHG emissions reduction.[3] The zero SAF results are equivalent to the line associated with Scenario 5 for technology and operational improvements as described above. The scenario with the largest contribution to GHG emissions reduction could supply more alternative jet fuel than is anticipated to be used in 2050. For the purposes of this analysis, production for the highest contribution scenario is ramped up to full replacement in 2050, based on Scenario 5.

If the alternative fuel industry growth were to follow an S-shaped curve, the highest growth rates would occur around 2035, in which 328 new large bio-refineries would need to be built each year at an approximate capital cost of US$29 billion to US$115 billion per year. Lower growth rates would be required in years closer to 2020 and 2050. If growth occurred linearly, complete replacement would require approximately 170 new large bio-refineries to be built every year from 2020 to 2050, at an approximate capital cost of US$15 billion to US$60 billion per year.

Achieving the most optimistic net CO_2 emissions scenario would require the highest levels of: agricultural productivity, availability of land for feedstock cultivation, residue removal rates, conversion efficiency improvements, and reductions in the GHG emissions of utilities. It would also require a strong market or policy emphasis on bioenergy in general, and alternative aviation fuel in particular. This implies that a large share of the globally available bioenergy resource would be devoted to producing aviation fuel, as

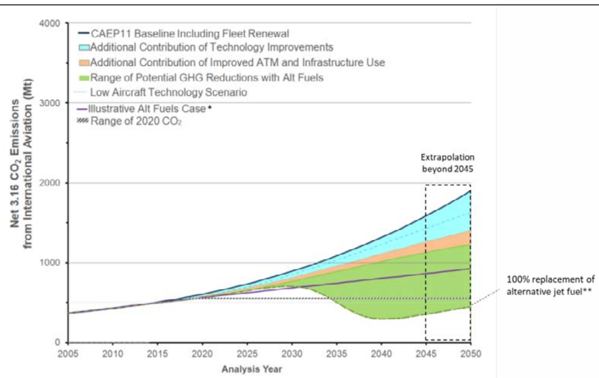
FIGURE 4: Conventional Fuel Consumption from International Aviation, 2005 to 2050, Including Potential Replacement by Alternative Fuels



*Illustrative case would require high availability of bioenergy feedstock, the production of which is significantly affected by price or other policy mechanisms;

**100% replacement of alternative jet fuel would require a complete shift in aviation consumption, from petroleum to biofuel based fuels, and a significant expansion of the agricultural sector, both of which would require substantial policy support.

FIGURE 5: Net CO_2 Emissions from International Aviation, 2005 to 2050, Including Alternative Fuels Life Cycle CO_2 Emissions Reductions (Based on 3.16 kg of CO_2 per 1 kg of fuel burn)



2 CAEP did not specify a function for connecting the 2020 results to the 2050 results in their outputs. However, CAEP did provide information on the range of options for connecting these results. CAEP anticipates that growth of a new industry such as that for SAF will follow an "S-shaped" trajectory, but it is not clear when investment, and therefore, growth of production capacity of the industry, will ramp up. Ramp up to alternative fuel production in 2050 is anticipated to be somewhere between linear and exponential growth (i.e., the lower end of the S-curve). Linear growth for intermediate and high net CO_2 emissions reduction scenarios is shown. No meaningful data exists with which to calibrate the curve. Therefore, values for the intervening years, between 2020 and 2050, for the SAF scenarios should be considered illustrative only.

3 These scenarios reflect a lack of bioenergy availability in general or a prioritization of other bioenergy usages over aviation.

opposed to other uses. It should be noted that all the CO_2 emission scenarios evaluated considered rainfed energy crop production only on land available after satisfying predicted 2050 food and feed demand. Additionally, primary forests and protected areas were not considered for conversion to cultivated energy crop production.

Achievement of carbon neutral growth at 2020 emissions levels out to 2050 would require nearly complete replacement of petroleum-based jet fuel with sustainable alternative jet fuel and the implementation of aggressive technological and operational scenarios. The effort required to reach these SAF production volumes would have to significantly exceed historical precedent for other alternative fuels, such as ethanol and biodiesel for road transportation.

Interpretation

In 2015, international aviation consumed approximately 160 Mt of fuel, resulting in 506 Mt of CO_2 emissions. By 2045, fuel consumption is projected to have increased 2.2, or 3.1 times the 2015 value, while revenue tonne kilometres are expected to increase 3.3 times under the most recent forecasts. Extrapolating to 2050, fuel consumption is projected to increase 2.4 to 3.8 times the 2015 value, while revenue tonne kilometres are expected to increase 3.9 times.

Under the most optimistic Scenario 5, as defined in Table 1, international aviation fuel efficiency, expressed in terms of volume of fuel per RTK, is expected to improve at an average rate of 1.29% per annum to 2045, and at 1.37% per annum, if extrapolated to 2050. This indicates that ICAO's aspirational goal of 2% per annum fuel efficiency improvement is unlikely to be met by 2050. While in the near-term (2015 to 2025), efficiency improvements from technology and improved ATM and infrastructure use are expected to be moderate, they are projected to accelerate in the mid-term (2025 to 2035). During that 2025 to 2035 period, fuel efficiency is expected to improve at an average rate of 1.08% per annum under Scenario 5. This is about as expected, given the 1.5% per annum fuel technology improvement associated with Scenario 5, and the variability of the forecasted RTK.

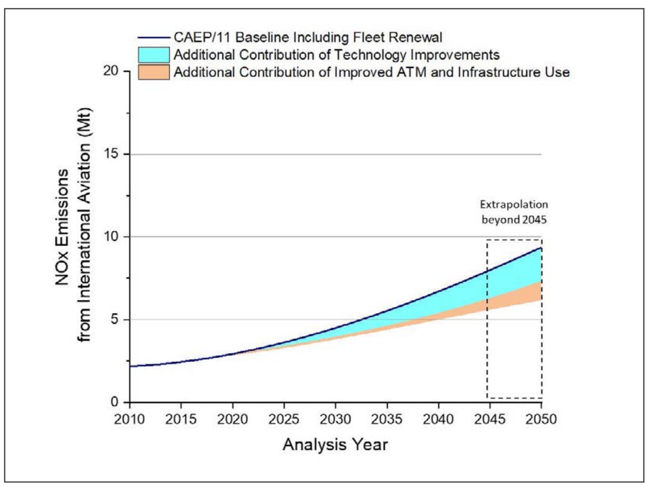
By 2025, it is expected that international aviation will require somewhere between 207 and 226 Mt of fuel, resulting in 655 to 713 Mt of CO_2 emissions. A number of near-term scenarios evaluated by CAEP indicate that up to 2.6% of fuel consumption needs by 2020 could be satisfied by SAF. This analysis also considered the long-term availability of sustainable alternative fuels, finding that it would be physically possible to meet 100% of demand by 2050 with SAF, corresponding to a 63% reduction in emissions. However, this level of fuel production could only be achieved with extremely large capital investments in sustainable alternative fuel production infrastructure, and substantial policy support.

Even under this scenario, achieving carbon neutral growth exclusively from the use of sustainable alternative fuels is unlikely to happen by 2020 or shortly thereafter as an initial ramp-up phase for the production of SAF is required before production can reach the levels mentioned above. Market-based measures are anticipated to help fill the gap to carbon neutral growth, although also later than 2020.

Trends in Full-Flight NOx Emissions

Trends in full-flight nitrogen oxides (NOx) emissions from international aviation are shown in Figure 6. The 2015 baseline NOx emissions were 2.50 Mt. In 2045, forecast NOx emissions range from 5.53 Mt under Scenario 3, to 8.16 Mt under Scenario 1. As with fuel burn, the long-term full-flight NOx from international aviation is lower by about 21% compared with the prior trends projections. This can be attributed to a combination of aircraft with lower NOx engines entering the fleet, as well as a reduction in forecasted long-term traffic demand.

FIGURE 6: Full-Flight NOx Emissions from International Aviation, 2010 to 2050



TRENDS IN AIRCRAFT NOISE

A range of scenarios was developed for the assessment of future noise trends. The noise indicators used are the total contour area and population inside the yearly average day-night level (DNL) 55 dB contours of 315 airports worldwide, representing approximately 80% of the global traffic.

Scenario 1 (CAEP/11 Baseline) assumes no further aircraft technology or operational improvements after 2015. Scenarios 2, 3, and 4 (low, moderate, advanced technology) assume that the noise levels of all new aircraft delivered after 2015 will reduce at a rate of 0.1, 0.2, and 0.3 EPNdB[4] per annum, respectively. For all scenarios, an additional 2% reduction is applied to the population counts inside the noise contours, to reflect a possible improvement of aircraft routing around airports.

Population counts for airports in the US, Europe, and Brazil rely on local census data. For all other airports, the NASA Gridded Population of the World, version 4 (GPW v4) was used.

Figure 7 shows the total 55 dB DNL noise contour area from 2010 to 2050. In 2015, this area was 14,400 square-kilometres, and the population inside that area was approximately 30 million people. By 2045, the area is expected to grow from 1.0 to 2.2 times, compared with 2015, depending on the technology scenario. Of note is that under the advanced aircraft technology scenario (Scenario 4), from about 2030 onwards, the total yearly average DNL contour area may no longer increase with an increase in traffic. The long-term total DNL 55 dB contour area is lower by about 10%, compared with the prior trends projections. This decrease can be attributed to a combination of quieter aircraft entering the fleet, as well as a reduction in the long-term traffic demand.

TRENDS IN EMISSIONS THAT AFFECT LOCAL AIR QUALITY

A range of scenarios have also been developed for the assessment of aircraft emissions that occur below 3,000 feet above ground level (AGL) and affect local air quality; namely NOx and total (volatile and non-volatile) particulate matter (PM). The NOx scenarios are the same as in Table 1. For assessing PM trends, there are two scenarios as follows: Scenario 1 (CAEP/11 Baseline) assumes no further aircraft technology or operational improvement after 2015. Scenario 2, represented by the bottom of the orange sliver, assumes that only operational improvements apply, with no aircraft technology improvements.

Figure 8 provides results for NOx emissions below 3,000 feet AGL from international aviation from 2010 to 2050. The 2015 NOx emissions were 0.18 Mt. In 2045, they are forecast to range from 0.44 Mt under Scenario 3, to 0.80 Mt under Scenario 1. The projections of NOx emissions below 3,000 feet are lower by about 2% compared with the prior

FIGURE 7: Total Aircraft Noise Contour Area Above 55 dB DNL for 315 Airports (km²), 2010 to 2050

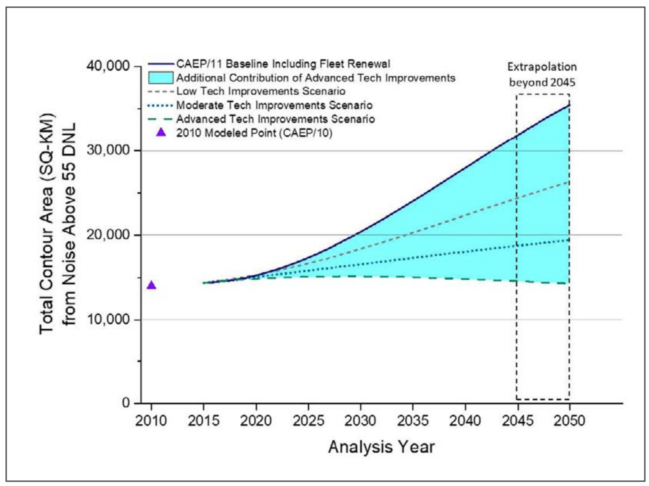
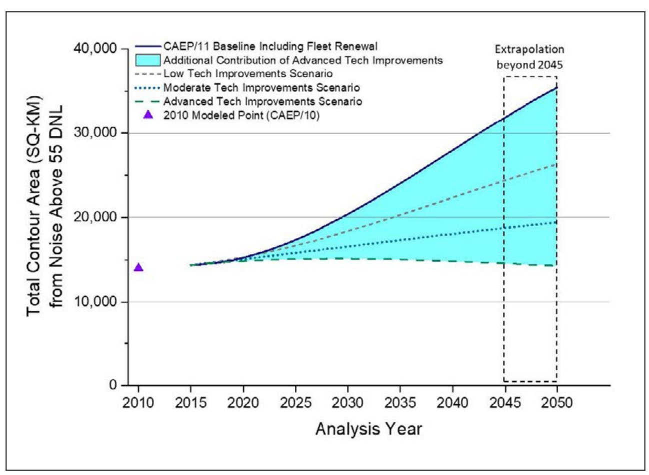


FIGURE 8: NOx Emissions below 3,000 Feet - International Aviation, 2010 to 2050.

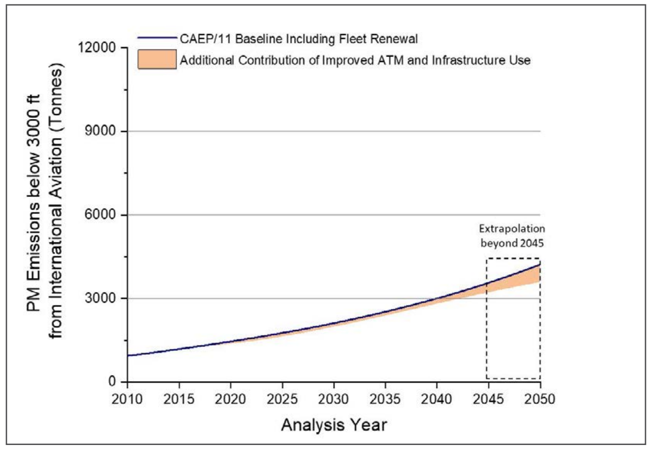


4 EPNdB is Effective Perceived Noise Level in Decibels.

trend projections. This will be due to three main factors: a combination of aircraft with lower NOx engines, a reduction in the long-term traffic demand, and a refinement to the method used for computing emissions below 3,000 feet.

The results for PM emissions from international aviation below 3,000 feet AGL follow similar trends as those for NOx, as shown in Figure 9. The 2015 PM emissions were 1,243 tonnes (t). In 2045, they are projected to range from 3,230 t under Scenario 2, and 3,572 t under Scenario 1.

FIGURE 9: PM Emissions Below 3,000 feet - International Aviation, 2010 to 2050.



CONCLUSION

Emissions from international aviation that affect the global climate and local air quality are expected to increase through 2050, by a factor ranging from approximately 2 to 4 times the 2015 levels, depending on the type of emissions (CO_2, NOx or PM), and the analysis Scenario used. Under an advanced aircraft technology scenario, the total area of day-night levels (DNL) noise contours around airports may stabilize after 2030. However, it should be kept in mind that the uncertainty associated with future aviation demand is notably larger than the range of contributions from technology and operational improvements.

International aviation fuel efficiency is expected to improve through 2050, however ICAO's aspirational goal of 2% per annum fuel efficiency improvement is unlikely to be met by then. The aspirational goal of carbon neutral growth after 2020 is also unlikely to be met. Sustainable alternative fuels have the potential to fill the gap to carbon neutral growth but not in the short term, and data is still lacking to confidently predict their availability over the long term. Market-based measures can help fill that gap as well, but also later than 2020.

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5 Bridging the gap – the role of international shipping and aviation

Lead authors:
Jasper Faber (CE Delft, the Netherlands) and David S. Lee (Manchester Metropolitan University, UK)

Contributing authors:
Susanne Becken (Griffith University, Australia), James J. Corbett (Energy and Environmental Research Associates, USA), Nick Cumpsty (Imperial College London, UK), Gregg Fleming (Volpe Center, U.S. Department of Transportation, USA), Tore Longva (DNV GL, Norway), Marianne Tronstad Lund (Center for International Climate Research – CICERO, Norway), Tristan Smith (University College London, UK)

5.1 Introduction and framing

Emissions from the shipping and aviation sectors have increased in the past decades (though they reduced in 2020 due to the COVID-19 pandemic) and accounted for approximately 2 $GtCO_2$ in 2019 (International Maritime Organization [IMO] 2020; Lee *et al.* in press). About two-thirds of these emissions are international, meaning they are not included in national totals reported to the United Nations Framework Convention on Climate Change (UNFCCC) and are instead added as memo items. Although international emissions are not covered under the nationally determined contributions (NDCs) of most signatories to the Paris Agreement, article 4 commits its signatories to reducing all anthropogenic greenhouse gas (GHG) emissions. No sector is exempt from this commitment. At present, the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) are the specialized United Nations agencies tasked with addressing international GHG emissions. Shipping and aviation both largely depend on liquid fossil fuels and have inherently long technology development and fleet turnover times, which make it difficult for the sectors to decarbonize. In addition to GHG emissions, both sectors emit other emissions that contribute to climate change, such as nitrogen oxides (NO_x), water vapour, back carbon (soot) and sulphur dioxide (SO_2) (Eyring *et al.* 2010; Eide *et al.* 2013; Lee *et al.* in press).

This chapter presents current and projected emissions to assess how much the international transport sectors are contributing to the emissions gap (section 5.2). Section 5.3 analyses the technical, operational and fuel options available to decarbonize shipping and aviation. Section 5.4 contrasts the projected emissions with global emissions pathways required to meet the Paris Agreement temperature goals in order to assess when, and to what extent, the decarbonization options should be implemented, while also evaluating the current policy goals in the context of the Paris Agreement. Section 5.5 concludes the findings.

5.2 Current emissions, projections and drivers

Increased globalization and diversified economies have led to a rapid growth in human mobility and the transport of goods. In turn, increasingly connected and affordable transport systems have further enabled globalization and associated economic development, bringing socioeconomic benefits to parts of the population. In addition to rising global average incomes, this has caused an increase in consumer demand for travel and traded goods, reaching record levels in 2019 with 1.4 billion international tourists (World Tourism Organization [WTO] 2019), 4.5 billion passengers, 61.3 million tons of air freight (International Air Transport Association [IATA] 2020a) and 11 billion tons of world seaborne trade recorded (United Nations Conference on Trade and Development [UNCTAD] 2019).

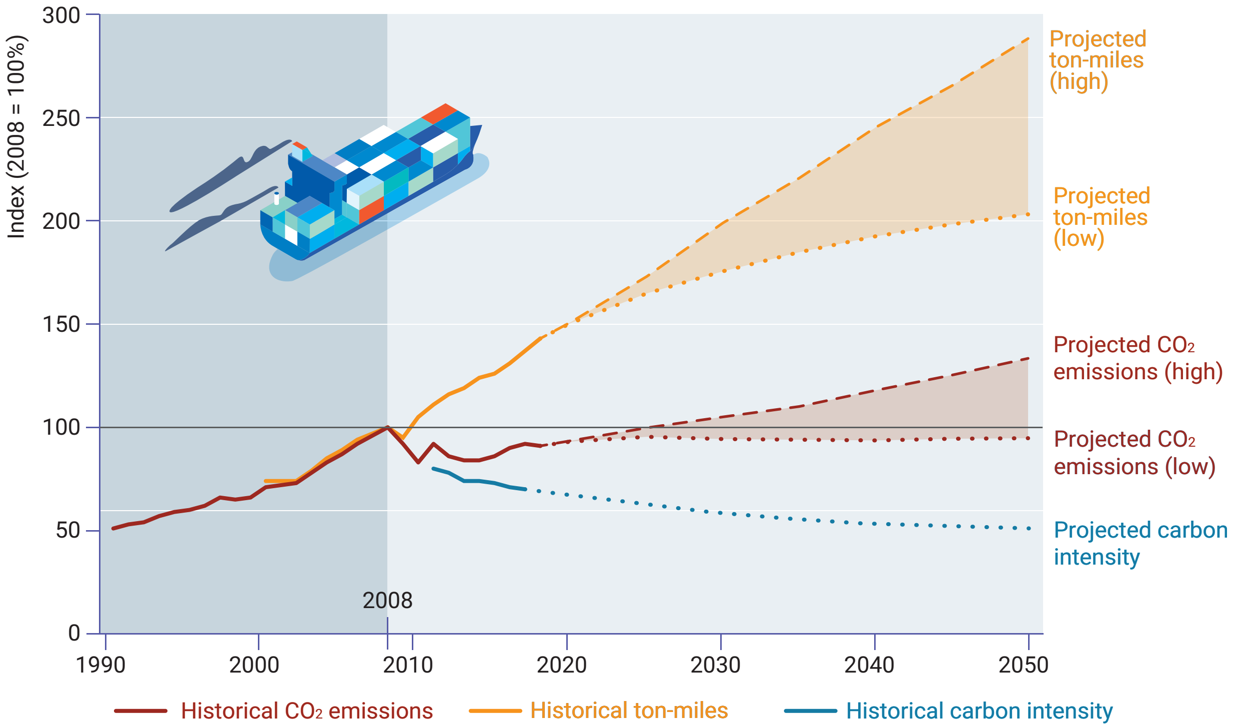
5.2.1 Shipping

GHG emissions from shipping, principally carbon dioxide (CO_2), totalled approximately 1 $GtCO_2$ in 2018, the latest year for which detailed data are available (IMO 2020), with small additional emissions of methane (CH_4) and nitrous oxide (N_2O). CH_4 emissions have risen in recent years (albeit from a low base), due to the increased number of liquified natural gas (LNG)-fuelled ships. Shipping also emitted around 100,000 tons of black carbon (soot) in 2018, which is a short-lived climate pollutant that contributes to warming (Comer *et al.* 2017; IMO 2020). Other non-CO_2 emissions (such as NO_x and SO_2) cause net cooling effects, largely through the formation of low-level clouds from SO_2 emissions (Fuglestvedt *et al.* 2009; Peters *et al.* 2012), although in January 2020, new air quality protection regulations for shipping entered into force, with the aim of reducing these emissions (Sofiev *et al.* 2018).

In 2018, international voyages (those between ports in different countries) were responsible for 71 per cent of the sector's CO_2 emissions (IMO 2020).[1] Many of the ships that undertake international voyages also undertake domestic voyages. For example, a ship may load cargo in a port in one country, sail to a second port in that same country to load more cargo, and then sail to a port in another country to discharge cargo.

CO_2 shipping emissions in 2018 were lower than in 2008, which was the historic peak. As shown in figure 5.1, seaborne trade and emissions were closely correlated between 1990 and 2008. At the end of 2007, an oversupply of ships led ships to reduce their speed in order to ensure optimal utilization of their cargo capacity, which consequently reduced emissions. This became even more prominent in 2008 due to the decline in transport demand caused by the global financial crisis. After 2008, ships permanently reduced their speed by about 10–20 per cent compared with their pre-2008 speed, and the average size of bulkers and container ships increased, resulting in further efficiency improvements.

Figure 5.1. Historical and projected international shipping emissions and trade metrics, indexed in 2008, for 1990–2050



Note: The effect of COVID-19 is not included.
Source: IMO (2020)

In future decades, CO_2 emissions from shipping are projected to increase by 4–50 per cent from 2018 levels according to a range of plausible business-as-usual (BAU) scenarios that assume no further policy intervention on shipping emissions. This is due to the projected 40–100 per cent increase in transport demand, despite projected fuel efficiency improvements in some scenarios (Faber *et al.* 2016; IMO 2020). The main driver of the increase in transport demand is the projected growth in wealth, as there is a strong positive correlation between gross domestic product (GDP) per capita and maritime transport demand.

DNV GL (2020) estimates that COVID-19 will cause the total demand for seaborne transportation to decline by approximately 8 per cent in 2020, which will vary between cargo segments. By May 2020, some segments had seen an increase in activity compared with the same period in 2019, though container shipping capacity reduced by 6 per cent. Manufacturing is typically more affected in an economic downturn, which in turn reduces the demand for seaborne trade of manufactured products and base materials. IMO (2020) did not foresee COVID-19 as impacting emissions projections for 2030 and beyond.

5.2.2 Aviation

In 2018, global CO_2 aviation emissions were approximately 1 Gt (Lee *et al.* in press), of which about 65 per cent were international and 35 per cent domestic (Fleming and de

1 According to another definition of international shipping emissions, which refers to ship types rather than to voyages, 87 per cent of emissions are international (IMO 2020).

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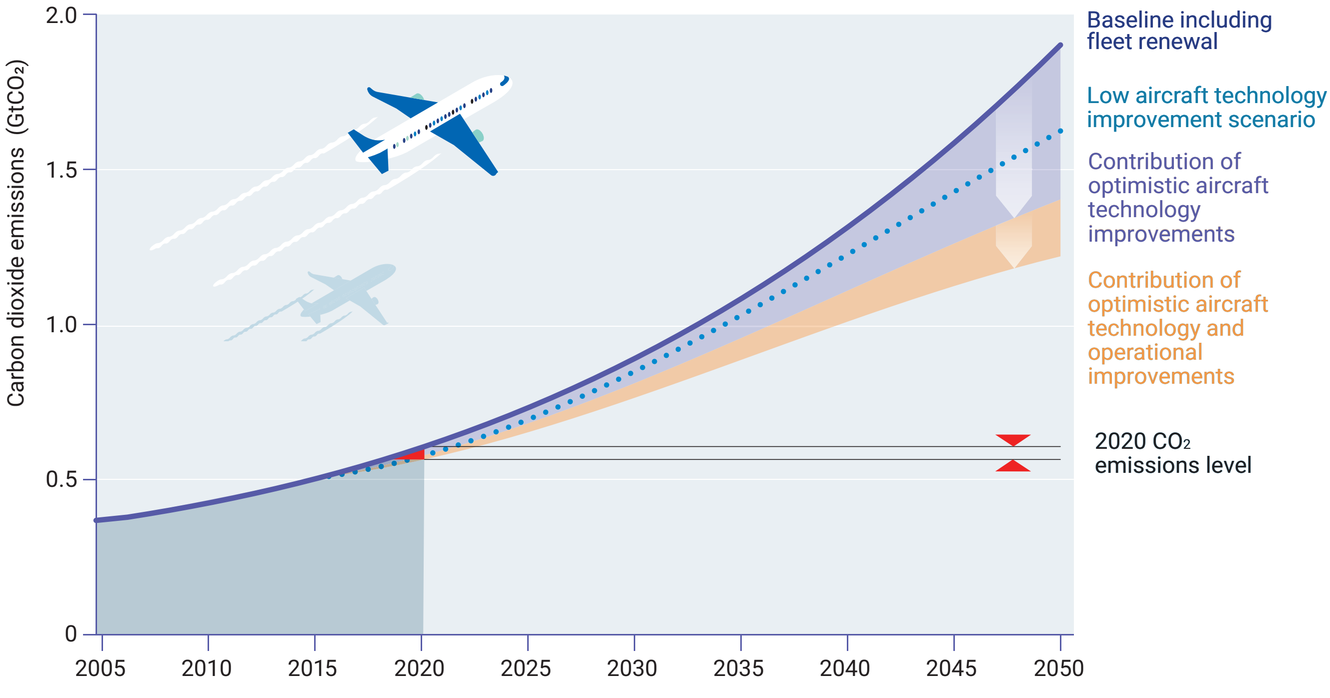
Lépinay 2019).[2] Emissions have increased by around 27 per cent over the last five years (an average annual increase of 4.6 per cent based on International Energy Agency (IEA) data), while passenger numbers have grown by 38 per cent (based on International Air Transport Association (IATA) data).

Despite increased access to mobility, aviation remains the preserve of high-income earners. Over 60 per cent of demand for aviation comes from inhabitants of high-income countries (Becken and Pant 2019). According to Gössling and Humpe (2020), approximately 1 per cent of the world's population account for more than half of the total emissions from passenger air travel, thus revealing a strong equity dimension to aviation as a consumer sector. Chapter 6 discusses some of the demand-side issues related to aviation emissions and how these can be managed and re-imagined in a post-pandemic future.

CO_2 emissions from international aviation, along with related non-CO_2 emissions from water vapour, NOx and soot/aerosol particles have a net warming impact on climate, with the total impact of both types of emission estimated at 3.5 per cent of all drivers of climate change from human activities (Lee *et al.* in press). Historical CO_2 emissions from global aviation result in approximately 34 per cent of present-day aviation-related effective radiative forcing (ERF), with non-CO_2 impacts accounting for approximately 66 per cent of ERF from (global) aviation (Lee *et al.* in press).

The aviation industry expects emissions to increase in the coming decades, despite the current COVID-19 pandemic, which is currently estimated to impact traffic until at least 2024 (IATA 2020b). The latest emissions projections from the eleventh meeting of the ICAO Committee on Aviation Environmental Protection (CAEP/11) (figure 5.2, prepared prior to the pandemic) suggest that emissions of international aviation will increase from about 0.5 $GtCO_2$ of emissions (2015) to 1.2–1.9 $GtCO_2$ by 2050 (Fleming and de Lépinay 2019). Revenue ton-kilometres (a metric for transport work in the aviation sector) are also expected to increase fourfold in the same period.

Figure 5.2. Projections of CO_2 emissions for international aviation



Note: Projections were made prior to the COVID-19 global pandemic.
Source: Fleming and de Lépinay (2019)

Figure 5.2 shows projections of CO_2 emissions for international aviation to 2050, and incorporates projected improvements in technology, operations and infrastructure use. These trends assume that growth is unconstrained by airport infrastructure or airspace operational constraints. A wide range of factors, such as fluctuations in fuel prices and global economic conditions, can affect such trends.

The current COVID-19 pandemic has severely affected demand for aviation transport, with 2020 passenger numbers expected to be 55 per cent lower than 2019 levels, and air cargo 12–15 per cent lower (IATA 2020b; IATA 2020c), though it is too early to tell what this will mean in terms of emissions. Current IATA forecasts suggest that short-haul traffic will recover more quickly than long-haul

2 Different data sources and emissions estimation methodologies are used in the literature, which may result in some differences. For example, 'top-down' methodologies are used for IEA data, while Fleming and de Lépinay (2019) use a 'bottom-up' approach for their emissions models.

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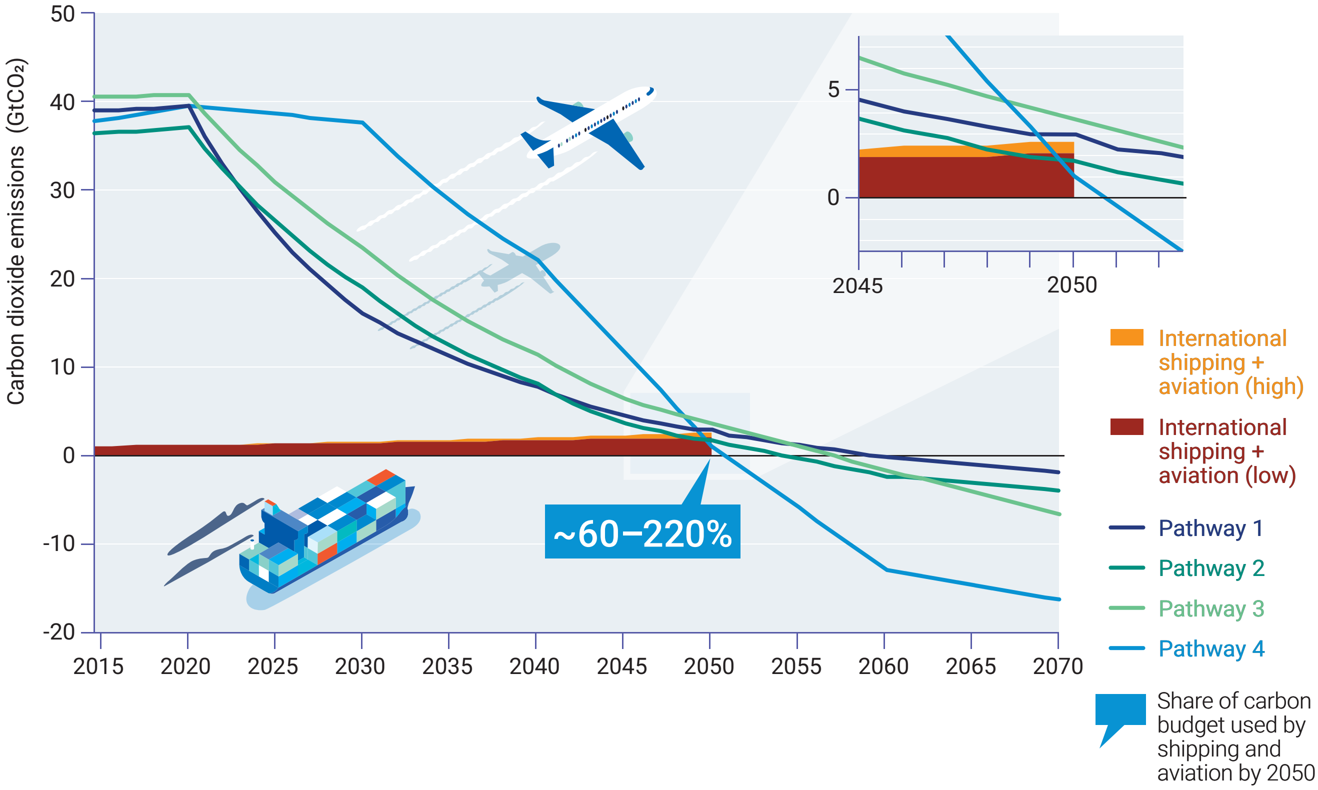
traffic. Market analysts suggest that some of the reductions in corporate travel could be permanent, which is supported by the Global Business Travel Association's ongoing polling (Global Business Travel Association [GBTA] 2020). Overall, emissions are likely to increase as traffic recovers, but there is significant uncertainty over the rate of recovery and impact on long-term projections.

5.2.3 International shipping and aviation emissions and the goals of the Paris Agreement

Unless States choose to include international shipping and aviation GHG emissions in their initial NDCs, these emissions are not addressed by national policies. The emissions trajectories from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) (2018) indicate that global temperature increase can only be limited to no more than 1.5°C if CO_2 emissions reach net zero by 2050 (interquartile range: 2045–2055), with active permanent removal of CO_2 from the atmosphere thereafter. To limit global warming to below 2°C, CO_2 emissions need to reach net zero by 2070 (66 per cent probability). Based on these pathways, it is clear that international shipping and aviation must be completely decarbonized by around 2050 for 1.5°C and by 2070 for 2°C.

This is illustrated in figure 5.3, which shows combined CO_2 emissions from international shipping and aviation as percentages of the available CO_2 budget, relative to IPCC illustrative 1.5°C scenarios. Without further mitigation action, combined international emissions will consume around 60–220 per cent of the available global CO_2 budget by 2050. This remains the case even when the benefits of technology are included to arrive at the 'low' estimates for fuel usage.

Figure 5.3. Global emissions pathways of CO_2 limiting global warming to 1.5°C under IPCC illustrative 1.5°C scenarios



Sources: Pathways redrawn from figure SPM3a, IPCC (2018); international aviation + shipping emissions of CO_2 from Fleming and de Lépinay (2019)

5.3 Mitigation options

5.3.1 Shipping

Improving supply chains and logistics

There is significant potential to improve efficiencies throughout transport networks, aligning transport demand with size, operations and functionality of ships as well as land-based infrastructure and logistics systems. Improving fleet efficiency can be achieved through increased utilization (for example, reducing ballast leg using larger vessels, assuming the increased capacity is utilized), alternative sea routes that have shorter distances, and reduced speed (DNV GL 2019).

Reducing ships' speed has large emissions reduction potential. The required propulsion power of a ship increases approximately to the third power of its speed. Since 2008, the shipping fleet has reduced its average speed and significantly reduced its emissions, though further reductions are possible (IMO 2020). Reducing the speed of large tankers from 12 knots to 11 knots for example,

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reduced emissions per ton-mile by around 8 per cent. Below 7 knots, the emissions begin to increase again (Lindstad and Eskeland 2015).

Improving ship design and operation

The newest generation of ships (built after 2015) are typically about 10–15 per cent more efficient than older ships, mainly due to optimized hull design and propeller efficiency and reduced auxiliary loads. This was at least partly driven by regulation on the Energy Efficiency Design Index (EEDI), an IMO efficiency standard that applies to new ships contracted from 2013 (Faber and 't Hoen 2016). Ships built in the next five years may improve by another 15–25 per cent through improved machinery and electricity systems, which could include measures such as hybridization (peak load shaving in conjunction with batteries) and waste heat recovery. Later generations could include a full-scale application of sails and kites, air lubrication and more advanced waste heat recovery, with another 5–10 per cent improvement on average (DNV GL 2017). Operational measures could reduce emissions by a further 5–10 per cent (DNV GL 2017; IMO 2020).

The total potential of improving the energy efficiency of shipping up to 2050, including logistics and supply chain improvements, speed reduction and ship design and operation, ranges from 35 to 55 per cent compared with 2018 (DNV GL 2019; Balcombe *et al.* 2020; IMO 2020). Most measures are expected to be cost-efficient with current fuel prices, though wind power, solar panels, air lubrication and waste heat recovery, which require significant investment, need a higher fuel price to be cost-efficient (IMO 2020).

5.3.2 Aviation

Technological improvements – engine and airframe

A recent review (ICAO 2019a) requested by ICAO using independent experts examined the two types of aircraft that burn the overwhelming majority of fuel, the single-aisle (such as the Boeing 737 and Airbus A320) and the twin-aisle (such as the Boeing 777 and 787, and Airbus A330 and A350), and estimated their performance in 10 and 20 years (2027 and 2037). According to the review, radical alteration in aircraft shape is unlikely by 2037, with improvements limited to 'tube and wing' type aircraft. The following targets were deemed challenging but possible by 2037: reductions in fuel burn for single-aisle and twin-aisle aircraft of 21.6 per cent and 21.0 per cent, respectively, which are annual improvements of 1.22 and 1.28 per cent. Prior to the COVID-19 pandemic, in October 2018, IATA forecasted compound annual growth in air travel of 3.5 per cent, which equates to a doubling over 20 years and is considerably greater than the reductions likely to follow from technological improvements.

In the ICAO/CAEP report, independent experts accepted the constraints on design that are currently imposed. In line with current practice, aeroplanes are designed for longer ranges than required, as this gives flexibility in terms of operations and makes resale easier, though at the expense of potential fuel-burn reductions. In a 2010 ICAO review (ICAO 2010), the following additional, but relatively small, savings were identified from changing design constraints:

- reducing the cruise Mach number from M=0.84 to 0.78 would give potential savings of around 4 per cent for twin-aisle aircraft
- increasing wingspan for some designs would reduce fuel burn, though this would require wider gates at airports or folding wings (as on the Boeing 777X)
- injecting water into engines to mitigate the high-temperature problems experienced at take-off would improve engine performance during cruise as less turbine cooling air would be required
- restricting top-of-climb performance (to make the clime rate smaller) would allow for better optimization of engines.

The independent experts also looked at advanced alternative aircraft types, such as the blended wing body (a design that merges fuselage with a large delta wing), and configurations with wider bodies, smaller wings and engines at the rear of the aeroplane. For the blended wing body, the fuel-burn reduction was 10–12 per cent compared with advanced conventional aircraft. Another alternative design, the Aurora D8, which was studied at the Massachusetts Institute of Technology (MIT) with support from the National Aeronautics and Space Administration (NASA), has wings and a separate fuselage, and offers roughly a 13 per cent improvement. Chen *et al.* (2019) estimate that blended wing bodies will be 31.5 per cent more efficient in terms of fuel burn than current aircraft. In general, there are likely to be improvements in aircraft airframes and engines in the next 20 or so years, which will improve the burn-fuel metric by around 1.2 per cent per year. However, the crucial conclusion is that the sum of the potential improvements does not come near to matching the projected growth in aviation, let alone to reducing emissions from the current level.

Operational improvements

In practice, the operation of aircraft is generally less than optimal as they often fly below full capacity and cannot take the best flight route due to diversions and holding patterns. Improved operations could be achieved from, for example, single-engine taxi procedures and ground holds in the terminal area, reduced or de-rated thrust on departure, more direct routing and weather-optimized routing en route, and continuous descent approach (CDA) during arrival. A recent ICAO study calculated that routing inefficiencies currently total 2–6 per cent (Brain and Voorbach 2019). Clearly, the scope for operational improvements to reduce CO_2 emissions is limited.

5.3.3 Alternative fuels

For both the aviation and shipping sectors, decarbonization cannot occur without a transition away from the fossil fuels

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that they currently burn to alternative fuels. Such fuels could include synthetic hydrocarbon fuels[3] produced from biomass, waste products or CO_2 direct air capture (DAC) from the atmosphere (The Royal Society 2019), zero-carbon fuels and energy carriers, such as hydrogen and ammonia (as long as they are produced without generating additional GHG emissions). This section discusses non-fossil alternative fuels for shipping and aviation that have low, zero or negative GHG emissions throughout their life cycle.

Biofuels

Various biofuels are currently used in shipping and aviation, albeit on a small scale, with estimates suggesting that these will comprise less than 1 per cent of total aviation fuel by 2024 (International Energy Agency [IEA] 2019). While biofuels can have lower life cycle emissions, assessing their merits is complex, as gains towards 'carbon neutrality' depend heavily on their feedstocks and processes, as well as on their direct and indirect emissions, particularly those resulting from land-use change (LUC) from biofuel production. Assuming that biofuel combustion is carbon neutral is therefore a fundamental accounting error that rests on implicit spatiotemporal boundaries and assumptions (Searchinger *et al.* 2009), as for many biofuels, the energy return on investment is comparatively low or possibly negative (Hall, Lambert and Balogh 2014; Chiriboga *et al.* 2020). The availability of land and water is also a key and potentially ethical constraint on the availability of biofuel (Nuffield Council on Bioethics 2011).

For shipping, biofuels are currently three to five times as expensive as conventional fuels (CE Delft and Ecorys forthcoming) and are of similar magnitudes for aviation (IEA 2018).

E-fuels from renewable energy

Other pathways have been discussed for the production of synthetic hydrocarbon fuels, such as power-to-liquid 'electro-fuels' (e-fuels) (Schmidt *et al.* 2018), or more broadly 'power-to-x pathways' (Kober *et al.* 2019) (for example, by incinerating municipal waste). The generation of such fuels critically requires the availability of renewable electricity, CO_2 and water to synthesize hydrocarbon fuels. To create carbon-neutral fuels, hydrogen needs to be produced via electrolysis powered by renewable energy, while CO_2 needs to be taken directly from the atmosphere by DAC and used in Fischer-Tropsch, methanation or methanol synthesis processes. DAC still represents a significant challenge, although some CO_2 may be captured from residual emissions, which includes processes such as fermentation and cement manufacturing.

In terms of environmental performance, e-fuels have much smaller land requirements than biofuel and do not depend on arable land (Schmidt *et al.* 2018), though they do require significant renewable electricity (Fuhrman *et al.* 2020). Notwithstanding the significant barriers of sufficient available renewable energy and CO_2 from DAC, creating synthetic fuel is technologically feasible, though at much greater costs than direct fossil fuel extraction and refining.

In the case of aviation, the use of renewably-generated synthetic fuels (or biofuels) would also benefit the climate through reducing contrail-related warming, due to their absence of soot particles (which are formed from fossil kerosene aromatics and cause the formation of contrails) (Bier *et al.* 2017; Bier and Burkhardt 2019).

Hydrogen and ammonia

Hydrogen can be used as a zero-carbon fuel, either in combustion engines or fuels cells. To ensure that hydrogen is carbon neutral, it must be generated from renewable energy sources or reformation of fossil fuels during carbon capture and storage (CCS).

Although liquid hydrogen (LH_2) has an energy density per unit mass approximately three times greater than aviation kerosene, it has a much lower energy density per unit volume. Thick layers of insulation are also required, which further increases the effective volume. Its use in aviation would therefore require radical aircraft design changes (McKinsey and Company 2020). Similarly, for ships, hydrogen requires about seven times the space of diesel tanks (DNV GL 2019) and would result in a loss of revenue and range. There are also many infrastructural barriers to LH_2-powered aircraft or ships, such as generation and distribution, meaning its development is only likely under a larger-scale hydrogen-oriented energy economy.

The energy content of hydrogen may be obtained without the problems of cryogenic or high-pressure storage by using a hydrogen-containing compound as a carrier. This is done with hydrocarbons but can also be done with nitrogen to form ammonia. Burning ammonia releases the energy of hydrogen on combustion without producing CO_2. Ammonia requires a volume of around 3.5 times the space of traditional fuel tanks (DNV GL 2019). Internal combustion engines can be modified to run on ammonia, though research and development are needed, including on ways to limit emissions of N_2O, a potent GHG (Valera-Medina *et al.* 2018).

Full-electric propulsion

Full-electric propulsion can be carbon neutral if the electricity is generated without emitting CO_2 (Epstein and O'Flarity 2019). However, a major barrier in both aviation and shipping is that the energy stored in batteries per unit mass is around 250 W-hr/kg, whereas hydrocarbon fuel has a calorific value of around 12,000 W-hr/kg. In addition, electrical machinery and control units are heavy and large.

3 Meaning hydrocarbon fuels generated from non-fossil fuel feedstocks and with renewable electricity in the manufacturing process (and avoiding an increase in fossil-powered electricity generation because of the increase in demand for electricity).

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For aircraft, the heaviness of batteries means that battery-propelled aircraft will be limited to shorter ranges. A recent paper by Langford and Hall (2020) states that electric propulsion makes economic sense for ranges between 50 and 200 miles, meaning it will only slightly contribute to reductions in aviation sector emissions. Similarly, batteries can be used as propulsion energy for ships undertaking short voyages, most obviously ferries, but not long voyages unless radical improvements are made.

Implications and key challenges: a focus on price signals and economic incentives

There are several options that the shipping sector can take to transition away from fossil fuels. Techno-economic analyses from the last two years (Ash and Scarbrough, 2019; Lloyd's Register [LR] and University Maritime Advisory Services [UMAS] 2019; DNV GL 2020; IEA 2020) all indicate that sustainable ammonia is the cheapest decarbonization option for shipping in many scenarios, and would only require a small evolution in current on-board machinery. However, the technology is just in development and full-scale pilots are unlikely for another three years, thus prolonging the period of uncertainty in least-cost fuels.

Non-hydrocarbon fuel options for aviation require radical airframe/engine and infrastructural changes. In contrast, 'drop-in' fuel options, which include alternative hydrocarbon fuels such as biofuels and e-fuels, require little or no changes to aircraft, though they still emit CO_2 when combusted in engines. Despite this, drop-in fuels achieve greater climate benefits compared with the life cycle of conventional jet fuel.

The use of alternative low- or zero-carbon fuels will involve massive investment, most of which (90 per cent) will finance the production and distribution infrastructure required, with far less required for on-board engines and fuel storage (Carlo *et al.* 2020). For operators, this will be reflected in the cost of fuel, which is significant for both shipping and aviation. Future carbon-neutral and zero-carbon fuel prices are estimated to cost in the range of US$20–100/GJ, which is significantly higher than current aviation fuel costs of around US$7.5/GJ. IEA estimated that the mean production costs of aviation biofuels in 2018 were approximately two to three times that of fossil jet kerosene (IEA 2018). The major uncertainty lies in the cost and availability of the primary energy sources, such as sustainable biomass and renewable electricity (DNV GL 2020; IMO 2020; LR and UMAS 2020). Shipping fuels traded at around US$8–9/GJ in summer 2020 (Ship & Bunker undated), although recent prices have reached over US$16/GJ.

A shift to fuels that emit low GHG emissions and are renewable provides a very strong economic signal that will further affect the fundamental inputs to fleet growth scenarios. If higher fuel costs translate into airfares, demand will reduce according to price elasticities, assuming all other factors remain equal. Elasticities for passenger air travel vary considerably (Smyth and Pearce 2008) but could average in the order of -1.1 across travel classes (Becken and Carmignani 2020). In the case of shipping, supply chains that adapt to these new economic conditions may enable fleets using renewable fuels to modify their services and modernize their technologies in such a way that allows GHG targets to be met with minimal impacts on the growth in demand for shipping services (Halim, Smith and Englert 2019).

Ultimately, the price gap between incumbent fossil fuels and post-fossil fuels represents a key challenge that prevents investment both in the sectors and infrastructure on land. Without sufficiently stringent regulation in place to force or enable a business case for zero-carbon fuel use, these investments are unlikely to flow at the required scale until there is either a customer preference or a price premium for zero-carbon shipping services.

5.4 Pathways to lower emissions

Section 5.2 shows that projected emissions from shipping and aviation are incompatible with emissions pathways that are consistent with the Paris Agreement temperature goals, given projected increases and the lack of permanent CO_2 removals. This means that the decarbonization options presented in section 5.3 need to be implemented despite their high costs. This section discusses the agreed policy goals for both sectors, concludes that they are not sufficient to achieve full decarbonization by 2050 or well before 2070 and discusses how policies could be intensified.

5.4.1 Current shipping policies

In 2011, the IMO adopted mandatory technical and operational energy efficiency measures that were expected to significantly reduce the amount of CO_2 emissions from international shipping. These mandatory measures (EEDI/Ship Energy Efficiency Management Plan – SEEMP) entered into force on 1 January 2013. In 2016, additional amendments were adopted to mandate the collection and reporting of ships' fuel oil consumption data. The IMO's Marine Environment Protection Committee (MEPC) adopted the Initial IMO Strategy on reduction of GHG emissions from ships in 2018, which sets out levels of ambition for shipping emissions. These are stated in the strategy as:

- phase out GHG emissions from international shipping as soon as possible through strengthened energy efficiency design requirements for ships
- improve the carbon intensity (CO_2 emissions per unit of transport work) of international shipping by at least 40 per cent in 2030 and 70 per cent by 2050, both relative to 2008
- set GHG emissions from international shipping on a declining pathway as soon as possible, reducing the total annual GHG emissions of international shipping by at least 50 per cent by 2050 compared with 2008 as a point on a pathway of emissions

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reductions consistent with the Paris Agreement temperature goals.

The IMO is due to agree on a Revised GHG Strategy in 2023, which will be a key opportunity to update the quantitative targets in line with the latest science, and to remove current ambiguities on their alignment to the Paris Agreement temperature goals. Currently, CO_2 emissions from domestic shipping are generally not addressed in NDCs.

Role of non-State actors and national strategies

The system change required for shipping to decarbonize is considerable and demands industry regulation in order to overcome a range of market barriers and failures. The IMO's most common regulatory target is ships and therefore shipowners, though significant evidence shows that there are many additional energy efficiency barriers and failures (Faber *et al.* 2012; Rehmatulla and Smith 2015).

Private standards and initiatives to reduce GHG emissions from shipping include the following:

- Getting to Zero Coalition: a collaboration of approximately 140 corporations focused on achieving the goal of establishing scalable zero-carbon energy solutions for international shipping from 2030 (Global Maritime Forum 2020).
- Poseidon Principles: a commitment to transparent annual reporting of portfolio operational carbon intensity relative to an interpretation of the Initial IMO Strategy by financial institutions representing approximately 30 per cent of the capital invested in international shipping (Poseidon Principles undated).
- Sea Cargo Charter: a commitment to transparent annual reporting of supply chain operational carbon intensity relative to an interpretation of the Initial IMO Strategy by charterers and cargo owners (Sea Cargo Charter undated).

Altogether, these create a growing set of decarbonization-aligned initiatives that will move capital and purchasing decisions and hold organizations accountable to the Paris Agreement temperature goals. Their connection to the Initial IMO Strategy and Paris Agreement temperature goals indicates that a clarification of the IMO's ambitions within its Revised Strategy could be easily translated into further private sector action.

5.4.2 Current aviation policies

ICAO, as a specialized United Nations organization, has the lead role in steering the aviation industry's response to climate change goals. It has developed two global aspirational climate change goals for international aviation, which are to improve fuel efficiency by 2 per cent per year until 2050, and to achieve carbon-neutral growth from 2020 onward. ICAO Member States have identified four main elements in a 'basket of measures' to achieve these goals: aircraft technologies, operational improvements, sustainable alternative fuels and a market-based mechanism. Member States are also exploring the feasibility of a long-term aspirational goal for international aviation (ICAO 2016; ICAO 2019b).

The means of *in-sector* reductions include aircraft technology improvements through the Aeroplane CO_2 Standard (ICAO undated a), along with guidance on operational improvement measures to minimize fuel burn (ICAO undated b) and sustainability criteria for aviation fuels. The Aeroplane CO_2 Standard is expected to deliver incremental reductions in line with historic improvements in efficiency. Recent reports suggest that about 1.2–1.4 per cent in fleet efficiency gain is possible per year (ICAO 2019; Fleming and de Lépinay 2019), which falls short of the ICAO target of 2 per cent per year and is significantly less than the projected annual growth in aviation.

The route taken by ICAO to achieve carbon-neutral growth is being predominantly pursued via *out-of-sector* measures, in particular through the offsetting element of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which sets a target of not increasing net CO_2 emissions from international aviation over average 2019–2020 levels for the 2021–2035 period (ICAO 2020).[4] CORSIA will require airlines to purchase eligible units to offset emissions above the baseline. Airlines can reduce their offsetting requirement by claiming emission reductions from CORSIA eligible fuels, thus incentivizing the use of fuels with a lower carbon footprint. It is crucial that the UNFCCC and Member States provide clarity on mechanisms to avoid double counting of units. The nature of offsetting means that there will be no absolute reductions in the aviation sector itself through the use of such credits, and could in fact result in a potential increase in CO_2 emissions. Instead, aviation relies on other sectors' avoidance or removal of carbon. By not only continuing to emit but potentially increasing emissions, the net effect will be that no overall reductions can be achieved. This outcome is in stark contrast with the reduction pathway necessary for limiting warming to within 1.5°C (Becken and Mackey 2017). Furthermore, the ambiguity of international aviation's CO_2 emissions in the Paris Agreement is a constraint to multilateral regulation.

Regardless of concerns around the net benefit of offsetting, Scheelhaase *et al.* (2018) estimate that CORSIA will result in the offset of only 12 per cent of total international and domestic aviation emissions by 2030.[5] Currently, offsets

4 This only refers to growth over and above the 2019–2020 levels. Owing to COVID-19 air travel disruptions, the ICAO Council has changed the baseline for the CORSIA pilot period to 2019 levels.

5 CORSIA only addresses international emissions.

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are almost exclusively provided by emissions avoidance. At a hypothetical maximum, if additionality is assumed, only 50 per cent of the emissions will be 'offset' (Becken and Mackey 2017) as the 'baseline' is an intention to emit two units of CO_2; if the avoidance is achieved, aviation still emits one unit. However, additionality is controversial as it inherently cannot be proven (Warnecke *et al.* 2019). More speculatively, it is possible that in the future, offsets – particularly sequestration offsets such as afforestation/reforestation – may become scarce as States use them in their NDC accounting (which also presents a potential double-counting issue).

CORSIA sits alongside several other policies, most notably the European Union Emissions Trading Scheme (EU ETS) that currently includes intra-European flights. How European flights will be treated in terms of compliance with both the EU ETS and CORSIA remains a point of uncertainty (Erling 2018; Scheelhaase *et al.* 2018; Maertens *et al.* 2019).

5.4.3 Intensifying policy measures to achieve decarbonization

The previous section shows that decarbonization of shipping and aviation in line with the Paris Agreement is very challenging but necessary and feasible. It requires policies that specify energy consumption reduction targets for existing fleets, along with policies that aim to achieve a rapid transition away from fossil fuels to alternative fuels with a lower carbon footprint. Policy instruments related to the introduction of new fuels should incentivize an early adoption phase this decade and take a full life cycle approach to emissions accountancy (DNV GL 2020). Policies should aim to rapidly scale the deployment of new fuels as soon as possible (given the long lifetimes of assets), encourage investment in production processes and ramp up the required generation of renewable electricity.

Suitable regulation to bridge the fuel pricing gap could start at the domestic or regional levels. Satellite observations of shipping activity reveal that an estimated 30 per cent of total shipping emissions fall directly within the responsibility of national governments, which is twice the magnitude previously estimated (UCL 2020). Governments could therefore take action on this policy area as part of their NDCs. Domestic or regional actions towards regulating shipping emissions could also prompt ambitious action at the international level (known as 'autonomous interaction' in international law) and serve as a signal to the industry (Martinez Romera 2016).

Given that supply and demand are interlinked, and because investors need to have confidence that fuels will find a market or that ships or aircraft will be able to purchase the type of fuel they require, it takes time to make a transition. Due to these various lag effects, it is important to start the transition early and gradually, taking into account all United Nations Sustainable Development Goals (SDGs).

5.5 Conclusions

1. If left unabated, the international shipping and aviation sectors are projected to emit increasing amounts of CO_2 and other GHG emissions in the coming decades. BAU scenarios indicate that international emissions from these sectors will consume between 60–220 per cent of allowable CO_2 emissions under the IPCC SR1.5 illustrative scenarios by 2050.

2. Current policy frameworks are insufficient and additional policies are therefore required to bridge the gap between the sectors' current BAU trajectories and GHG pathways consistent with the Paris Agreement temperature goals.

3. Improvements in technology and operations can increase the fuel efficiency of transport if further policies incentivize them. However, due to expected increases in demand (even considering the potential impacts of the current global COVID-19 pandemic), improvements are unlikely to result in decarbonization and absolute reductions of CO_2 for either the shipping or aviation sectors.

4. Both sectors will therefore need to combine a maximization of energy efficiency with a rapid transition away from fossil fuel. Fossil fuel substitutes will need to be produced without combustion of fossil fuels, which will require a decarbonization (and rapid scale-up) of new production and supply chains.

5. International aviation currently intends to meet its ICAO goals through heavily relying on carbon offsets, which do not represent absolute reductions, but at best, provide time to transition to low-carbon fuels and introduce energy efficiency improvements. At worst, offsets create a disincentive for investment in in-sector decarbonization and delay the necessary transition. Current carbon offsetting is clearly not a long-term solution and therefore needs to be minimized and eventually phased out. ICAO recognizes this through the CORSIA review scheduled for 2032.

6. For the next few decades it is highly likely that aircraft will be fuelled with hydrocarbons due to their inherent advantages as fuels. Compared with aeroplanes, ships have a less constrained design in terms of volume and mass of fuel, and therefore have greater options, including ammonia.

7. Biofuels can have a lower carbon footprint than fossil hydrocarbon fuels, but this is sensitive to induced LUC emissions, either direct or indirect, which are difficult to quantify. Large-scale production of fossil fuel substitutes will be difficult, expensive and potentially detrimental to the environment.

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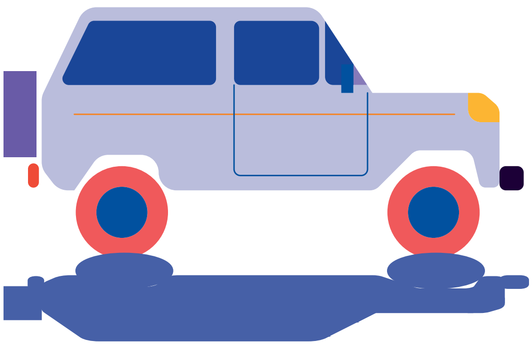
8. The hydrogen feedstock used in ammonia and synthetic hydrocarbon fuel will only present net benefits if the production is powered by renewable electricity and if large amounts of CO_2 are available without additional combustion of carbon-containing material. The use of synthetic fuels and biofuels in aviation would help reduce warming from contrail cirrus.

9. Although there are large uncertainties surrounding demand and price, the cost of fuel could increase severalfold, regardless of the feedstock and process. Any increases in the cost of fuel will raise the cost of both aviation and shipping. This will likely supress demand, especially for aviation, which may ultimately be the most effective means to manage the sector's emissions.



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Appendix S3

Influence of propulsion efficiency on contrail formation

Ulrich Schumann *

Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Postfach 1116, 82230 Wessling, Germany

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Abstract Aircraft cause contrails when flying in an atmosphere colder than a threshold temperature which depends on the overall efficiency η of propulsion of the aircraft/engine combination. Higher η causes contrails at higher ambient temperatures and over a larger range of flight altitudes. The ratio of temperature increase relative to moisture increase in engine plumes is lower for engines with higher η. Thermodynamic arguments are given for this fact and measurements and observations are reported which support the validity of the given criterion. The measurements include contrail observations for identified aircraft flying at ambient temperature and humidity conditions measured with high precision in-situ instruments, measurements of the temperature and humidity increases in an aircraft exhaust plume, and an observation of contrail formation behind two different four-engine jet aircraft with different engines flying wing by wing. The observations show that an altitude range exists in which the aircraft with high efficiency causes contrails while the other aircraft with lower efficiency causes none. Aircraft with more efficient propulsion cause contrails more frequently. The climatic impact depends on the relative importance of increased contrail frequency and reduced carbon dioxide emissions for increased efficiency, and on other parameters, and has not yet been quantified. © 2000 Éditions scientifiques et médicales Elsevier SAS

contrail / aircraft propulsion / efficiency / atmosphere

Zusammenfassung **Einfluss des Antriebswirkungsgrades auf die Bildung von Kondensstreifen.** Kondensstreifen bilden sich hinter Flugzeugen, die in einer Atmosphäre fliegen, die kälter ist als eine Grenztemperatur, deren Wert vom Antriebs-Gesamt-Wirkungsgrad η der Flugzeug/Triebwerks-Kombination abhängt. Für größeres η entstehen Kondensstreifen bei höheren Umgebungstemperaturen und über einen größeren Höhenbereich. Die Zunahme der Temperatur im Vergleich zur Feuchte im Abgas ist um so kleiner je größer η ist. Die thermodynamischen Gründe hierfür werden erklärt und es werden Messungen und Beobachtungen berichtet, die diese Zusammenhänge bestätigen. Die Messungen umfassen Beobachtungen von Kondensstreifen hinter bekannten Flugzeugen mit genauen lokalen Messungen der Temperatur und Feuchte der Atmosphäre im Flugniveau, Messungen der Temperatur- und Feuchtedifferenz zwischen Abgasfahne und Umgebung, und Beobachtungen des Einsetzens von Kondensstreifen hinter zwei dicht nebeneinander fliegenden vierstrahligen Strahlflugzeugen mit verschiedenen Triebwerken. Die Beobachtungen belegen, dass es einen Höhenbereich gibt, in dem nur das Flugzeug mit hohem Wirkungsgrad einen Kondensstreifen bildet. Verbesserungen des Antriebs-Gesamt-Wirkungsgrades führen zu mehr Kondensstreifen. Der damit verbundene Klimaeinfluss hängt außer von den vermehrten Kondensstreifen auch von den verminderten Beiträgen zu Kohlendioxid in der Atmosphäre bei effektiveren Flugzeugen ab und von weiteren Parametern und ist bisher nicht quantifiziert. © 2000 Éditions scientifiques et médicales Elsevier SAS

Kondensstreifen / Flugzeug-Antrieb / Wirkungsgrad / Atmosphäre

* E-mail: ulrich.schumann@dlr.de

Nomenclature

c_p	specific heat capacity of air at constant pressure
C	$c_p\Delta q/\Delta h_p$, contrail factor
e	water vapour partial pressure
e_{sat}	water vapour saturation pressure over liquid water
EI_{H_2O}	water emission index: mass of water emitted per mass of fuel burnt
F	thrust
G	$\Delta e/\Delta T$, slope of the mixing line
h_p	$= h + 1/2(V_p - V)^2$, mass specific plume enthalpy
h_t	$= h + 1/2V_p^2$, mass specific total enthalpy
V	true air speed
$\dot{m}_f$	fuel mass flow rate
$\dot{m}_j$	mass flow rate through engine
p	pressure
q	water vapour mass concentration
Q	combustion heat of fuel
SFC	$= \dot{m}_f/F$, specific fuel consumption
T	temperature
T_C	threshold temperature for contrail formation
V_j, V_p	speeds of jet and plume air
Δe	water vapour partial pressure difference between plume and ambient air
ΔT	temperature difference between plume and ambient air
ε	$= R_{air}/R_{H_2O} = 0.622$, ratio of gas constants of air and water vapour
η	$= FV/(\dot{m}_f Q)$, overall efficiency
Indices	
e, E	environmental
f	fuel
j	jet
p	plume
C	critical (threshold)
M	maximum

1. Introduction

The Special Report of the Intergovernmental Panel on Climate Change (IPCC) on ‘Aviation and the Global Atmosphere’ [10] notes that engine efficiency improvements reduce the specific fuel consumption and, hence, most types of emissions, but contrails may increase. It also notes that contrail cover is projected to grow faster than aviation fuel consumption in the long-term future, partly because future aircraft will have higher propulsion efficiency. These statements are explained in chapter 3 of that report [7] and papers cited therein. The statements were highly debated during the final acceptance procedure of the report and not all critics could be convinced that they are correct. Therefore this paper explains the basic thermodynamic arguments behind these statements and reports on recent experiments which support the theory.

The overall efficiency of propulsion [5] is the ratio

$$\eta = FV/(\dot{m}_f Q) \qquad (1)$$

between the work rate FV performed by the thrust F of the engine at air speed V relative to the amount of chemical energy $\dot{m}_f Q$ provided by the fuel with specific combustion heat Q at flow rate $\dot{m}_f$. The value of Q varies little between aviation fuels, and V as well as the specific fuel consumption SFC, SFC $= \dot{m}_f/F$ [5], are often published by engine manufacturers. Since the overall efficiency depends on speed V, and the thrust F balances the aircraft drag, it is actually not a parameter of the engine alone but characterises the engine/aircraft combination and its state of operation.

Contrails form, if, during mixing the plume gases become saturated with respect to liquid water. Contrails form at temperatures below a threshold temperature which is higher the steeper the mixing line in a diagram of water vapour partial pressure e versus temperature T, see *figure 1* [2,28]. The slope G of the mixing line is the larger the higher η, and hence propulsion efficiency influences contrail formation [31].

The importance of the split of combustion heat into work to propel the aircraft and heat that warms the exhaust plume was first noted by Schmidt [28], and later by others [14,17,19,25]. Peters [23] found that contrails were observed under conditions where the classical Appleman criterion predicts that no contrails should appear. He found empirically that observations fit the thermodynamic explanation better when assuming different contrail parameters related to G for low, medium and high bypass engines, without detailed thermodynamic reasoning. Engine-type dependent contrail factors were later also used by several other authors [4,8,21,29,30, 38]. Busen and Schumann [3] were the first who showed experimentally the ‘η-effect’, i.e., that observed contrail

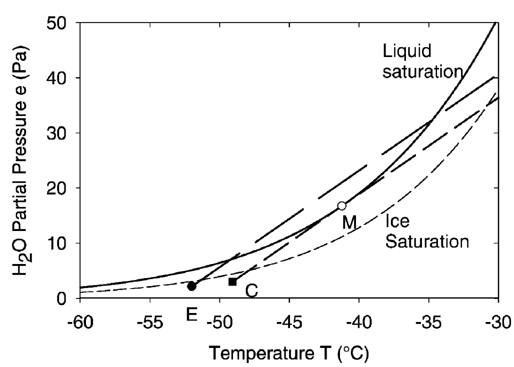

Figure 1. Mixing lines (dashed) and saturation curve over liquid water (full) in a diagram of partial water vapour pressure e versus temperature T. The mixing lines are plotted for environmental conditions with environmental temperature T_e below (point E) and at (point C) the threshold temperature. The point M is that of maximum relative humidity during mixing under threshold conditions.

formation can be explained when accounting for the fact that only the fraction $(1-\eta)$ of the combustion heat contributes to warming the air in the aircraft plume where contrails form, and they showed that η and hence G depends not only on the type of engine but also on the drag and speed of the aircraft.

The overall efficiency η was close to 0.2 in the 1950s, near 0.3 on average for the subsonic airliner fleet in 1992, and may reach 0.5 for new engines to be built by 2010 [10,15]. The efficiency is 0.35 for a B747 aircraft with CF6-80C2B1F engines cruising with Mach 0.86 at 11.9 km altitude, and 0.40 for a Concorde with Olympus 593 engines cruising with Mach 2 at 16.5 km, on 6400 km missions [6].

The η-effect is important because it implies that better engines, though using less fuel for the same propulsive thrust (i.e. less SFC), do produce contrails at higher ambient temperatures and hence at lower altitudes in the troposphere and larger altitudes in the stratosphere, i.e. over a larger range of altitudes.

The disturbances induced by global aviation cause an additional radiative forcing (heating) of the Earth-atmosphere-system by aircraft of about 0.05 W m^{-2} or about 3.5% of the total radiative forcing by all anthropogenic activities in 1992. The accumulated carbon dioxide emissions from aviation until 1992 and the contrail cover in 1992 have been estimated to have contributed both about 0.02 W m^{-2} while nitrogen oxides emissions (by changing ozone and methane concentrations) contributed the rest. These values are increasing because of increasing air traffic causing more contrail cover and increasing aircraft emissions [10,26]. Of climatic importance are only the long-lasting contrails which form in ice-saturated ambient air, mainly in the upper troposphere [9,11,20,27,31].

The η-effect is of quantitative importance in assessing the climatic effects from contrails. In the troposphere, an increase of η from 0.3 to 0.5 in the standard atmosphere increases the threshold formation temperature of contrails by 4.2 to 4.9 K (increasing with ambient humidity), equivalent to 650 to 760 m lower threshold altitude [31]. In the stratosphere, the same change in η increases the formation temperature even more (by 14 K), equivalent to 2130 m higher altitude (for zero ambient humidity, and $-56.5°$C ambient temperature, the altitude is 13.8 and 15.9 km for $\eta = 0.3$ and 0.5, respectively). However contrails remain usually short in the very dry stratosphere.

In a fuel consumption scenario of 1992, the global mean contrail cover is computed to amount to about 0.1% for $\eta = 0.3$, and changes by 10% of this value if η varies from 0.25 to 0.35 [27]. The contrail cover reacts to η more strongly locally than globally. In a baseline scenario of traffic and fuel consumption development from 1992 to 2050 used in IPCC [10], traffic increases by a factor of about 6, fuel consumption by a factor of about 3.2, fuel consumption in the upper troposphere (where contrails form preferentially) by a factor of about 4, contrail cover by a factor of 5, and radiative forcing by a factor of about 6. The about 3-fold increase in fuel consumption from 1992 to 2050 causes a 6-fold increase in the radiative forcing by contrails because of increase of fuel consumption (factor 3.2), relatively stronger increase of fuel consumption in the upper troposphere (factor 1.36), more contrail cover because of more efficient engines (factor 1.24), and because more traffic will occur in regions with high specific forcing per contrail cover (factor 1.11) [9,20]. Hence propulsion efficiency is responsible for 20% (0.24/1.24) of the expected future increase in contrail cover and radiative forcing. In this paper, the theory of the η-effect is explained and data are presented supporting the theory.

2. Contrail formation conditions

The exhaust heat and the mass of exhaust gases leaving the engine are contained within a region called 'plume' which grows in cross-section by mixing with ambient air. The young plume coincides with the 'jet' of high speed exhaust gases which forms initially by merging the jet from the core engine and the jet of air passing through the fan in the engine bypass surrounding the core engine, see *figure 2*. At engine exit, temperature and humidity profiles of the core and bypass jets are much different, because the core jet contains a large fraction of the combustor heat and all of the water vapour formed resulting from burning the hydrocarbon fuel with air while the bypass jet carries part of the heat but no combustion water vapour, and the jets have different velocities. After engine exit, the jets expand to outside pressure and approach isobaric conditions. A few engine diameters after engine exit, possibly depending on whether the bypass and core jets are premixed internally in an engine with shrouded bypass, a uniform turbulent jet forms in which the temperature and humidity profiles

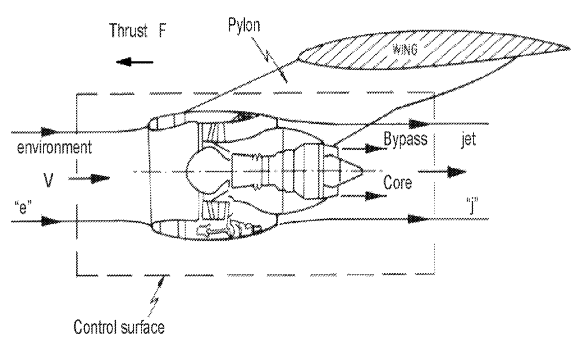

Figure 2. Control surface surrounding the engine, with environmental air (e) at entry (speed V), and core and bypass jets combining into one jet with jet speed V_j at the downstream exit plane (j) of the control volume. The static pressure is assumed to be constant at the control surface. The engine transfers thrust F to the wing via the pylon. (adapted from [5], with the author's permission).

approach a similar shape. Numerical simulations have shown that the remaining differences in the temperature and humidity profiles may enhance the maximum relative humidity reached in the plume by about 10% and the threshold temperature for contrail formation by about 1 K [33]. This effect is neglected in the following analysis.

The jet carries energy initially both in the form of internal enthalpy h and kinetic energy per unit mass. During mixing, the specific energy $1/2(V_p - V)^2$ due to velocity differences between the speed V_p of the jet (or plume) air and the speed V of ambient air gets converted into internal enthalpy, so that the jet ceases. During this mixing process the specific plume enthalpy

$$h_p = h + 1/2(V_p - V)^2 \tag{2}$$

is a conserved property of the plume gases. The speed values refer to the frame of reference fixed to the aircraft. As a consequence of the split into two forms of energy, the plume temperature is smaller than is to be expected from the released combustion heat. In principle, this enhances the tendency for contrail formation and the corresponding threshold temperature, and the effect grows with $(1-\eta)^2 V^2/(c_p \eta^2)$, where c_p is the specific heat capacity of air at constant pressure [31]. However, most of the kinetic energy is converted to heat by mixing and dissipation before a contrail forms, so that the threshold temperature increases only by 0.1 to 0.2 K for typical airliners. Hence, to a good approximation, the plume temperature at the point where contrails form is directly related to h_p, and the state of the plume during mixing with ambient air follows essentially a straight line in a water concentration-enthalpy ($q - h_p$) diagram from the state approximating the engine exit conditions to the state of the ambient atmosphere (e.g., point E in *figure 1*).

The mass specific water concentration q is related to partial water vapour pressure e in an ideal gas,

$$e/p = q R_{air}/R_{H_2O} = q/\varepsilon, \quad \varepsilon = 0.622, \tag{3}$$

with given gas constants R of air and water vapour. Plume enthalpy h and temperature T are linearly related for constant c_p, which is a reasonable assumption for typical contrail conditions. Hence the mixing line is close to straight also in an e–T-diagram, see *figure 1*. The slope of the mixing line is:

$$G = \Delta e/\Delta T = p c_p \Delta q/(\Delta h_p \varepsilon). \tag{4}$$

(The ratio $C = c_p \Delta q/\Delta h_p$ is also known as contrail factor [2].) Here Δe and ΔT are the differences between the values of water vapour partial pressure and temperature in the plume and the respective values in the ambient air. *Figure 1* shows also the saturation pressure e_{sat} of water vapour over liquid water which grows strongly with temperature T [37]. The relative humidity $U = e/e_{sat}$ is very low near the engine exit and often low in the ambient atmosphere, but may reach saturation during mixing at point M of *figure 1* when the ambient temperature T_e equals the threshold temperature T_C. As can be understood from *figure 1*, the threshold temperature T_M for 100% relative humidity in the ambient air follows from $de_{sat}(T_M)/dT = G$. Its value can be evaluated with high precision for $-60°\text{C} \leqslant T_M \leqslant -10°\text{C}$ from

$$T_M = -46.46 + 9.43 \ln(G - 0.053) + 0.720\big[\ln(G - 0.053)\big]^2, \tag{5}$$

with T_M in °C and G in Pa K^{-1} [31]. Likewise, the threshold temperature T_C for given ambient humidity U follows from:

$$T_C = T_M - \big[e_{sat}(T_M) - U e_{sat}(T_C)\big]/G. \tag{6}$$

This can be evaluated directly for $U = 0$ or $U = 1$, and with a Newton iteration otherwise (a Fortran routine for that purpose is available from the author). Other, often less accurate, approximate solutions have been proposed [4,8,21].

3. Engine energy budget

For convenience, we consider an engine contained within a control volume fixed with boundaries far enough upstream and downstream of the engine as shown in *figure 2* so that the pressure is close to uniform across the volume boundary. Moreover, we assume that the fuel mass flow rate $\dot{m}_f$ is small compared to the mass flow rate $\dot{m}_j$ of gases through the engine and ignore any minor energy fluxes, such as electric energy production, bleed air for aircraft heating, or heat losses from the engine other than with the jet flow. Also, we do not distinguish between core and bypass ducts and jets, rather than consider the whole engine as a black box, and assume that the engine produces a jet of exhaust gases that result from the mixed sum of bypass and core jets. These assumptions could be avoided but that would result in a more complex analysis without gain of insight and without changing the conclusions. Since the nominal air speed of the aircraft is V, air enters the control volume from the front (index e for environmental) with speed V relative to the aircraft and leaves the control volume at the rear (index j for jet) with speed V_j. The engine performs thrust F, a force that propels the aircraft.

3.1. Momentum budget

The momentum budget gives the balance between the thrust F of the engine and the momentum inflow and outflow, with different speeds but same mass flux rate $\dot{m}_j$:

$$F = \dot{m}_j (V_j - V). \tag{7}$$

The thrust grows with the mass flux $\dot{m}_j$ and the increase in speed of the jet compared to ambient air.

3.2. Energy budget

The principle of energy conservation is independent of which frame of reference is being used, but the formulation of the energy budget depends on the frame of reference because of the frame-dependence of kinetic energy.

3.2.1. Energy budget in a frame of reference fixed to the aircraft

In a frame of reference fixed to the aircraft, the speed of the aircraft is zero and the speed of ambient air is negative the same as the nominal air speed of the aircraft. The energy budget expresses the change in the sum of internal and kinetic energy between engine exit and entry as the result of the addition of combustion heat due to burning of fuel inside the engine at the flow rate $\dot{m}_f$ with mass specific combustion heat Q. The specific enthalpies at inflow and outflow are $h_e + 1/2V^2$ and $h_j + 1/2V_j^2$. Thus:

$$\dot{m}_j\left[h_j - h_e + 1/2\left(V_j^2 - V^2\right)\right] = \dot{m}_f Q. \qquad (8)$$

In this reference frame, the thrust F does not change the energy budget because the engine does not move in this frame. Hence this form of energy budget is independent of η. In terms of total enthalpies, $h_t = h + 1/2V^2$, the budget reads simply:

$$\dot{m}_j[h_{t,j} - h_{t,e}] = \dot{m}_f Q. \qquad (9)$$

This simple form is the reason why total enthalpies are popular in propulsion engineering. However, this form is not suitable for plume analysis, since h_t is not conserved in the plume during turbulent conversion of kinetic energy into internal enthalpy, because the plume mixes with ambient air and the ambient air moves relative to the frame of aircraft.

3.2.2. Energy budget in a frame of reference fixed to the ambient air

Alternatively, in a frame of reference fixed to the ambient air, the engine is moving and the thrust now performs work. With specific enthalpies at inflow and outflow, h_e and $h_j + 1/2(V_j - V)^2$, follows:

$$\dot{m}_j\left[h_j - h_e + 1/2(V_j - V)^2\right] = \dot{m}_f Q - FV = \dot{m}_f Q(1-\eta). \qquad (10)$$

Here η is the overall efficiency, see equation (1). Therefore:

$$\Delta h_p = h_j - h_e + 1/2(V_j - V)^2 = Q(1-\eta)\dot{m}_f/\dot{m}_j. \qquad (11)$$

The plume enthalpy $h_p = h + 1/2(V_p - V)^2$ is different from the total enthalpy $h_t = h + 1/2V_p^2$. Nevertheless, both versions of the energy budget are, of coarse, formally equivalent. One can be converted into the other by replacing F by $\dot{m}_j(V_j - V)$, equation (7). However, for our purpose only the latter version is suitable because only h_p and not h_t is conserved during conversion of kinetic to internal enthalpy during mixing of the plume with ambient air. Only the velocity difference $1/2(V_j - V)^2$ and not $1/2V_j^2$ is converted from kinetic to internal enthalpy by turbulent mixing.

3.3. Mass budget for water vapour

The exhaust gases carry more water vapour than the air which enters the engine, because of combustion of hydrogen containing fuels according to EI_{H_2O}, the emission index, which gives the mass of water produced in the engine per mass of fuel burnt:

$$\Delta q = q_j - q_e = EI_{H_2O}\dot{m}_f/\dot{m}_j. \qquad (12)$$

3.4. Consequence for contrail parameter G

As a consequence of equations (4), (11) and (12) it follows that:

$$G = [\Delta q/\Delta h_p]pc_p/\varepsilon = EI_{H_2O}pc_p/[\varepsilon Q(1-\eta)]. \qquad (13)$$

G is independent of the mass flux ratio $\dot{m}_f/\dot{m}_j$ and independent of dilution with growing plume age. We see that G, and hence T_M and T_C, equations (5) and (6) grow with the overall efficiency η. Engines with higher η cause exhaust plumes with higher relative humidity, and hence contrails already at higher ambient temperature and more frequently.

3.5. Discussion

Equation (11) shows that only the fraction $(1-\eta)$ of the combustion heat Q enters the exhaust plume. The remainder does not heat the young exhaust jet, but is used to overcome friction and to induce kinetic energy of turbulence and vortex motions in the airframe's boundary layer and in the wake behind the aircraft. The kinetic energy of the wake vortices gets dissipated to heat long after the contrail has formed, and the dissipation of turbulence in the turbulent boundary layer heats mainly air outside the young exhaust plume.

As a consequence of less energy in the exhaust jet, the exhaust gases of modern engines exhibit a lower ratio of $\Delta T/\Delta q$. This does not imply lower temperatures everywhere in the engines. In fact, the opposite is the case. The overall efficiency is the product of thermal and propulsive efficiencies [5]. Modern engines use combustors with higher temperatures and higher pressures, causing a higher thermal engine efficiency [5]. However, this fact does not contradict a lower ratio $\Delta T/\Delta q$ in the plume.

A higher overall efficiency may also result from a larger bypass ratio. The propulsive efficiency increases with the bypass ratio, i.e., ratio between the mass fluxes through the bypass duct of the engine relative to the core duct of the engine [5]. For given thrust, the speed of the jets is the smaller the larger the mass flux through the engine, and hence the smaller are the losses in terms of kinetic energy.

We note that the overall efficiency η is zero at the ground for a fixed engine, simply because $V = 0$, see equation (1). For the same reason, h_p equals h_t in that case. Hence ground measurements of engine exit conditions, after proper mixing of core and bypass jets, in terms of total enthalpy or temperatures (including kinetic energy), would always give the same ratio of $\Delta T_t/\Delta q$, regardless of the performance of the engine.

Moreover, $\eta = 0$ at flight, if the engine is idle with zero thrust for finite fuel consumption (such as during descent). Therefore contrails are expected to disappear at higher altitude during descent than they occur during ascent, and an aircraft may avoid contrail formation, at least near threshold conditions, by flying with reduced power.

From equation (13) we see that the previously defined contrail factor [2] is:

$$\begin{aligned} C &= c_p \Delta q/\Delta h_p = G\varepsilon/p \\ &= EI_{H_2O} c_p/[Q(1-\eta)]. \end{aligned} \tag{14}$$

For $\eta = 0$, $EI_{H_2O} = 1.25$, $c_p = 1004$ J kg^{-1} K^{-1}, and $Q = 43$ MJ kg^{-1}, the contrail factor is 0.0292 g kg^{-1} K^{-1}, and certainly above 0.0277 g kg^{-1} K^{-1} for typical kerosene fuels (hydrogen content > 13.5%, $EI_{H_2O} > 1.2$, $Q < 43.5$ MJ kg^{-1}). Values below this minimum, as reported in reference [30], are impossible. Peters [23] suggested values of the contrail factor of 0.036, 0.040, and 0.049 g kg^{-1} K^{-1} for non-bypass, low bypass and high bypass engines. These values appear to be rather large, because they imply large η-values of 0.19, 0.27, 0.40. Smaller values of $C = 0.030$, 0.034, and 0.039 g kg^{-1} K^{-1} for the various engine types were used in references [8,21,30]. Contrail factors for bypass engines are higher than those for non-bypass engines not because the core exit temperature is reduced by extracting some energy to turn the fan [29], but because of higher overall efficiency of bypass engines. However, C is not only a function of the engine but also of the aircraft performance. Much larger contrail factors would apply for hydrogen fuels [16,31].

4. Experimental validation

4.1. Observed and computed threshold conditions

The dependence of contrail formation conditions on overall propulsion efficiency has been verified to different degrees by various experiments. Several of these experiments were originally designed to investigate the impact of fuel sulphur on contrail formation, but the experiments showed that fuel sulphur has only a small impact on the threshold temperature [7,12].

Busen and Schumann [3], during the German experiment SULFUR 1, observed a contrail behind the Advanced Technology Testing Aircraft System (ATTAS) jet aircraft (type VFW 614 with two Rolls-Royce/SNECMA M45H Mk501 turbofan engines with bypass ratio 3 and 32.4 kN take-off thrust) under conditions where the classical Appleman criterion, which implies $\eta = 0$, would predict that no contrail forms. They showed that the observed contrail was explainable when the Appleman criterion was extended to include the η-effect. They estimated $\eta = 0.15$ for this case from measured fuel flow rate, known combustion heat, and computed thrust using engine analysis and aerodynamic drag calculations. The contrail formation temperature was observed within an accuracy of about 0.5 K, whereas the difference in threshold temperatures for $\eta = 0$ and 0.15 was about 2 K, hence the measured agreement between observed and computed threshold conditions was significant. However, they had to rely on ambient temperature and humidity data derived from a nearby radiosounding.

Later Schumann et al. [32] repeated such observations (experiment SULFUR 2) in four cases with high precision measurements of temperature and humidity using in-situ instruments (platinum resistance thermometers and frost-point hygrometers) onboard the research aircraft Falcon following the observed contrail forming aircraft ATTAS at very close distance and at the same altitude outside the aircraft plume. Contrail formation was documented in videos and photos. In spite of large differences in the sulphur content of the different fuels burnt on the two engines, the contrail onset was observed to occur at temperatures as predicted by the theory independent of aerosol properties, including the η-effect (here $\eta = 0.18$, larger than in the previous experiment because of higher speed), with an uncertainty of less than 0.4 K.

Similar measurements were performed within the NASA project SUCCESS using the NASA-DC8 as contrail forming aircraft and for high precision measurements of ambient temperature and humidity values together with visual contrail observations from various carriers [11]. Again, the data were consistent with the theoretical explanation when taking an engine efficiency of about $\eta = 0.3$ for the DC8.

During a further experiment, SULFUR 3, Petzold et al. [24] measured ambient conditions during contrail formation behind an Airbus A310. In this case the engine efficiency ($\eta = 0.28$) was deduced from engine analysis, taking into account the relatively small aircraft speed during these measurements.

During the European project POLINAT, ten wide-body aircraft of types B747, DC-10 and A340 were similarly observed with respect to contrail formation and the ambient conditions were measured with the Falcon using high-precision frost-point hygrometers [22]. The engine efficiency of the cruising wide-body aircraft was estimated to be $\eta = 0.33$ based on engine analysis. All these data were compiled into a figure and presented and discussed by Kärcher et al. [13]. Recently, data for two more contrail observations (behind an A340 and behind the NASA DC-8) became available during the joint SONEX/POLINAT 2 experiment from measurements with the Falcon [35].

Figure 3 extends that shown in Kärcher et al. [13] collecting all the results available up to now from the 46 case studies in which observers noted and documented whether a contrail was visible or not and in which the ambient temperature and humidity was measured with high precision instruments from a research aircraft that followed the contrail forming aircraft at close distance and at the same altitude outside the aircraft plume. Moreover, the observers noted the type of aircraft and of the engines and the fuel flow rate which allowed to provide estimates of the expected overall efficiency. Symbols in *figure 3* depict the measured ambient conditions and the straight lines departing from these symbols are the mixing lines. The gradient G of the mixing lines is computed as a function of measured ambient pressure p, known values of EI_{H_2O} (about 1.25) and combustion heat Q (43 MJ kg^{-1}), specific heat capacity at fixed pressure c_p (1004 J kg^{-1} K^{-1}), and estimated overall efficiency η. *Figure 3* also includes the curves of vapour pressure for saturation over liquid water (full) and ice (dashed). The cases are assigned to the three panels according to whether the observers reported that a contrail was visible (a), was just forming or disappearing (b), or that no contrail was visible behind the observed aircraft (c).

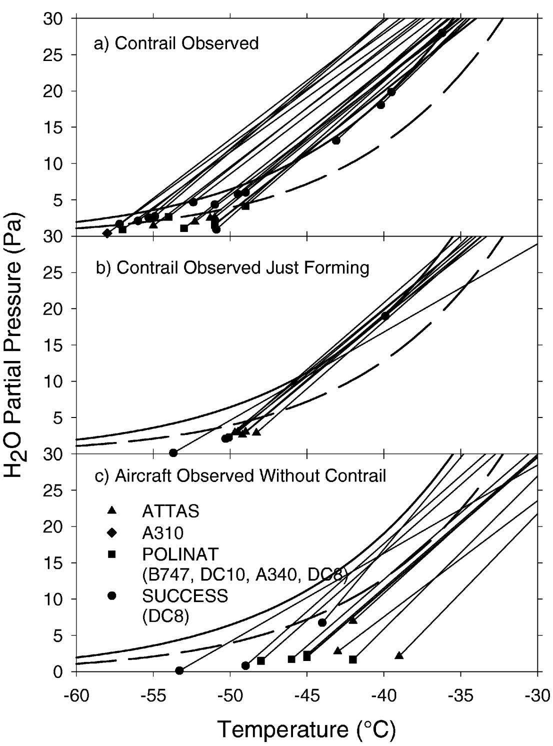

Figure 3. Water vapour partial pressure e versus temperature T. Full thick curves: saturation pressure over liquid water, full dashed: saturation pressure over ice, symbols: measured ambient conditions for various cruising aircraft, full lines: mixing lines with gradients $G = EI_{H_2O} c_p p [0.622 Q (1-\eta)]^{-1}$. The cases are split and presented in three panels: (a) cases where aircraft have been observed to cause visible contrails, (b) aircraft were observed with a contrail just forming or disappearing (threshold conditions), (c) aircraft were observed to fly without a visible contrail. The different symbols refer to different sets of experiments: ATTAS [32], A310 [24], POLINAT [35], SUCCESS [11].

For all cases in *figure 3*, the mixing lines in (a) cross the liquid saturation curve as expected for contrail formation, in (b) come close to the saturation curve within the accuracy of the measured ambient conditions (better than ± 1 K in temperature and $\pm 10\%$ in relative humidity), in (c) stay below saturation. Hence all the observed cases are explainable consistently with the given theory. This does not prove that the theory is correct (such a proof is impossible) but the fact that a large number of cases is consistent with the theory supports the assumption that the theory is correct.

Figure 4 highlights those cases where the mixing line exceeds the saturation curve over ice but where no contrails were observed. These cases show that liquid saturation is, indeed, required for contrail formation.

Figure 5 shows those cases where contrails have been observed but where the mixing line does not touch liquid saturation if computed for $\eta = 0$. These cases give evidence for the fact that some contrail formation can be explained only when taking the η-effect into account, and that the classical Appleman theory, which assumes that all combustion heat gets discharged into the exhaust

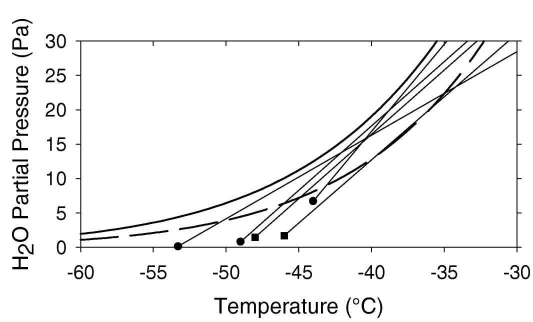

Figure 4. Subset of cases from *figures 3(c)*, where no contrails have been observed but where the mixing line crosses the ice saturation curve.

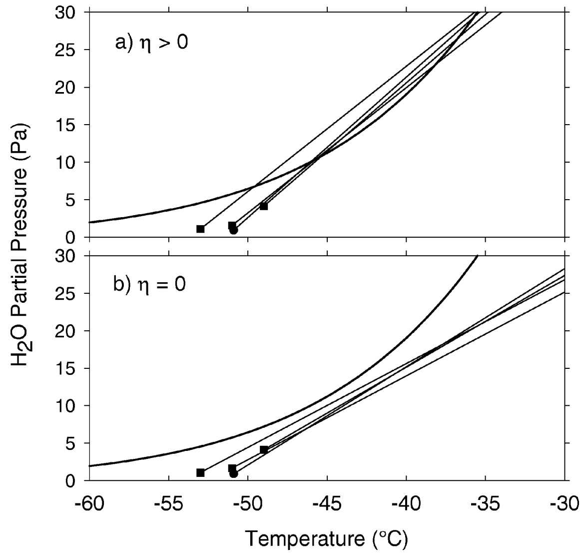

Figure 5. Subset of cases from *figures 3(a)*, where contrails have been observed and where the mixing line crosses the liquid saturation curve if computed for $\eta > 0$ (a), but does not so if computed for $\eta = 0$ (b).

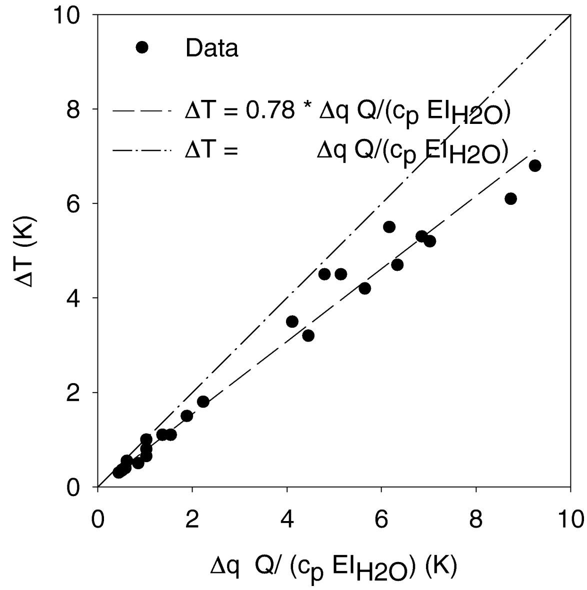

Figure 6. Measured temperature difference ΔT versus measured water vapour mass concentration increase Δq, normalised to an equivalent temperature by means of multiplication with combustion heat Q, specific heat capacity c_p, and emission index EI_{H_2O}, as obtained by measurements with the Falcon in the plume of the ATTAS aircraft during the SULFUR 5 experiment ([34], data provided by R. Baumann). The diagonal and a least square fit line are indicated showing that the data would be best fit for $\eta = (1 - 0.78) = 0.22$. The computed overall efficiency of the ATTAS aircraft is 0.17.

($\eta = 0$), gives wrong results for the threshold temperature value.

Other observational studies [21,30,38] generally support the extended Schmidt–Appleman criterion, but provide less stringent validation tests because of missing or less precise data, in particular for ambient temperature and humidity and aircraft/engine performance at the location and time of contrail observations.

4.2. Measured ratio of temperature and concentration increases in plumes

The measurements cited above did measure T and q in the ambient air, but not the excess values ΔT and Δq in the exhaust plume above ambient values. Hence they cannot be used to experimentally verify that the ratio $\Delta T/\Delta q = (1 - \eta)Q/(c_p EI_{H_2O})$ is the lower the higher η.

Measurements of ΔT and Δq have been performed in the exhaust plume of the ATTAS aircraft during SULFUR 3, with computed efficiency $\eta = 0.17$, for plume ages of 0.5 to 17 s [34]. The data, see *figure 6*, are consistent with the expected ratio. Large ΔT-values correspond to young plumes with strong jet flows. Here the ratio $\Delta T/\Delta q$ may be smaller than later because part of the kinetic energy has still to be converted to internal energy. The measured ΔT values are systematically smaller than the normalised values for Δq. The ratio between the two values is close to the value $(1 - \eta)$ supporting the theory. However, the accuracy of the measured data may not be sufficient to determine the effective factor $(1 - \eta)$ from the data reliably. This is the case in particular for plume ages larger than 4 s, where the temperature differences are less than 1 K, and where small random changes of ambient temperature cause large uncertainties in determining ΔT and also Δq.

Like water vapour, carbon dioxide also gets emitted from combustors burning kerosene into the engine plume independently of engine efficiency and undergoes the same mixing as heat. Values of temperature increase ΔT and carbon dioxide increase ΔCO_2 in young exhaust plumes were measured simultaneously within the SNIF campaign [1], and were used to test the η-dependence of the $\Delta T/\Delta CO_2$ ratio. However, the data scatter strongly around a mixing line and do not provide a significant test of the theory because the instruments measuring the plume properties used inlets at different positions on the fuselage of the measuring aircraft.

4.3. Direct test of the η-dependence

For a direct test of the theory, a formation flight of two different large jet aircraft was arranged, wing by wing, during an ascent and a descent of the aircraft. Contrail formation and ambient conditions were observed simultaneously from a research aircraft. The two contrail forming aircraft were (i) a Boeing B707 equipped with four jet engines of type JT3D-3B with bypass-ratio of 1.4 and

Figure 7. Photo of an Airbus A340 with contrails (left) and a Boeing B707 without contrails (right) at 10.5 km altitude taken from the Falcon cockpit [36].

(ii) an Airbus A340-300 with four jet engines of type CFM56-5C4 with bypass-ratio of 6.8. Ambient conditions were measured and the contrail formation was observed from a research aircraft flying less than 1 km behind the two contrail forming aircraft. As documented in several photos, an altitude range exists in which the A340 causes contrails while the B707 causes none. *Figure 7* shows an example as taken during descent. We clearly see the four contrails forming from the four engines of the A340 while the B707 is seen flying without contrails. The details of these observations and their interpretation with an engine cycle model are described by Schumann et al. [36]. The observations support directly the validity of the theory: The aircraft with more efficient engines causes contrails while the aircraft with less efficient engines causes none during flight at the same altitude under very similar conditions.

5. Conclusions

The thermodynamic analysis, which is the result of first-principle arguments, implies that aircraft and engines, performing with a higher overall propulsion efficiency release a smaller fraction of the combustion heat during cruise into the exhaust plume, and hence cause plume conditions which during mixing reach higher relative humidity for the same ambient temperature and hence form contrails also at higher ambient temperatures. Hence aircraft will form contrails more frequently when using more fuel efficient engines. The theory implies that the ratio of $\Delta T/\Delta q$ in exhaust plumes remote from the engine is the lower the higher η.

This effect can be verified only during flight and not on test rigs (at the ground) because fixed engines produce thrust F but do not perform work FV because of zero speed V.

A large set of observations of aircraft flying with and without contrails and with measured ambient conditions has been compiled. The observations are consistent with the extended Schmidt–Appleman criterion which includes the η-effect. The data also show that liquid saturation is required for contrail formation. Some observed contrails cannot be explained with the Schmidt-Appleman criterion when the η-effect is ignored.

Existing measurements in plumes of temperature and concentration increases are consistent with the theory, but the accuracy of existing data may not be high enough for a rigorous test.

A recent case study with two airliners with different engines, with details reported in a parallel publication [36], shows that an altitude range exists in which the aircraft with high overall propulsion efficiency causes contrails while the aircraft with lower efficiency causes none, as predicted by the theory.

The analysis of contrail impact on radiative forcing performed so far [7,18,20] implies that future aircraft with higher propulsion efficiencies cause more contrails and hence more warming of the atmosphere. However, these analysis methods are only first order estimates. They were performed for fixed fuel consumption scenarios. Hence they do not account for savings in fuel consumption and carbon dioxide emissions when engines and aircraft get improved for fixed traffic. The relative importance of carbon dioxide emissions, contrails and other short-lived effects depends on the development of traffic and emissions with time, because contrails impact radiative heating of the atmosphere immediately while carbon dioxide emissions impact the atmosphere only after long periods of accumulation in the atmosphere [10,16, 26]. Moreover the analysis uses fuel consumption scenarios and meteorological analysis data but does not account for the yet unknown details of induced contrail-cirrus as a function of aircraft properties, ambient conditions, and particle emissions. Understanding of the induced cirrus is certainly more important now than further experiments on contrail threshold conditions. As stated in the IPCC report, our limited scientific understanding of "the influence of contrails and aerosols on cirrus clouds" remains one of the "key areas of scientific uncertainty that limit our ability to project aviation impacts on climate".

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Appendix S4

Hydrogen Analytical Annex

Analytical Annex to the Hydrogen Strategy, Net Zero Hydrogen Fund consultation, Low Carbon Hydrogen Business Model consultation, and Low Carbon Hydrogen Standards consultation

August 2021

Contents

Acronym Glossary

Name	Abbreviation
Auto-Thermal Reformer	ATR
Business Model	BM
Capital expenditure	CAPEX
Carbon Capture, Usage and Storage	CCUS
CO2 Transmission and Storage	CO2 T&S
Final investment decision	FID
Gas Heated Reformer	GHR
Hydrogen	H2
Levelised cost of hydrogen	LCOH
Load factor	LF
Megawatt	MW
Megawatt-hour	MWh
Operating expenditure	OPEX
Proton Exchange Membrane	PEM
Solid Oxide Electrolysis	SOE
Steam Methane Reformation	SMR

Introduction

Low carbon hydrogen will be critical for meeting the UK's legally binding commitment to achieve net zero by 2050, with potential to help decarbonise vital UK industry sectors and provide flexible energy across heat, power and transport. As part of the Ten Point Plan for a Green Industrial Revolution[1], in November 2020 the prime minister announced the UK's ambition to deploy 5GW of low carbon hydrogen production capacity by 2030, to be supported by a range of measures including a Net Zero Hydrogen Fund and a proposed hydrogen business model. In August 2021, the government published a package of policy documents building on these announcements and adding to the existing policies supporting growth of hydrogen economy[2]:

- Hydrogen Strategy[3]: strategy setting out a series of commitments from government which clearly set out how we will deliver our vision for a low carbon hydrogen economy in 2030 and beyond.
- Net Zero Hydrogen Fund (NZHF) consultation[4]: consultation on proposed position on the scope, design and delivery of upfront support under the NZHF.
- Low Carbon Hydrogen Business Models consultation[5]: consultation on our minded-to position on the commercial design of the business model for low carbon hydrogen production.
- Low Carbon Hydrogen Standards consultation[6]: consultation on a potential emissions standard to define and standardise what is meant by 'low carbon' hydrogen.

This document provides the analysis and evidence underpinning these publications. Chapters 1 and 2 focus on the whole hydrogen economy, setting out the strategic context and exploring the market barriers to uptake of low carbon hydrogen across the value chain. Building on this wider context, Chapters 3-5 focus on policy measures to support low carbon hydrogen production through the NZHF and hydrogen business models, and Chapter 6 focuses on low carbon hydrogen standards.

[1] HM Government (2020), 'The Ten Point Plan for a Green Industrial Revolution' (viewed on 18 June 2021).
[2] For more detail on existing policies see section 1.2 of the Designing the Net Zero Hydrogen Fund consultation document.
[3] BEIS (2021), 'UK Hydrogen Strategy' (viewed in July 2021).
[4] BEIS (2021), 'Designing the Net Zero Hydrogen Fund' (viewed in July 2021).
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[6] BEIS (2021), 'Designing a UK Low Carbon Hydrogen Standard' (viewed in July 2021).

1. Strategic Context

Current role of hydrogen

In 2019, the International Energy Agency (IEA) estimated global hydrogen production was around 2,800 TWh per year[7]. The biggest uses of hydrogen worldwide are in oil refining (33%) and ammonia production (27%). Almost all hydrogen currently produced is not low carbon: the IEA report suggests the vast majority of the current global supply is produced through high carbon methods such as steam methane reformation (SMR) and coal gasification, with only 2% produced by electrolysis, which is still only as low carbon as the electricity source it uses[8].

There is significant uncertainty around how much hydrogen is currently used in the UK: data are not regularly collected, and hydrogen production is often embedded in industrial processes, making it challenging to measure. A 2016 report by the Energy Research Partnership (ERP)[9] estimated UK production was around 27 TWh/year, while evidence gathered for the Hy4Heat programme on known UK hydrogen production sites suggested production of around 10 TWh/year[10]. Data from the Fuel Cells and Hydrogen Observatory (FCHO)[11] estimated less than 1% of UK hydrogen production capacity was electrolysis, with over 75% SMR; the remainder was mostly a by-product of industrial processes. Around 70% of production capacity was captive production, where hydrogen is produced and used on site, with another 20% produced as a by-product. Only 10% of production capacity was merchant production, where hydrogen is produced for sale to other users.

In chapter 5 of the Hydrogen Strategy, we have committed to collecting and publishing data on UK hydrogen production in the annual Digest of UK Energy Statistics (DUKES). This will improve our understanding of the current hydrogen landscape and allow us to monitor our progress against the outcomes set out in chapter 1 of the Hydrogen Strategy.

Future role of hydrogen

The Climate Change Committee's (CCC) Carbon Budget 6 (CB6) advice[12] suggests low carbon hydrogen will be essential for meeting net zero. Hydrogen could play a key role in decarbonising hard to electrify sectors and providing flexible energy across heat, power, industry and transport, contributing to meeting our CB6 target. This section presents evidence on the role hydrogen could play in different sectors and how low carbon hydrogen could be supplied.

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[7] IEA (2019), 'The Future of Hydrogen' (viewed on 18 June 2021).
[8] Further detail on low carbon hydrogen production methods can be found in Chapter 3.
[9] ERP (2016), 'Potential Role of Hydrogen in the UK Energy System' (viewed on 18 June 2021).
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[12] CCC (2020), 'The Sixth Carbon Budget – The UK's path to Net Zero' (viewed on 18 June 2021).

Hydrogen demand

To meet our CB6 and net zero targets, hydrogen demand is likely to increase rapidly over time. In most of the pathways modelled by BEIS for the CB6 impact assessment[13], hydrogen demand doubles between 2030 and 2035, and continues to increase rapidly over the 2030s and 2040s. By 2050, 250 – 460 TWh of hydrogen could be needed, delivering 20 – 35% of final energy consumption[14]. Other pathways to net zero are possible, but these scenarios illustrate the potential scale and rate of increase of hydrogen demand over time.

This section presents potential ranges for hydrogen demand in end use sectors in 2030, 2035 and 2050: these aim to illustrate the potential scale of demand in each sector, and do not represent demand targets or policy positions. The ranges draw on a number of sources, including whole systems energy modelling in the UKTIMES model[15] carried out by BEIS for the CB6 impact assessment; modelling of decarbonisation of specific end use sectors; and evidence on the project pipeline gathered through industry engagement. Further detail on how ranges for each sector were estimated can be found in boxes 1-4.

The analysis in this section suggests that hydrogen has a role to play in reaching net zero across a range of sectors. However, there is significant uncertainty around estimates of demand for hydrogen shown throughout this section. The ranges presented illustrate our current understanding of the opportunity presented by hydrogen in each sector, but in most cases do not represent a full range of potential outcomes for hydrogen. Changes in technologies and markets over the next decades could mean there are net zero-consistent scenarios where demand for hydrogen is higher or lower than the ranges presented.

Demand by 2030

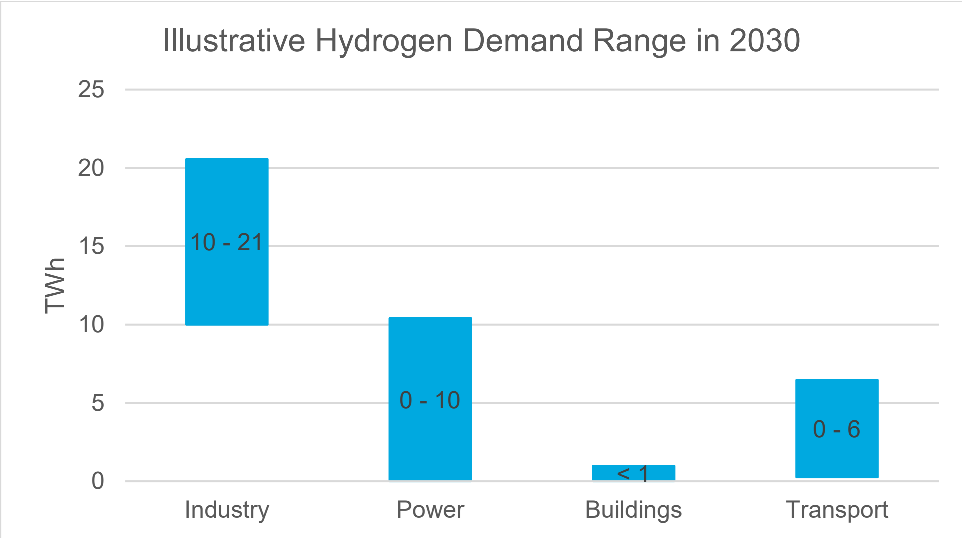
Figure 1 below shows an overview of illustrative hydrogen demand across end use sectors in 2030.

[13] BEIS (2021), 'Impact Assessment for the sixth carbon budget' (viewed on 18 June 2021).

[14] Hydrogen as a proportion of final energy consumption in 2050 in agriculture, industry, residential, services and transport sectors. Excludes energy demand for resources, processing and electricity generation.

[15] The UKTIMES model is a least-cost optimisation model for the whole UK emissions (including land use) and energy system covering the period 2010 to 2060. Based on input assumptions, the model identifies the least-cost way of meeting a given greenhouse gas emissions reduction trajectory while also meeting assumed demand for energy services. Further detail can be found on pages 26 and 63 (Annex 2) of the CB6 impact assessment.

Figure 1. Illustrative hydrogen demand in 2030[16]



Source: see boxes for each sector (1-4).

- **Industry** is likely to be one of the main users of hydrogen in 2030, with the range driven by the availability of hydrogen outside of industrial clusters and the relative cost-effectiveness of hydrogen compared to electrification.
- Hydrogen could play an important role in **power**, playing a similar role to unabated gas in the generation mix, with range dependent on build out of hydrogen power plants and hydrogen availability and price.
- Hydrogen use for **heat in buildings** is expected to be low in 2030 due to lead-in times needed to complete safety testing and set up infrastructure, regulations and markets following strategic decisions on heat decarbonisation; demand is expected to be limited to hydrogen heating trials.
- Demand in **transport** is dependent on the speed of rollout of zero emission vehicles and supporting infrastructure and the relative costs and benefits of hydrogen relative to battery electrification.

In addition to demand in the sectors presented in Figure 1, there is potential for some **blending** of hydrogen in the gas grid prior to 2030, subject to evidence on the safety and value for money of blending. Blending could offer security for hydrogen production investment decisions by providing a commercial option to sell hydrogen for gas consumer use, up to around 35 TWh per annum by the year 2030[17]. It is unlikely that this maximum potential will be reached, as the actual amount blended will depend on market conditions and how hydrogen

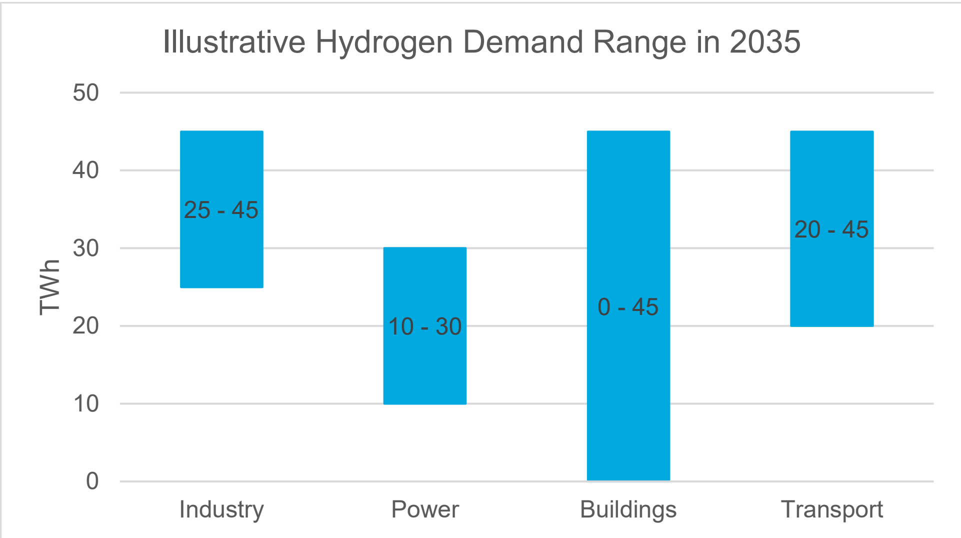
[16] Note: figures do not include blending.
[17] Assuming gas demand equal to 2019 gas demand, blending 20% on distribution network and 2% on the transmission network, blending maximised every day. This assumes that the delivery principle within the Hydrogen Strategy of blending low carbon hydrogen across the gas distribution networks up to 20% by volume (within safe limits) is maximised. This is consistent with evidence on the amount of blending that is tolerable without needing any alterations to existing gas boilers. We also assume a 2% blend onto the National Transmission System, as proposed by SGN (https://sgn.co.uk/about-us/future-of-gas/hydrogen/aberdeen-vision).

use evolves across other sectors. As set out in Chapter 2.5 of the Hydrogen Strategy, blending can support initial development of the low carbon hydrogen economy but is not a preferred long-term source of demand.

Demand over the 2030s

Across all sectors, hydrogen demand is expected to ramp up significantly in the 2030s in order to meet our CB6 target. Figure 2 shows illustrative hydrogen demand in 2035.

Figure 2. Illustrative hydrogen demand in 2035



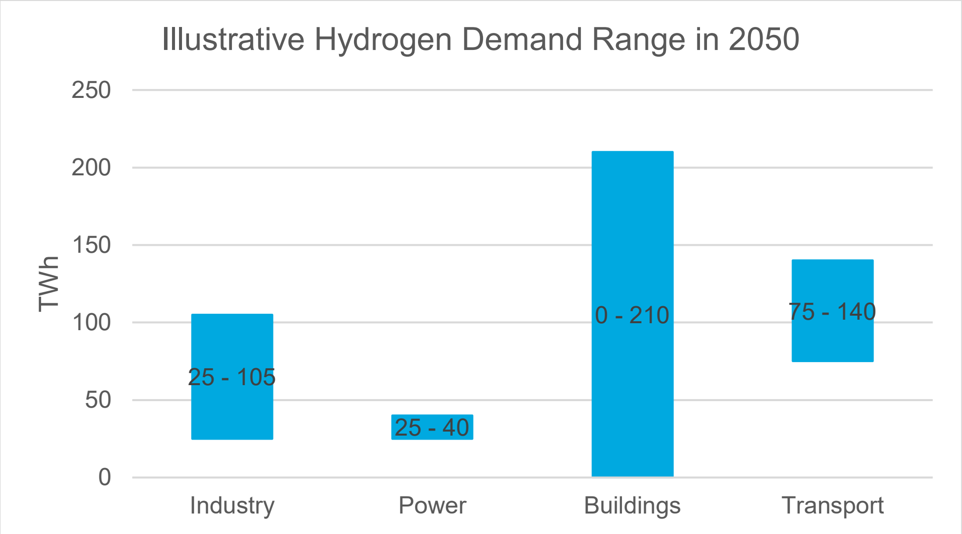
Source: see boxes for each sector (1-4).

- **Industry**, **transport** and **power** could all be significant sources of hydrogen demand in 2035, as decarbonisation across sectors accelerates to meet CB6.
- Significant further demand could come from **buildings,** but this is dependent on strategic decisions on heat decarbonisation: in a scenario where hydrogen is used for heat, appliance conversion is expected to start in the early 2030s.

Demand by 2050

Hydrogen is expected to play a significant role in meeting our target for net zero emissions by 2050. Figure 3 shows how hydrogen demand could be split across end use sectors by 2050.

Figure 3. Illustrative hydrogen demand in 2050



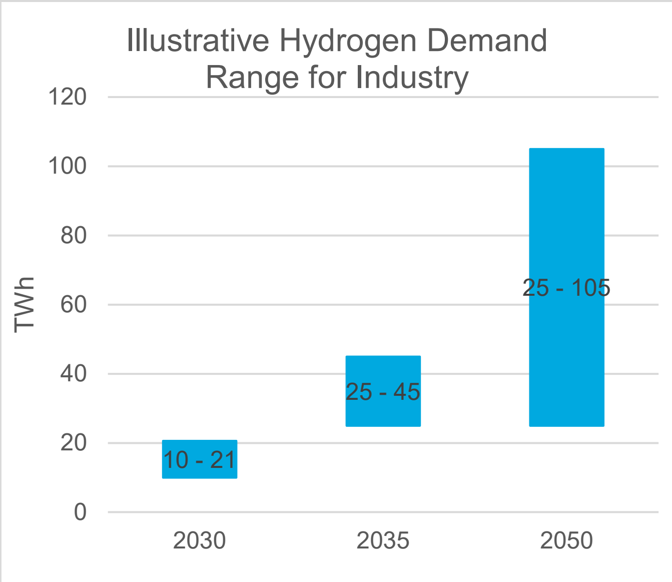
Source: see boxes for each sector (1-4).

- Hydrogen or hydrogen-based fuels (such as ammonia) are the leading option for decarbonisation of sectors that cannot be easily electrified, including **shipping** and some **industrial processes**.
- Demand for hydrogen in **power** is not as high as in other sectors, but hydrogen could play an important role in providing flexible low carbon electricity generation, helping us achieve a fully decarbonised low-cost power sector.
- There is more uncertainty in sectors such as **heat, heavy road transport** and other **industry** where there are a number of competing decarbonisation options, and the most cost-effective solution is dependent on how markets develop over the coming decades.
- Hydrogen demand for **heat** could range from zero in a scenario where heat is mostly electrified, to being the largest source of hydrogen demand if there is widespread use of hydrogen for heat.

Demand by sector

Box 1. Hydrogen demand in industry

Figure 4. Illustrative hydrogen demand in industry



Key conclusions:

- Hydrogen will be one of several options to decarbonise industrial fuels including electrification and biofuels. Fuel availability and cost, technical feasibility of switching to hydrogen, and site locations in relation to potential hydrogen and CCUS networks will determine which option is most suitable for different sectors and sites, and hence the hydrogen demand in different industrial sectors.
- Hydrogen could play a significant role in the early decarbonisation of fuels used on industrial clusters. For sites not on industrial clusters, some demand for hydrogen could be met by local electrolytic production. A larger role for hydrogen is likely in scenarios where it is increasingly available through local and national hydrogen networks.
- A significant proportion of early demand could come from a relatively small number of larger on-cluster sites that could act as 'pathfinders' to help foster initial demand.
- Hydrogen demand is expected to increase over time, as developments in technologies and networks mean hydrogen becomes available for a wider range of processes and sites, and as changes in costs including an increasing carbon price incentivise switching to low carbon fuels.
- Analysis for the Industrial Decarbonisation Strategy (IDS)[18] suggests sectors consuming the most hydrogen are likely to include: chemicals, iron and steel, refining, paper, other minerals and food and drink.
- The steel sector could create substantial demand for hydrogen from the 2030s if it opts to decarbonise with hydrogen direct reduced iron coupled with electric arc furnace technology.
- Processes using industrial boilers and combined heat and power (CHP) units have the potential to drive the greatest demand and IDS analysis indicates this could represent up to two thirds of demand by 2050.

[18] BEIS (2021), 'Industrial Decarbonisation Strategy' (viewed on 18 June 2021).

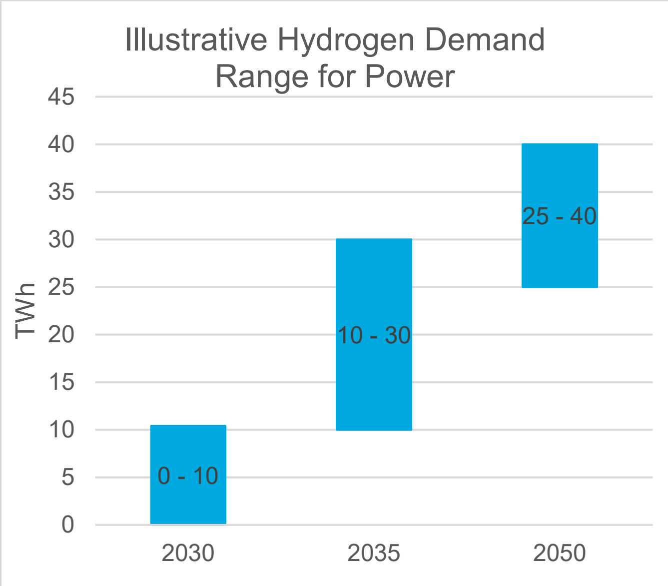
- IDS analysis also suggests a number of processes are able to opt solely for hydrogen conversion including furnaces for vehicles, non-cement kilns, generators and metal rolling and melting.

Methodology:

- Ranges based on BEIS analysis for the Industrial Decarbonisation Strategy (IDS) and CB6 impact assessment.
- IDS analysis is based on two scenarios: first where hydrogen availability is limited to industrial clusters and second where it becomes increasingly available at dispersed sites through national hydrogen networks. Analysis considers where hydrogen is the most cost-effective option to decarbonise, with assumptions for the availability of hydrogen and the cost of using it compared to alternatives technologies.
- IDS analysis is supplemented with CB6 analysis which has a different definition of ‘industry’ that includes non-road mobile machinery and excludes energy for industrial buildings.
- Range shows a set of plausible pathways to net zero, but does not represent a maximum or minimum conceivable demand for hydrogen in industry. Ranges for demand will change as our understanding of relevant technologies and industries develops.

Box 2. Hydrogen demand in power

Figure 5. Illustrative hydrogen demand in power



Key conclusions:

- Hydrogen is likely to play an important role in flexible electricity generation as we move towards net zero, providing a low carbon option for meeting peak demand.
- Hydrogen could play a role in the power sector in 2030, with some early deployment possible in the 2020s. This could include turbines using 100% hydrogen or blends of hydrogen and natural gas.
- Demand for hydrogen in the power sector is expected to increase in the 2030s, contributing to power sector decarbonisation and helping to achieve CB6 and net zero.
- As set out in chapter 2, there are a range of barriers to hydrogen uptake in end use sectors: while the strategy sets out a number of actions we will take to address these barriers and enable hydrogen use in power, there remains uncertainty around when and how much hydrogen could be available to the power sector in the CB6 period. To ensure we are able to meet our stretching CB6 target and maintain optionality, hydrogen in power will need to be developed alongside rapid deployment of other low carbon generation.
- Demand for hydrogen in power depends on overall and peak electricity demand levels, and the relative costs and benefits of hydrogen compared to other low carbon flexible generation technologies. It also depends on the mix of technologies in the power sector, for example a system with a higher share of renewables could need more hydrogen to address intermittency but could also use otherwise curtailed energy to produce hydrogen, while a system with more flexibility through demand side response, storage and interconnectors could be less dependent on hydrogen for both system balancing and meeting peak demand.
- If hydrogen is available, the power sector could achieve lower emissions at lower cost than scenarios without hydrogen. It is possible that hydrogen could reduce the requirement for other generation and reduce overall system costs, because hydrogen is assumed to operate with flexibility. The extent of the impact is dependent on the quantity and cost of hydrogen available for generating electricity.

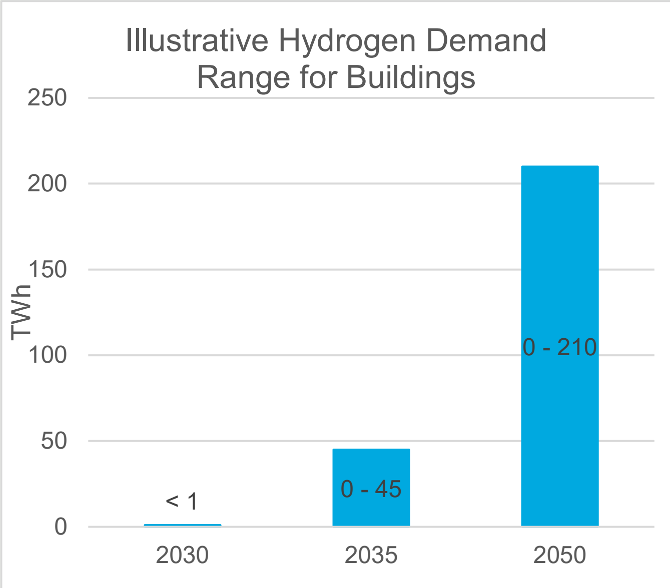
Methodology:

- 2050 range based on BEIS CB6 impact assessment analysis. Scenarios look at impact of technology availability and performance and resource conditions.
- 2030 and 2035 ranges supplemented with evidence on pipeline of hydrogen projects gathered through industry engagement.
- Evidence on impact of having hydrogen available in the power sector is based on the 'Modelling 2050: electricity system analysis' published alongside the Energy White Paper[19]. Further detail can be found in section 4.1 of the report.

[19] BEIS (2020), 'Modelling 2050: electricity system analysis' (viewed on 18 June 2021).

Box 3. Hydrogen demand in buildings

Figure 6. Illustrative hydrogen demand in buildings



Key conclusions:

- Hydrogen demand in buildings is highly uncertain and dependent on strategic decisions on the role of hydrogen relative to electrification in heat.
- Demand for hydrogen for heat in buildings in 2030 is expected to be small. A programme of testing and trials is planned in the 2020s to inform strategic decisions on heat decarbonisation. If this programme concludes hydrogen has a role to play in heat, market and regulatory frameworks will need to be set up and infrastructure will need to be rolled out. These are unlikely to be in place by 2030, so demand for hydrogen for heat outside of trials is expected to be low.
- In a scenario where hydrogen is used for heat, conversion of the gas grid and appliances to hydrogen is expected to start in the early 2030s, so the potential demand for hydrogen for heat in buildings in 2035 will be highly dependent on the timing and speed of this conversion. Given that 2035 represents an early stage of hydrogen deployment for heat we would not expect deployment in this period to strongly determine the range of potential demand in 2050.
- There is a wide range for demand in 2050, driven by uncertainty around the cost and performance of hydrogen relative to electrification of heat. The high scenario assumes widespread use of hydrogen for heat, while the low scenario assumes heat is fully electrified. There could be scenarios in between the high and low ranges where a mixture of hydrogen and electrification are deployed, for example where there are regional differences or where hybrid heating systems are used.
- There are potential scenarios with higher demand for hydrogen for heat, for example where hydrogen is used more widely in existing buildings on the gas grid. However, as flagged by the CCC in their CB6 advice, such scenarios may face challenges around residual emissions from increased use of methane reformation with CCUS to meet the demand, which could increase overall system costs.

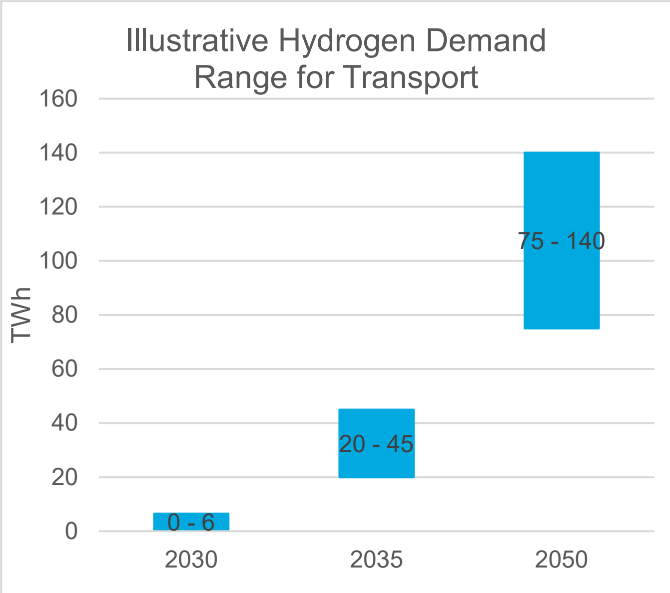
Methodology:

- 'Buildings' covers both domestic and non-domestic buildings.
- 2030 demand is from trials only, including the potential hydrogen town pilot. Range does not include blending (see page 8).

- 2035 demand based on the CCC's analysis for their CB6 advice: high scenario uses hydrogen demand for buildings from the 'Headwinds' scenario, assuming grid conversion radiates out from industrial clusters. Low scenario assumes heat is fully electrified.
- 2050 demand based on BEIS CB6 analysis: high scenario assumes most existing homes on gas grid are converted to hydrogen boilers, except for segments of the housing stock where alternatives (e.g. heat pumps, heat networks) are potentially more cost-effective. Also assumes gas consumption in non-domestic buildings not covered by existing decarbonisation policies is replaced by hydrogen. Low scenario assumes heat is fully electrified.

Box 4. Hydrogen demand in transport

Figure 7. Illustrative hydrogen demand in transport



Key conclusions:

- In general, hydrogen and hydrogen-based fuels become more competitive with current battery electrification technology as vehicles get larger and travel longer distances, as hydrogen vehicles have higher energy density, longer range and/or faster refuelling times than battery electric vehicles. Subject to funding, there are trials planned across a range of transport modes in the 2020s that will improve our understanding of the role of hydrogen in transport (see Chapter 2.4.4 of the hydrogen strategy for detail).
- There is uncertainty around demand from HGVs, buses and rail, driven by uncertainty around the costs and benefits of hydrogen relative to battery electrification. Demand in 2030 and 2035 is also dependent on the rollout rate of heavy duty zero emission vehicles, which is expected to accelerate in the 2030s.
- It is estimated that the demand for hydrogen-based fuels from shipping could start ramping up significantly between 2030 and 2035. By 2050, it is estimated that there could be 75 – 95 TWh of demand for hydrogen-based fuels (principally in the form of ammonia) from UK domestic shipping and UK international shipping. However, these estimates do not reflect the full range of uncertainty. It is also important to note that hydrogen-based fuels used by UK shipping may not all be purchased in the UK.
- If it proves feasible and cost-effective, hydrogen use in aviation could be a significant additional source of demand, either through hydrogen planes which could be available in the long term, or hydrogen-based sustainable aviation fuels (SAF) in the nearer term. The Clean Sky 2 report[20] suggests that by 2050 an average regional airport could need around 0.75 TWh of liquid hydrogen per year, and an average large hub airport would need around 7.5 TWh of liquid hydrogen per year, which is significant in the context of our range of 75 – 140 TWh from all other transport modes.
- The ranges do not include any hydrogen used in cars or vans, so demand could be higher than shown if some hydrogen does end up being used in a significant number of cars or vans.

[20] Clean Sky 2 (2020), 'Hydrogen-powered aviation' (viewed on 18 June 2021).

Methodology:

- The estimated demand for hydrogen in HGVs, buses and rail is based on analysis by the Department for Transport (DfT) for the Transport Decarbonisation Plan[21]. Ranges reflect different assumptions on how the costs of hydrogen and other decarbonisation options will develop.
- The estimated demand for hydrogen-based fuels in shipping is based on research commissioned by DfT[22], covering UK domestic shipping and UK international shipping[23]. The range for shipping reflects different levels of ambition for reducing the greenhouse gas emissions from international shipping[24].
- No hydrogen use is modelled in aviation due to the relative immaturity of technology and lack of modelling to date. Illustrative estimates of hydrogen demand for an airport are based on the Clean Sky 2 report.
- No hydrogen use is modelled in cars or vans as current evidence suggests battery electrification is likely to be the preferred vehicle technology and the lowest cost route to zero emissions for cars and vans.

[21] Department for Transport (2021), 'Decarbonising transport: a better, greener Britain' (viewed on 19 July 2021).
[22] UMAS, E4Tech, Frontier Economics, CE Delft (2019), 'Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution. Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs. A Report for the Department for Transport' (viewed on 18 June 2021).
[23] Based on the definition of UK international shipping that was adopted in the research above, the estimates for UK international shipping represent the potential hydrogen demand associated with the international shipping activity that transports UK imports. Other definitions of UK international shipping would result in different estimates.
[24] Scenarios D and E from the research above have been used for UK international shipping. Scenario D has also been used for UK domestic shipping.

Hydrogen supply

2030 ambition

The Government's Ten Point Plan for a Green Industrial Revolution[25] set out that, working with industry, the UK is aiming for 5GW of low carbon hydrogen production capacity by 2030, with a hope to see 1GW of hydrogen production capacity by 2025, putting us on a credible trajectory that aligns with a pathway to Carbon Budget 6 and Net Zero. Our analysis suggests that a 2030 5GW ambition is stretching but feasible. The ambition was informed by engagement with industry to understand the characteristics of both CCUS-enabled methane reformation and electrolytic hydrogen production projects in the pipeline. Based on the information provided we developed deployment scenarios. We then compared the scenarios against a variety of constraints, including technical certainty; demand readiness and availability; carbon capture, transport and storage readiness and availability; low cost and low carbon electricity availability; realistic build rates allowing learning benefits to be captured; and potential costs. This assessment, together with a consideration of other countries' ambitions, led us to a 5GW ambition by 2030, consisting of both CCUS-enabled methane reformation and electrolytic hydrogen production projects. The mix of hydrogen production technologies making up supply in 2030 is dependent on a range of factors set out in the next section.

The success of the ambition will be judged in part by the decarbonisation it delivers through use of hydrogen in end use sectors. As such there is significant interdependency between the 5GW ambition and the demand for low carbon hydrogen. Delivering 5GW of low carbon hydrogen is dependent on stretching deployment rates being achieved across end use sectors, reaching near the top end of the ranges presented in the previous section.

Supply beyond 2030

As set out in the previous section, hydrogen demand is expected to increase rapidly over the 2030s and 2040s, so to ensure supply can meet demand, hydrogen production capacity will have to increase correspondingly. To meet the demand estimates presented above, hydrogen production capacity would have to increase from 5 GW in 2030 to 7 – 20 GW in 2035 and 15 – 60 GW in 2050 if plants run at a 95% load factor. In practice, plants may run at lower load factors, requiring even higher hydrogen production capacity to be installed.

Analysis done by BEIS for the CB6 impact assessment[26] suggests that in 2050, hydrogen produced in the UK could be supplied through a mix of methane reformation with CCS, electrolysis from renewable electricity, and biomass gasification with CCS (BECCS); this conclusion is supported by the CCC's CB6 advice[27]. However, there is significant uncertainty around how hydrogen will be supplied over time: the proportion of hydrogen supplied by each technology depends on a range of assumptions around hydrogen production technologies and the wider energy system, including:

[25] HM Government (2020), 'The Ten Point Plan for a Green Industrial Revolution' (viewed on 18 June 2021).
[26] BEIS (2021), 'Impact Assessment for the sixth carbon budget' (viewed on 18 June 2021).
[27] CCC (2020), 'The Sixth Carbon Budget – The UK's path to Net Zero' (viewed on 18 June 2021).

- **Relative cost and performance of each production technology**: the mix of production technologies depends on the capital and operating costs of each technology, the efficiency of production processes, and the rate at which costs decrease and performance improves over time. The Hydrogen Production Cost 2021 report[28] sets out our current evidence on the levelised cost of hydrogen production for different technologies, including sensitivity analysis which shows how levelised costs are affected by varying assumptions on fuel and electricity prices, capital and operating costs, efficiencies and load factors. Importantly, the report notes that the evidence base is fast moving and that we are seeking stakeholder views on the continued relevance of it. It also explains that further sensitivities are possible and therefore the range of results might be wider. The report highlights that it takes a simplistic, illustrative approach to technology configurations: for example, electrolysis either uses grid, dedicated or curtailed electricity sources, when in reality combinations of these are possible. The report suggests that CCUS-enabled methane reformation is currently the lowest cost hydrogen production technology, but over time, electrolysis costs are expected to decrease and in some cases become cost-competitive with CCUS-enabled methane reformation as early as from 2025 onwards. BECCS is relatively high cost, but costs fall rapidly when the value of negative emissions are included. Box 7 in chapter 3 gives more detail on costs of different production technologies, and further detail can be found in chapters 6 and 7 of the Hydrogen Production Cost report.
- **CCUS performance**: deployment of hydrogen produced via methane reformation depends on carbon capture rates, as residual emissions from CCUS-enabled hydrogen production need to be offset by removals elsewhere in the energy system. Higher capture rates reduce residual emissions, and hence the cost of offsetting these residual emissions; this could lead to higher deployment of CCUS-enabled methane reformation.
- **Availability of low-cost and low carbon electricity**: deployment of electrolytic hydrogen depends on availability of low-cost electricity. Power sector scenarios with a higher share of renewables could support more electrolysis, as electrolysers can use electricity that would have otherwise been curtailed to produce hydrogen at low cost and low emissions intensity.
- **Availability of sustainable biomass**: deployment of BECCS for hydrogen production depends on the overall availability of biomass in the economy, and the relative benefits of using biomass in hydrogen production relative to use in other sectors such as industry and electricity generation.
- **Scale of hydrogen demand**: the constraints on availability of biomass and low-cost electricity limit the amount of low-cost and low carbon hydrogen that can be produced by BECCS and electrolysis, so additional demand above this level is likely to be met by hydrogen production via CCUS-enabled methane reformation. Scenarios with very high hydrogen demand could therefore have a higher proportion of CCUS-enabled methane reformation.

[28] BEIS (2021), 'Hydrogen Production Cost 2021' (viewed in July 2021).

- **Technology availability**: the production mix is also dependent on when technologies become commercially available. For example, BECCS hydrogen technology is not currently expected to deploy until the mid-2030s, although technological and market developments could bring this date forward.

As CCUS-enabled methane reformation is currently lower cost than other technologies and available for build at larger scale, it is expected to provide the majority of hydrogen supply in the short term. However, electrolysis projects are expected to increase in size over the 2020s, leading to an expected deployment scale up in the late 2020s and 2030s as capital costs reduce and low cost, low carbon electricity availability increases, while commercial BECCS may also become available in the 2030s. The timing and scale of this shift in production methods is dependent on the factors set out above.

Analysis carried out by BEIS for the CB6 impact assessment suggests that in 2050, CCUS-enabled methane reformation could supply 10 – 335 TWh, electrolysis could supply 20 – 135 TWh, and BECCS could supply 50 – 100 TWh of hydrogen. These ranges are broadly consistent with analysis by the CCC[29], Aurora[30] and National Grid[31] on the UK hydrogen supply mix. This analysis is specific to the UK: supply mixes in other countries or global regions could be very different as the factors listed above vary significantly depending on the regional hydrogen context. The CB6 IA analysis varies assumptions on CCUS performance and availability, hydrogen demand and resource availability to illustrate a range of net zero-consistent scenarios[32]. However, this does not cover all possible hydrogen supply scenarios: varying any of the factors listed above would lead to a different mix of hydrogen supply technologies, which in some cases could be outside the range modelled.

The supply mix could also be affected by new technologies which are in early stages of development so are not yet possible to include in analysis, including existing and future nuclear technologies, methane pyrolysis and thermochemical water splitting. Producers may also apply existing technologies in novel ways, using a combination of different energy inputs and production technologies to deliver low carbon hydrogen. As these technologies develop, they will be integrated into our modelling as appropriate to improve our understanding of the role they could play in the hydrogen economy. Depending on how the global hydrogen market develops, UK-produced hydrogen has the potential to be exported, and there could also be some hydrogen supplied through imports.

Costs

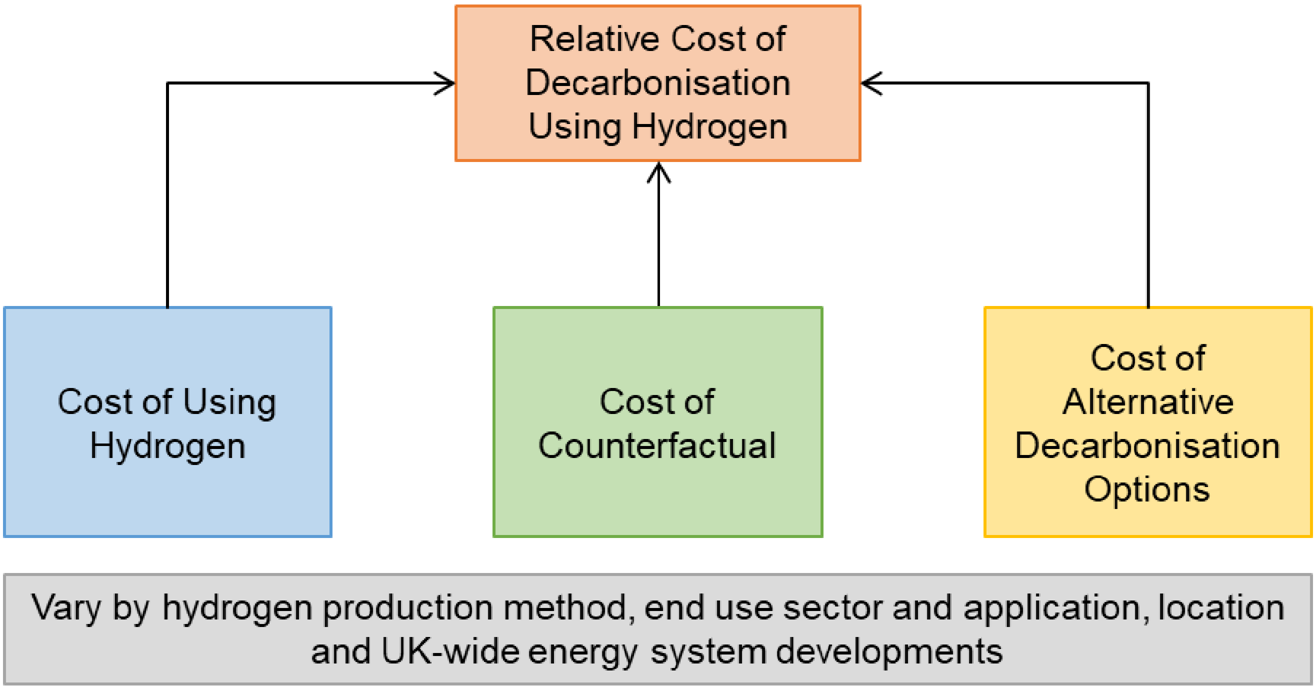
The costs of decarbonisation using hydrogen are highly uncertain and depend on a variety of factors. They will evolve over time as hydrogen is deployed more widely across the economy and the market develops. This section sets out three areas that need to be considered when

[29] CCC (2020), 'The Sixth Carbon Budget – The UK's path to Net Zero' (viewed on 18 June 2021).
[30] Aurora (2020), 'Hydrogen for a Net Zero GB' (viewed on 18 June 2021).
[31] National Grid (2020), 'Future Energy Scenarios 2020' (viewed on 18 June 2021).
[32] See section 2.2 of CB6 IA for further detail.

thinking about the costs of hydrogen, and some key factors that influence these costs. More detailed analysis on costs will be conducted as policies to develop the hydrogen economy are rolled out.

The relative costs of hydrogen's role in decarbonising the UK economy depend on the cost of using hydrogen itself, but also on the relative cost of hydrogen compared to counterfactual fuels and alternative decarbonisation options, as shown in Figure 8 and detailed below.

Figure 8. Key aspects of the cost of hydrogen decarbonisation



Cost of using hydrogen

The first key component of the relative cost of decarbonisation using hydrogen is the absolute cost of using hydrogen, including the cost of hydrogen production, distribution, transmission and storage, as well as the cost of converting or replacing equipment to use hydrogen. Chapter 2 gives some detail on cost barriers across the value chain. The Hydrogen Production Cost 2021 report[33] provides more detail on the levelised cost of hydrogen production using different production methods and the factors that influence this, including fuel and electricity prices, capital and operating costs, efficiencies and load factors. Costs can also be affected by location and developments in the energy system, for example the mix of technologies deployed in the power sector. The costs of hydrogen equipment vary depending on the end use sector and application.

[33] BEIS (2021), 'Hydrogen Production Cost 2021' (viewed in July 2021).

Cost of counterfactual

As well as the absolute cost of using hydrogen, it is important to think about the cost of the energy vector being used currently, as this will determine the additional cost of hydrogen relative to the counterfactual. The counterfactual fuel varies depending on the end use sector and application: in many cases hydrogen will replace natural gas, but it could replace a range of other fuels, for example petrol, diesel, fuel oil or kerosene in transport applications. As well as fuel costs, counterfactual costs can also include taxes, charges, and policy costs such as carbon prices under the UK Emissions Trading Scheme. There is significant uncertainty around how all of these costs will change in future. Figure 14 in chapter 3 illustrates how costs vary across some different counterfactual fuels.

Cost of alternative decarbonisation options

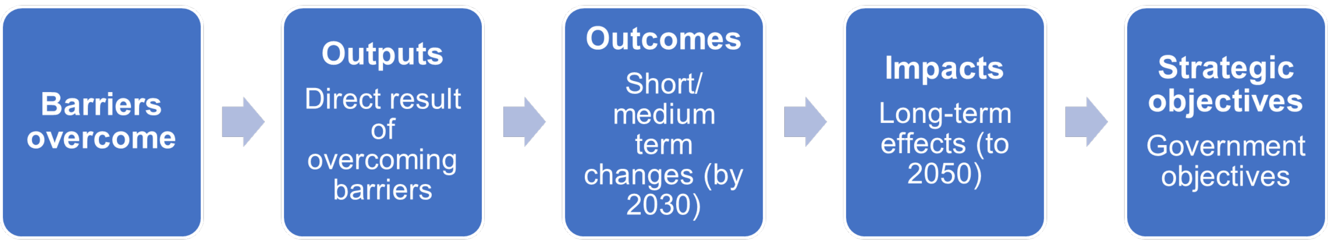
Finally, the cost of hydrogen should be considered alongside the cost of other options for decarbonising a specific sector or application, including capital, fuel and operating costs. As set out in boxes 1 – 4, one of the key drivers of the ranges in hydrogen demand is the relative cost of hydrogen compared to other decarbonisation options such as electrification, CCUS or biofuels. The cost and feasibility of alternative options varies depending on the sector and application, as well as by location and developments in the wider UK energy system. In some sectors hydrogen is the leading option: for example, in shipping, hydrogen-based fuels are currently the leading option as the available evidence suggests that electrification is only expected to be competitive under limited circumstances. For other uses such as many industrial processes, HGVs, rail and buses, hydrogen competes with alternative options and it is not yet clear which technology will be most cost-effective.

2. Market Barriers

Chapter 2 starts with a Theory of Change for the hydrogen economy, which uses the Theory of Change approach set out in the BEIS monitoring and evaluation framework[34] to provide a high-level visualisation of the hydrogen economy. The strategic framework diagram can be used to:

- Understand what **barriers** need to be overcome to deliver key outputs
- See how these outputs translate into the **outcomes** (set out in chapter 1 of the hydrogen strategy) needed to achieve our vision for the hydrogen economy in 2030 and unlock the role of hydrogen described in Chapter 1 of this document,
- Show how the outcomes contribute to long-term impacts and, ultimately, to **strategic objectives,**
- Illustrate the **interactions** and **dependencies** between different parts of the hydrogen value chain, helping us understand how outcomes are dependent on overcoming barriers across different parts of the hydrogen value chain.

Figure 9. Theory of Change framework



Chapter 2 then goes into more detail on some of the market barriers shown in the hydrogen economy Theory of Change, articulating some of the challenges to developing a hydrogen economy.

Taken together, the hydrogen economy Theory of Change and market barriers analysis can also be used as a starting point for understanding how specific actions or policies can contribute to developing the hydrogen economy. Chapters 2-6 explore some of the barriers in more detail and how the NZHF, hydrogen business models, low carbon hydrogen standards and commitments in the strategy contribute towards overcoming these. The Theory of Change for producer support in Chapter 3 also draws on the hydrogen economy Theory of Change and barriers analysis to support the rationale for intervention in the hydrogen production sector by illustrating the outcomes and impacts of support for hydrogen production.

[34] BEIS (2020), 'BEIS Monitoring and Evaluation Framework' (viewed on 18 June 2021).

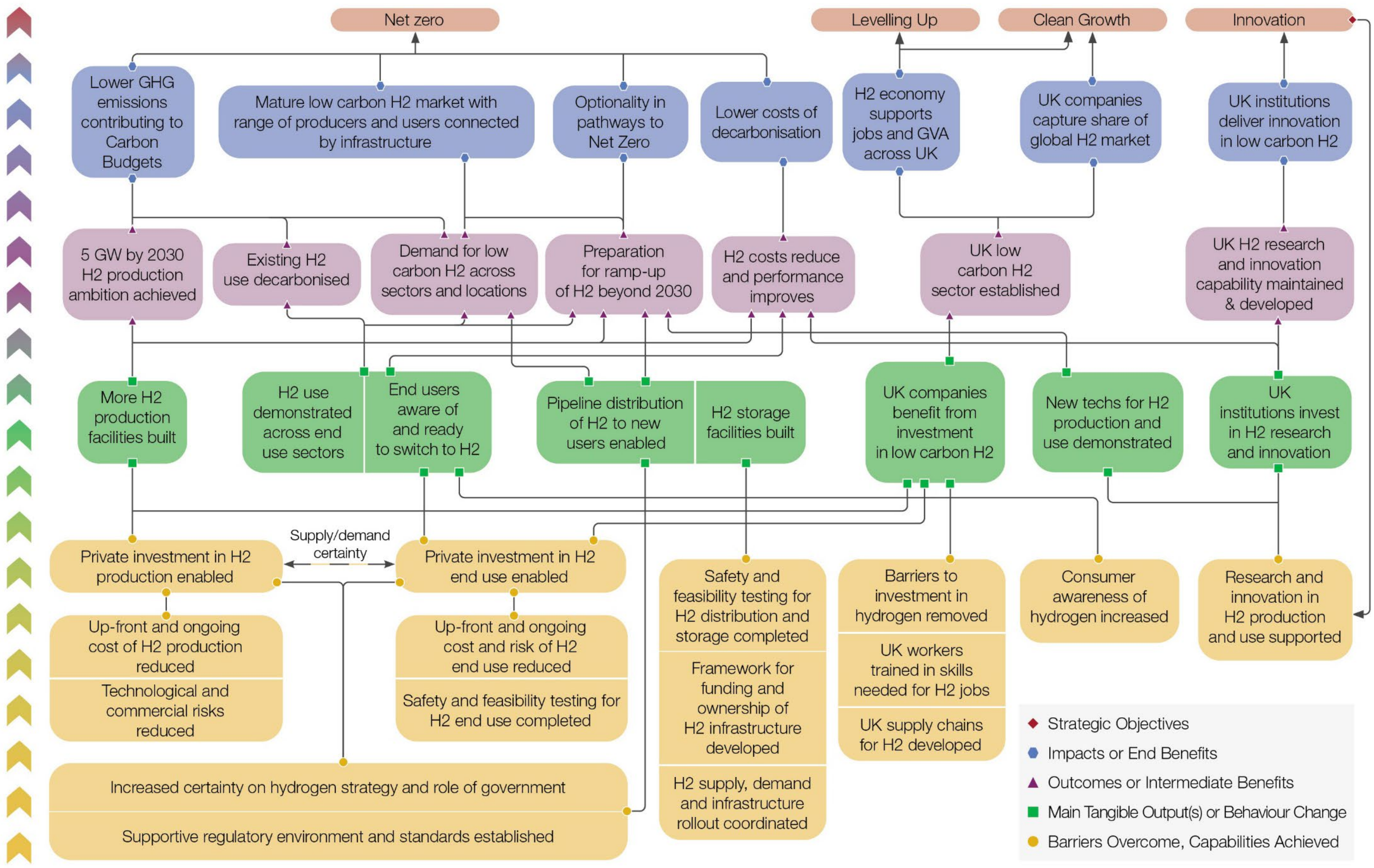
Chapter 5 of the Hydrogen Strategy sets out how we will track our progress against the outcomes, with potential indicators and metrics shown in Table 5.1.

The hydrogen economy Theory of Change and market barriers analysis are static, representing the key barriers to delivering the outcomes we want in 2030. The hydrogen economy will develop over time, as detailed in the 2020s roadmap in chapter 2 of the Hydrogen Strategy; for example, we would expect the number of end users for a typical hydrogen production project to increase over time. The desired outcomes will therefore evolve, and hence the barriers and their relative importance will change. The Theory of Change will be kept under review to reflect these developments.

Hydrogen Economy Theory of Change

The diagram in Figure 10 uses the Theory of Change framework shown in Figure 9 to show the outputs, outcomes and impacts of addressing specific barriers to low carbon hydrogen uptake across the value chain, and how these feed into the strategic objectives.

Figure 10. Hydrogen economy theory of change



Market barriers

This section provides some further detail on some of the barriers to achieving the capabilities set out in the hydrogen economy Theory of Change, in particular those relating to hydrogen production, demand, and transmission, distribution and storage infrastructure. These barriers are linked to market failures, where the free market results in outcomes that are not optimal at a societal level, but also consider some wider constraints currently holding back the development of a low carbon hydrogen system. Looking at barriers allows us to consider the full range of challenges to establishing a hydrogen economy. However, we also present how the barriers are underpinned by market failures to show where government intervention could be needed. Market failures are defined and mapped against barriers in Table 1.

Across all parts of the value chain, there are some common barriers, including high relative cost, risk, policy and regulatory uncertainty, safety testing, lack of market structure, and interdependencies with other parts of the value chain. However, the barriers affect each part of the value chain in different ways, which are explained further in the rest of this chapter.

As noted above, this section focusses on the key barriers to hydrogen deployment in the 2020s, but as the hydrogen economy develops and some outcomes are achieved, the barriers are likely to evolve, particularly as growth of hydrogen economy continues post- 2030.

Production barriers

The key market barriers to the production of low carbon hydrogen are summarised below. These barriers are explored in further detail in Chapter 3.

- **Production cost**: the cost of low carbon hydrogen is higher than most high-carbon fuel alternatives. The lack of a fully developed market, imperfect information and the presence of a negative externality linked to carbon (see Table 1 below for more detail) all contribute to the lack of cost competitiveness. On the one hand, this is due to the relative immaturity of low carbon hydrogen production technologies. Whilst this disadvantage might fall away over time, in the short-term, not only will hydrogen need to compete against cheaper alternatives for end users such as electricity, natural gas or biomass, but it will also rely on them for production inputs. This will generate efficiency losses, which are avoided when end use sectors directly use these alternatives. On the other hand, the high carbon alternatives have a cost advantage as their price does not capture the full societal cost of carbon they generate. UK carbon pricing policy (primarily the UK Emissions Trading Scheme (ETS)) addresses this by requiring businesses within scope to pay a price for every tonne of CO_2 equivalent emitted. However, the scope of the UK ETS does not currently include all sectors of the economy where low carbon hydrogen potentially has value; and for sectors within scope, low carbon hydrogen is not yet competitive as an abatement option in the ETS market.
- **Technological and commercial risk**: there are considerable technological and commercial uncertainties and risks associated with developing low carbon hydrogen production projects, which are more acute for the earliest projects. Low carbon

hydrogen production technologies are risky for investors as they have not been proven at a commercial scale in the UK: this reflects market failures including nascent markets and imperfect information. There is a first mover disadvantage, where project developers for the first hydrogen production projects bear significant learning costs and risks but may not capture the full benefits of the investment, as market competitors capture their know-how.

- **Demand uncertainty**: as there is currently very limited use of low carbon hydrogen in the UK, its producers have no certainty if their supply will be matched by market demand. This could lead to the producers having to sell at low prices or build-up stocks and could pose a risk to the economic viability of the project. There are significant barriers to hydrogen use which contribute to this demand uncertainty, which are set out below. Once again, the market failures at play here are related to the market's immaturity (nascent market) but also to coordination failures.
- **Lack of market structure**: there is currently no regulated market for low carbon hydrogen. In the short term, where suppliers are likely to be dependent on a small number of end users to buy their hydrogen (oligopsony), an unregulated market could risk abuse of market power by end users of hydrogen. This could lead to producers having to accept low prices or unfavourable conditions for selling their hydrogen, risking the profitability of the project.
- **Distribution and storage barriers**: coordination failures might lead to suboptimal market outcomes (e.g. undersupply) as lack of investment in one section of the market deters investment elsewhere. To facilitate sales, hydrogen production plants require infrastructure to transport hydrogen to the end users. They may also need hydrogen storage infrastructure to help balance hydrogen supply and demand, for example where offtakers have a variable demand profile. Insufficient investment in the infrastructure will limit entries on the production side. Equally, early infrastructure that is not sufficiently future-proofed (i.e. not ready to accommodate future expansion in production capacity) might limit market entry in the medium to long term. Barriers to distribution and storage are set out below.
- **Policy and regulatory uncertainty**: the lack of a clear and consistent long-term policy and regulatory framework for low carbon hydrogen deters investors as it adds risk to the investment process. Once again, this is linked to the immature market (nascent market & imperfect information). Investors may not have the information available to fully consider the implications of the 2050 net zero target when making investment decisions, and may also perceive a high risk of stranded assets if subsequent policy and regulatory decisions markedly change the operating environment for their chosen technologies (e.g. if policy framework is in development but not yet finalised). Hydrogen also sits within a broad and complex regulatory landscape, which can sometimes create barriers to hydrogen production: for example, Orkney Hydrogen Strategy 2019 cites regulatory barriers related to grid connections as one of the obstacles to implementation of

hydrogen into islands' energy systems.[35] Further detail on the regulatory framework can be found in Section 2.5 of the hydrogen strategy.

Demand barriers

There are also a range of barriers to hydrogen end use. These barriers broadly apply to new users across all end use sectors, but the relative importance of each barrier and the extent to which they prevent hydrogen uptake varies depending on the end use sector. Crucially, for the market to emerge all the relevant barriers will have to be addressed in a coordinated way.

- **User cost**: similarly to the producer side, hydrogen demand is affected by the issues related to nascent markets, imperfect information and negative externalities from high carbon fuels. As set out above, the cost of low carbon hydrogen is higher than fossil fuels or high carbon hydrogen, so hydrogen can be more expensive for users than high carbon alternatives. In addition, users will face up-front costs of transitioning to hydrogen, including investment in new equipment, such as boilers or fuel cells: these can be more expensive than conventional equipment as they do not benefit from economies of scale or mature supply chains. There can also be switching costs associated with changing to a new system.
- **Technological and commercial risk**: there is significant risk associated with switching to low carbon hydrogen as most technologies have not yet been commercially demonstrated. The market might fail to deliver optimal results due to its immaturity, imperfect information, and the fact there is a first mover disadvantage as the earliest users of hydrogen will bear learning costs and risks which create benefits captured by subsequent users.
- **Supply uncertainty**: there is currently no commercially available low carbon hydrogen in the UK, so potential users of hydrogen cannot be sure they will have a secure supply. Disruption in supply could have negative impacts on business, for example if an industrial process is unable to run, so supply uncertainty could deter end users from switching to hydrogen. This is an example of a suboptimal equilibrium where market growth requires sufficient number of participants to enter at the same time (coordination) but where the supply risks deter new entrants.
- **Lack of market structure**: in the short term, end users of hydrogen may be more likely to be dependent on a small number of suppliers (oligopoly). Lack of a regulated market (nascent market) could lead to abuse of market power by suppliers, which could lead to high prices for hydrogen.
- **Distribution and storage barriers**: markets can fail to deliver optimal results when there is insufficient coordination. Hydrogen end use requires infrastructure to transport hydrogen from the production facility to the end users, and for many end uses will also require hydrogen storage facilities. There is also some uncertainty whether the emerging infrastructure will be sufficiently future-proofed, i.e. able to accommodate new

[35] Energy of Orkney (2019), 'Orkney Hydrogen Strategy' (viewed on 18 June 2021).

demand in the medium to long term. Barriers to distribution and storage are set out below.

- **Policy and regulatory uncertainty**: the current lack of a long-term policy and regulatory framework for low carbon hydrogen, resulting from the nascent character of the market, could deter investors from switching to hydrogen. Users face uncertainty in cases where policy framework is in development but not yet finalised and, as hydrogen sits within a complex regulatory framework, emerging regulations in related areas (e.g. energy market regulations) might affect the low carbon hydrogen market (see section 2.5 of hydrogen strategy).
- **Safety and feasibility testing**: as the market for hydrogen is still emerging, the safety and technical case for low carbon hydrogen use at scale has not been established for many end uses, and low carbon hydrogen use has not been demonstrated at commercial scale.
- **Consumer awareness and acceptance**: as low carbon hydrogen is an emerging technology in a nascent market, consumers may not be aware of the option of using it, or may not be willing to do so.

Transmission, distribution and storage infrastructure barriers

There is currently limited transmission, distribution and storage infrastructure for hydrogen, as hydrogen use is small-scale and the hydrogen is often produced and used in the same location. Transmission and distribution include both pipeline and non-pipeline (e.g. through road transport) distribution methods, as well as the potential for blending into the gas grid. Storage covers above ground vessels, underground storage, and the infrastructure allowing, for example, pressurisation, liquification or conversion to so called ‘hydrogen carriers’ (e.g. ammonia). There are a range of barriers to infrastructure being established:

- **Supply and demand uncertainty**: there is a risk of coordination failure if hydrogen infrastructure built to support early deployment is not suitable for wider rollout of hydrogen. There is uncertainty around the scale and location of hydrogen supply and demand, and hence the size and location of distribution and storage infrastructure required. This could lead to stranded assets. That said, in practice we do expect initial pipelines to be built in the industrial clusters and expand out from there.
- **Cost and funding uncertainty**: due to the nascent market, there is a lack of clarity on the commercial frameworks and ownership structures that will apply to building and operating distribution and storage infrastructure. There is also a first mover disadvantage as the earliest developers of infrastructure bear significant risks and costs.
- **Lack of market structure**: as the market for low carbon hydrogen is still emerging it is unclear how it will be structured and regulated.
- **Regulatory uncertainty**: there is currently no established regulatory framework for hydrogen distribution and storage (nascent market & imperfect information) and this might impede required investment. Private connections are exempt from regulations

covering existing gas infrastructure, but it is not clear at what point networks will stop being considered private and start to be regulated. Further detail on the regulatory framework can be found in section 2.5 of the hydrogen strategy.

- **Safety and feasibility testing**: outside of current industrial uses, distribution and storage of hydrogen has not been fully safety tested at scale, and it is not clear what purity standards are required for hydrogen distributed in pipelines to be used by different end users (nascent market & imperfect information). This also applies to blending, where the safety profile and commercial feasibility are still being established.

Market failures

Table 1 below summarises how the barriers identified in the previous sections map onto the market failures most relevant for hydrogen adoption. Market failures and barriers provide two alternative ways of conceptualising the obstacles for hydrogen roll-out.

Table 1. Market failures and barriers

		Barriers underpinned by market failure		
Market failure	**Description**	**Production barriers**	**Demand barriers**	**Distribution and storage barriers**
Nascent markets & imperfect information	Market mechanisms can fail to support emerging technologies due to: a) competitive disadvantage relative to mature technologies, b) uncertainties surrounding new technologies (e.g. around future demand, regulations, etc.); c) immature markets leading to inefficient outcomes (e.g. excessive market concentration).	Production cost; Technological and commercial risk; Demand uncertainty; Lack of market structure; Policy and regulatory uncertainty.	User cost; Technological and commercial risk; Lack of market structure; Policy and regulatory uncertainty; Safety and feasibility; Consumer awareness and acceptance	Cost and funding uncertainty; Lack of market structure; Regulatory uncertainty; Safety and feasibility testing.
First mover disadvantage	Underinvestment due to early adopters taking significant initial risks but 'sharing' benefits with later entrants (knowledge spill-overs).	Technological and commercial risk	Technological and commercial risk	Cost and funding uncertainty
Coordination failure	Lack of coordinated investment across the supply chain can lead to suboptimal market outcomes.	Demand uncertainty; Distribution and storage barriers	Supply uncertainty; Distribution and storage; Consumer awareness and acceptance	Supply and demand uncertainty
Negative externality – social cost of carbon	Low carbon fuels at a competitive disadvantage, due to the social cost of emissions not being captured in the market price for high carbon fuels.	Production cost	User cost	

Hydrogen Strategy Commitments

Our 5GW 2030 ambition sets a clear framework to consider what outcomes are needed. We considered the outcomes that were needed to achieve our ambition, taking a systematic approach considering the shape of the current and future hydrogen economy to determine a credible series of 2030 outcomes that we could measure success against and to establish a baseline for achieving CB6.

- **Progress towards 2030 ambition**: 5GW of low carbon hydrogen production capacity with potential for rapid expansion post 2030; hope to see 1GW production capacity by 2025.
- **Decarbonisation of existing UK hydrogen economy**: existing hydrogen supply decarbonised through CCUS and/or supplemented by electrolytic hydrogen injection.
- **Lower cost of hydrogen production**: a decrease in the cost of low carbon hydrogen production driven by learnings from early projects, more mature markets and technology innovation.
- **End-to-end hydrogen system with a diverse range of users**: end user demand in place across a range of sectors and locations across the UK, with significantly more end users able and willing to switch.
- **Increased public awareness**: public and consumers are aware of and accept use of hydrogen across the energy system.
- **Promote UK economic growth and opportunities, including jobs**: established UK capabilities and supply chain that translates into economic benefits, including through exports. UK is an international leader and attractive place for inward investment.
- **Emissions reduction under Carbon Budgets 4 and 5**: hydrogen makes a material contribution to the UK's emissions reduction targets, including through setting us on a pathway to achieving CB6.
- **Preparation for ramp up beyond 2030 – on a pathway to net zero**: requisite hydrogen infrastructure and technologies are in place with potential for expansion. Well established regulatory and market framework in place.

Realising these outcomes means addressing a series of barriers, articulated in the hydrogen economy Theory of Change and in the market barriers section of this chapter. These barriers are focused on key parts of the value chain, and we recognise that there are more specific and detailed set of barriers and challenges that are presented in the main hydrogen strategy, as well as barriers, such as those needed to establish a strong UK supply chain and skills base.

Building on outcome and barrier identification, we then considered what existing commitments are addressing these barriers, and what additional commitments were needed to address them. As set out in chapter 5 of the Hydrogen Strategy, we will monitor our progress towards achieving our outcomes by tracking against a set of key indicators and metrics. Based on our review of progress, and with consideration of our principles for government action, we will explore potential further action needed during the 2020s to deliver our 2030 ambition and to support further scale up in line with CB6.

The table below present a ‘flow chart’ articulating our approach to mapping our desired outcomes, barriers and commitments for key parts of the value chain across two of our outcomes by 2030, as a guide for the approach we have taken.

Table 2. Mapping of outcomes, barriers and commitments

Outcomes by 2030	Barriers faced	Example commitments
Lower cost of hydrogen production: a decrease in the cost of low carbon hydrogen production driven by learnings from early projects, more mature markets and technology innovation.	Production cost, technology and commercial risk, demand uncertainty	We will work with industry to deliver our ambition for 5GW of low carbon hydrogen production capacity by 2030. In doing so, we would hope to see 1GW production capacity by 2025. Launch ITT for £60m Low Carbon Hydrogen Supply 2 Expression of Interest which will develop novel hydrogen supply solutions for a growing hydrogen economy. We will develop further detail on our production strategy and twin track approach including less developed production methods by early 2022.
End-to-end hydrogen system with a diverse range of users: end user demand in place across a range of sectors and locations across the UK, with significantly more end users able and willing to switch.	Production barriers plus: Lack of market structure, distribution and storage barriers, policy and regulatory uncertainty, safety and feasibility testing of demand	We will undertake a review of hydrogen network requirements for first of a kind and next of a kind projects in the 2020s. We will undertake a review of likely scenarios for storage need up to and beyond 2030, including its potential role as a critical enabler for some end use sectors. We will engage with industry later this year on possible requirements for a hydrogen pilot research and innovation facility to support hydrogen use in industry and power. We will work across Government to highlight the potential role of hydrogen in the future energy system and consider whether and how this should be reflected in the design of wider energy markets and policies (e.g. capacity market, green gas support scheme). We will continue to work with industry and regulators to consider what regulatory changes may be appropriate across the hydrogen value chain, in line with the commitments made in this Strategy.

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Appendix S5

MODELLING AND ANALYSIS

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How green is blue hydrogen?

Robert W. Howarth[1] | **Mark Z. Jacobson**[2]

[1]Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, New York, USA

[2]Department of Civil & Environmental Engineering, Stanford University, Stanford, California, USA

Correspondence
Robert W. Howarth, Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, NY 14853, USA.
Email: howarth@cornell.edu

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Abstract

Hydrogen is often viewed as an important energy carrier in a future decarbonized world. Currently, most hydrogen is produced by steam reforming of methane in natural gas ("gray hydrogen"), with high carbon dioxide emissions. Increasingly, many propose using carbon capture and storage to reduce these emissions, producing so-called "blue hydrogen," frequently promoted as low emissions. We undertake the first effort in a peer-reviewed paper to examine the lifecycle greenhouse gas emissions of blue hydrogen accounting for emissions of both carbon dioxide and unburned fugitive methane. Far from being low carbon, greenhouse gas emissions from the production of blue hydrogen are quite high, particularly due to the release of fugitive methane. For our default assumptions (3.5% emission rate of methane from natural gas and a 20-year global warming potential), total carbon dioxide equivalent emissions for blue hydrogen are only 9%-12% less than for gray hydrogen. While carbon dioxide emissions are lower, fugitive methane emissions for blue hydrogen are higher than for gray hydrogen because of an increased use of natural gas to power the carbon capture. Perhaps surprisingly, the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat and some 60% greater than burning diesel oil for heat, again with our default assumptions. In a sensitivity analysis in which the methane emission rate from natural gas is reduced to a low value of 1.54%, greenhouse gas emissions from blue hydrogen are still greater than from simply burning natural gas, and are only 18%-25% less than for gray hydrogen. Our analysis assumes that captured carbon dioxide can be stored indefinitely, an optimistic and unproven assumption. Even if true though, the use of blue hydrogen appears difficult to justify on climate grounds.

KEYWORDS
blue hydrogen, decarbonization, greenhouse gas footprint, hydrogen, methane, methane emissions

1 | INTRODUCTION

Hydrogen is widely viewed as an important fuel for a future energy transition. Currently, hydrogen is used mostly by industry during oil-refining and synthetic nitrogen fertilizer production, and little is used for energy because it is expensive relative to fossil fuels.[1] However, hydrogen is increasingly being promoted as a way to address climate change, as

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indicated by a recent article in the New York Times.[2] In this view, hydrogen is to be used not only for hard to decarbonize sectors of the economy such as long-distance transportation by trucks and airplanes but also for heating and cooking, with hydrogen blended with natural gas and distributed to homes and business through existing pipeline systems.[2] Utilities are also exploring the use of hydrogen, again blended with natural gas, to power existing electric generating facilities.[3] In Europe, a recent report from Gas for Climate, an association of natural gas pipeline companies, envisions large scale use of hydrogen in the future for heating and electricity generation.[4] The Hydrogen Council, a group established in 2017 by British Petroleum, Shell, and other oil and gas majors, has called for heating all homes with hydrogen in the future.[5]

The vast majority of hydrogen (96%) is generated from fossil fuels, particularly from steam methane reforming (SMR) of natural gas but also from coal gasification.[6] In SMR, which is responsible for approximately three quarters of all hydrogen production globally,[7] heat and pressure are used to convert the methane in natural gas to hydrogen and carbon dioxide. The hydrogen so produced is often referred to as "gray hydrogen," to contrast it with the "brown hydrogen" made from coal gasification.[8] Production of gray hydrogen is responsible for 6% of all natural gas consumption globally.[7] Hydrogen can also be generated by electrolysis of water. When such electricity is produced by a clean, renewable source, such as hydro, wind, or solar, the hydrogen is termed "green hydrogen." In 2019, green hydrogen was not cost competitive with gray hydrogen,[9] but that is changing as the cost of renewables is decreasing rapidly and electrolyzers are becoming more efficient. Still, the supply of green hydrogen in the future seems limited for at least the next several decades.[2,5]

Greenhouse gas emissions from gray hydrogen are high,[10,11] and so increasingly the natural gas industry and others are promoting "blue hydrogen".[5,8,9] Blue hydrogen is a relatively new concept and can refer to hydrogen made either through SMR of natural gas or coal gasification, but with carbon dioxide capture and storage. As of 2021, there were only two blue-hydrogen facilities globally that used natural gas to produce hydrogen at commercial scale, as far as we can ascertain, one operated by Shell in Alberta, Canada, and the other operated by Air Products in Texas, USA.[12] Often, blue hydrogen is described as having zero or low greenhouse gas emissions.[8,9] However, this is not true: not all of carbon dioxide emissions can be captured, and some carbon dioxide is emitted during the production of blue hydrogen.[1] Further, to date no peer-reviewed analysis has considered methane emissions associated with producing the natural gas needed to generate blue hydrogen.[1] Methane is a powerful greenhouse gas. Compared mass-to-mass, it is more than 100-times more powerful as a warming agent than carbon dioxide for the time both gases are in the atmosphere and causes 86-times the warming as carbon dioxide over an integrated 20-year time frame after a pulsed emission of the two gases. Approximately 25% of the net global warming that has occurred in recent decades is estimated to be due to methane.[13] In a recent report, the United Nations Environment Programme concluded that methane emissions globally from all sources need to be reduced by 40%-45% by 2030 in order to achieve the least cost pathway for limiting the increase in the Earth's temperature to 1.5°C, the target set by COP 21 in Paris in December 2015.[14]

Here, we explore the full greenhouse gas footprint of both gray and blue hydrogen, accounting for emissions of both methane and carbon dioxide. For blue hydrogen, we focus on that made from natural gas rather than coal, that is gray hydrogen combined with carbon capture and storage. In China, brown hydrogen from coal now dominates over gray hydrogen from natural gas, due to the relative prices of natural gas and coal, but globally and particular in Europe and North America, gray hydrogen dominates.[1]

2 | ESTIMATING EMISSIONS FROM PRODUCING GRAY HYDROGEN

Greenhouse gas emissions from the production of gray hydrogen can be separated into two parts: (a) the SMR process in which methane is converted to carbon dioxide and hydrogen; and (b) the energy used to generate the heat and high pressure needed for the SMR process. For blue hydrogen, which we discuss later in this paper, emissions from the generation of electricity needed to run the carbon dioxide capture equipment must also be included. In this analysis, we consider emissions of only carbon dioxide and methane, and not of other greenhouse gases such as nitrous oxide that are likely to be much smaller. For methane, we consider the major components of its lifecycle emissions associated with the mining, transport, storage, and use of the natural gas needed to produce the hydrogen and power carbon capture. Emissions are expressed per unit energy produced when combusting the hydrogen, to aid in comparing the greenhouse gas footprint with other fuels.[15,16] In this paper, we use gross calorific values.

We start by estimating how much methane is consumed and how much carbon dioxide is produced in the two aspects of production of gray hydrogen. From this information, we can subsequently below estimate emissions of unburned methane.

2.1 | Consumption of methane and production of carbon dioxide in SMR process

In the SMR process, 1 mole of carbon dioxide and 4 moles of hydrogen gas (H_2) are produced per mole of methane consumed, according to this overall reaction:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (1)$$

The gross caloric calorific heat content of hydrogen is 0.286 MJ per mole,[17] or inverting this value, 3.5 moles H_2 per MJ. The carbon dioxide produced during the SMR process is given by:

$$(3.5 \text{ moles } H_2/\text{MJ}) * (1 \text{ mole } CO_2/4 \text{ moles } H_2) = 0.875 \text{ moles } CO_2 \text{ per MJ} \quad (2)$$

With a molecular weight of 44.01 g per mole, the amount of carbon dioxide produced during the SMR process is 38.51 g CO_2 per MJ (Table 1). The amount of methane consumed is given by:

$$(3.5 \text{ moles } H_2/\text{MJ}) * (1 \text{ mole } CH_4/4 \text{ moles } H_2) = 0.875 \text{ moles } CH_4 \text{ per MJ} \quad (3)$$

With a molecular weight of 16.04 g per mole, 14.04 g CH_4 per MJ is consumed during the SMR process (Table 1). There is essentially no uncertainty in these estimates of how much methane is consumed, and how much carbon dioxide is produced during the SMR process: the relationship is set by the chemical stoichiometry shown in Equation (1).

2.2 | Consumption of methane and production of carbon dioxide from energy needed to drive SMR process

The production of hydrogen from methane is an endothermic reaction and requires significant input of energy, between 2.0 and 2.5 kWh per m^3 of hydrogen, to provide the necessary heat and pressure.[18] This energy comes almost entirely from natural gas when producing gray hydrogen, and therefore, also presumably when producing blue hydrogen proposed for Europe or North America.[1] Using a mean value of 2.25 kWh per m^3 of hydrogen, we estimate the energy in natural gas (methane) required to produce a mole of hydrogen as follows:

$$(2.25 \text{ kWh}/m^3 \text{ of } H_2) * (3.6 \text{ MJ/kWh}) * (1 \text{ m}^3/1000 \text{ L}) * (22.4 \text{ L/mol}) = 0.1814 \text{ MJ per mole } H_2 \quad (4)$$

That is, 0.1814 MJ of energy from burning methane is required per mole of hydrogen produced. When burning natural gas for heat, 50 g CO_2 per MJ in emissions are produced, using gross calorific values.[19] Note that higher carbon dioxide emission values are reported when using net calorific values.

Therefore,

$$(0.1814 \text{ MJ/mole } H_2) * (50 \text{ g } CO_2/\text{MJ}) = 9.07 \text{ g } CO_2 \text{ per mole } H_2. \quad (5)$$

As noted above, the gross calorific heat content of hydrogen is equivalent to 3.5 moles H_2 per MJ. Therefore,

$$(9.07 \text{ g } CO_2/\text{mole } H_2) * (3.5 \text{ moles } H_2/\text{MJ}) = 31.8 \text{ g } CO_2/\text{MJ} \quad (6)$$

So 31.8 g of carbon dioxide are produced to generate the heat and pressure to drive the SMR process per MJ of hydrogen produced (Table 1). Since one mole of methane in natural gas is burned to produce one mole of carbon dioxide emissions, we can estimate the methane consumed as follows:

$$(31.8 \text{ g } CO_2/\text{MJ}) * (1 \text{ mole } CO_2/44.01 \text{ g } CO_2) * (16.04 \text{ g } CH_4/\text{mole } CH_4) * (1 \text{ mole } CH_4/\text{mole } CO_2) = 11.6 \text{ g } CH_4/\text{MJ} \quad (7)$$

See Table 1.

2.3 | Total carbon dioxide and methane emissions for gray hydrogen

The sum of the carbon dioxide from the SMR process (38.5 g CO_2 per MJ) and from the energy used to generate the heat and electricity for the SMR (31.8 g CO_2 per MJ) is 70.3 g CO_2 per MJ. Additionally, it takes energy to produce, process, and transport the natural gas used to generate the hydrogen. Using the analysis of Santoro et al.[20] as reported in Howarth et al,[21] these indirect upstream emissions are approximately 7.5% of the direct carbon dioxide emissions for natural gas, or an additional 5.3 g CO_2 per MJ (7.5% of 70.3 g CO_2 per MJ). Therefore, the total quantity of carbon dioxide produced is 75.6 g CO_2 per MJ (Table 1).

The total quantity of methane in natural gas consumed to generate gray hydrogen is the sum of that used in the SMR process (14.04 g CH_4 per MJ) and the amount burned to generate the heat and high pressure needed for the process (11.6 g CH_4 per MJ) or 25.6 g CH_4 per MJ. It is not possible to produce and use natural gas without having some methane emitted unburned to the atmosphere, due both to leaks and to purposeful emissions including venting.[21,22] Below, we briefly discuss the recent literature that characterizes methane emissions from natural gas operations, and use a range of values in a sensitivity analysis. Here, for our default estimation of the greenhouse gas footprint of gray hydrogen, we rely on a recent synthesis on "top–down" emission studies.[16] Top–down estimates use information such as from satellites or airplane flyovers that characterize an integrated flux. The mean value of estimates from 20 different studies in 10 major natural gas fields in the United States, normalized to gas production in those fields, indicates that 2.6% of gas production is emitted to the atmosphere.[16] This is a good estimate for the upstream emissions that occur in the gas fields. Methane is also emitted from storage and transport to consumers, and the data in the top–down study of Plant et al[23] suggests this is an additional

TABLE 1 Comparison of methane that is consumed, of carbon dioxide that is produced, and of emissions of both methane and carbon dioxide for each step in the processing of methane to hydrogen for gray hydrogen, blue hydrogen with carbon dioxide capture from the SMR process but not from the exhaust flue gases created from burning natural gas to run the SMR equipment, and blue hydrogen with carbon dioxide capture from both the SMR process and from the exhaust flue gases

	Gray H_2	Blue H_2 (w/o flue-gas capture)	Blue H_2 (w/flue-gas capture)
SMR process			
CH_4 consumed (g CH_4/MJ)	14.0	14.0	14.0
CO_2 produced (g CO_2/MJ)	38.5	38.5	38.5
Fugitive CH_4 emissions (g CH_4/MJ)	0.49	0.49	0.49
Fugitive CH_4 emissions (g CO_2eq/MJ)	42.1	42.1	42.1
Direct CO_2 emissions (g CO_2/MJ)	38.5	5.8	5.8
CO_2 capture rate	0%	85%	85%
Energy to drive SMR			
CH_4 consumed (g CH_4/MJ)	11.6	11.6	11.6
CO_2 produced (g CO_2/MJ)	31.8	31.8	31.8
Fugitive CH_4 emissions (g CH_4/MJ)	0.41	0.41	0.41
Fugitive CH_4 emissions (g CO_2eq/MJ)	35.3	35.3	35.3
Direct CO_2 emissions (g CO_2/MJ)	31.8	31.8	11.1
CO_2 capture rate	0%	0%	65%
Energy to power carbon capture			
CH_4 consumed (g CH_4/MJ)	0	3.0	6.0
CO_2 produced (g CO_2/MJ)	0	8.2	16.3
Fugitive CH_4 emissions (g CH_4/MJ)	0	0.11	0.21
Fugitive CH_4 emissions (g CO_2eq/MJ)	0	9.5	1
Direct CO_2 emissions (g CO_2/MJ)	0	8.2	16.0
Indirect upstream CO_2 emissions (g CO_2/MJ)	5.3	5.9	6.5
Total CH4 consumed (g CH_4/MJ)	25.6	28.6	31.6
Total CO_2 emitted (g CO_2/MJ)	75.6	51.7	39.7
Total fugitive CH_4 emissions (g CO_2eq/MJ)	77.4	86.9	95.4
Total emissions (g CO_2eq/MJ)	153	139	135

Note: The methane leakage rate is 3.5%.

0.8%.[16,24] Combined with the 2.6% for field-level emissions, we estimate a total of 3.4% of production is emitted to the atmosphere overall. Note that in addition to some methane being lost between production and consumption due to leaks, methane is also burned by the natural gas industry to power natural gas processing and transport. This is important to consider, since we want to evaluate how much methane is emitted for the methane in natural gas that is consumed in producing hydrogen. In 2015, natural gas production in the United States was 817 billion m^3, while consumption was 771 billion m^3,[25,26] (converting cubic feet to cubic meters). Using this information, we can estimate the methane emission as a percentage of gas consumption as follows:

$$(3.4\% \text{ of production}) * (817 \times 109 \text{ m}^3 / 771 \times 109 \text{ m}^3) = 3.5\% \text{ of consumption} \quad (8)$$

With this value and the quantity of methane consumed to produce gray hydrogen, we can estimate the upstream emissions of methane:

$$(3.5\% \text{ of consumption}) * (\text{consumption of } 25.6 \text{ g CH}_4 \text{ per MJ}) = 0.90 \text{ g CH}_4 \text{ per MJ} \quad (9)$$

To compare methane emissions with carbon dioxide emissions requires a specified time frame, since the half-life of methane in the atmosphere is only 12 years or so, far less than that of carbon dioxide.[13] Greenhouse gas inventories often compare methane with carbon dioxide for an integrated period of 100 years following pulsed emissions of both gases. However, this underestimates the role of methane in global warming over shorter time periods. An increasing number of scientists have called for using a 20-year integrated time period instead of or in addition to the 100-year period.[15,21,24,27,28]

The 20-year time frame is now mandated by law in the State of New York, as part of the Climate Leadership and Community Protection Act of 2019.[24] And a 20-year period is more appropriate than a 100-year time frame given the urgency of reducing methane emissions globally over the coming decade.[14] Here, we use the 20-year time frame using the Global Warming Potential (GWP) for 20 years of 86.[13] We also consider other GWP values in a sensitivity analysis presented below. Using the 86 value, we estimate upstream methane emissions associated with the production of gray hydrogen in units of carbon dioxide equivalents (CO_2eq) thus:

$$(0.90 \text{ g } CH_4 \text{ per MJ}) * (86 \text{ g } CO_2\text{eq/g } CH_4) = 77.4 \text{ g}CO_2\text{eq per MJ} \quad (10)$$

The sum of emissions of carbon dioxide (75.6.0 g CO_2 per MJ) and unburned methane (77.4 g CO_2eq per MJ) for the production of gray hydrogen is 153 g CO_2eq per MJ (Table 1).

There are remarkably few published peer-reviewed papers with which to compare our estimate. Many non peer-reviewed reports give estimates for carbon dioxide emission from gray hydrogen that are in the range of 10 tons carbon dioxide per ton of hydrogen,[1,7] although data in support of these values are generally absent, perhaps because they are based on confidential information.[11] Since the gross calorific heat energy content of hydrogen is 0.286 MJ per mole,[17] 10 tons of carbon dioxide per ton of hydrogen corresponds to 70 g CO_2 per MJ. This is similar to but somewhat lower than our value of 75.6 g CO_2 per MJ. Most of these non peer-reviewed reports do not include methane in their estimates,[1] or if they do, they provide no detail as to how they do so. The most thorough peer-reviewed analysis of carbon dioxide emissions for gray hydrogen is that of Sun et al[11] who obtained data on both rates of hydrogen production and emissions of carbon dioxide from many individual facilities across the United States. They concluded that on average, carbon dioxide emissions for gray hydrogen are 77.8 g CO_2 per MJ, remarkably close to our value of 75.6 g CO_2 per MJ. They did not estimate methane emissions.

3 | ESTIMATING EMISSIONS FOR BLUE HYDROGEN

Blue hydrogen differs from gray hydrogen in that, with blue hydrogen, some of the carbon dioxide released by the SMR process is captured. In another version of the blue-hydrogen process, additional carbon dioxide is removed from the flue gases created from burning natural gas to provide the heat and high pressure needed to drive the SMR process. A third set of emissions, not usually captured, is the carbon dioxide and methane from the energy used to produce the electricity for the carbon-capture equipment.

3.1 | How much carbon dioxide is emitted after carbon capture?

As noted above, only two facilities that produce blue hydrogen from natural gas are in commercial operation in 2021. Thus, only limited data are available on the percentage of carbon dioxide that can be captured. For the carbon dioxide generated during SMR, the reported capture efficiencies range from 53% to 90%.[29] Actual data from one of the two commercially operating facilities, the Shell plant in Alberta, show a capture a mean capture efficiency of 78.8%, with daily rates varying from 53% to 90% except for one outlier of 15%.[30] For our baseline analysis, we use a capture rate of 85%, roughly half way between the 78.8% for the Shell plan and the best-case of 90%. Applying 100% minus the capture efficiency to the carbon dioxide produced in SMR:

$$(15\%) * (38.5 \text{ g } CO_2 \text{ per MJ}) = 5.8 \text{ g } CO_2 \text{ per MJ} \quad (11)$$

That is, 5.8 g CO_2 per MJ are emitted from the SMR process after emissions are treated for carbon capture (Table 1).

For the blue-hydrogen facilities so far in commercial operation, carbon capture has focused only on the SMR process, and no attempt has been made to capture the carbon dioxide generated from the combustion of natural gas used to provide the heat and high pressure. If these combustion emissions are captured, the carbon dioxide capture efficiency may be lower than that from the SMR process because the carbon dioxide is more dilute in the former case. We are aware of no data on carbon-capture efficiency from any plant, including any electric power plant, that combusts natural gas, but capture efficiencies of carbon dioxide from the exhaust stream of two coal-burning power plants are reported in the range of 55%-72%.[31-33] Note that efficiencies of up to 90% have been observed in one of the plants when running at full load. However, this does not reflect long-term performance, which is evaluated at average load. Load is less than full load either when the carbon-capture equipment is down for repair or when the demand for carbon dioxide is lower than it is at full load. In this analysis, we use a value of 65% capture efficiency from flue gases for our baseline analysis. Applying 100% minus this factor for emissions from the natural gas burned to produce the heat and pressure:

$$(35\%) * (31.8 \text{ g } CO_2 \text{ per MJ}) = 11.1 \text{ g } CO_2 \text{ per MJ} \quad (12)$$

Therefore, total carbon dioxide emissions from the SMR process, including the energy used to drive the process, are in the range of 16.9 g CO_2 per MJ if the combustion flue is captured (5.8 g CO_2 per MJ plus 11.1 g CO_2 per MJ) to 37.6 g CO_2 per MJ (5.8 g CO_2 per MJ plus 31.8 g CO_2 per MJ) if the flue gases are not treated (Table 1).

3.2 | Consumption of methane and production of carbon dioxide from electricity used to capture carbon dioxide

Energy is required to capture the carbon dioxide, and often this is provided by electricity generated from burning additional natural gas.[7] The existing blue-hydrogen facilities make no effort to capture the carbon dioxide from the fuel burned to generate this electricity, nor has there been any effort to do so in the case of carbon capture from coal-burning power plants.[31] Often, an energy penalty of 25% is assumed for this additional electricity.[34-36] However, this estimate is based on very little publicly available, verifiable information and may be optimistically low. A recent analysis of carbon capture from the flue gases of a coal-burning power plant, where the electricity for carbon capture came from a dedicated natural gas plant, found that the carbon dioxide emissions from the natural gas were 39% of the carbon dioxide captured from the coal-flue gases.[31] Carbon dioxide is more concentrated in the gases produced through SMR than in the flue exhaust from combustion, suggesting that it can be captured more easily.

For this analysis, we assume that the energy used in the carbon-capture results in carbon dioxide emissions equal to 25% of the carbon dioxide captured from the stream reforming process, based on IPCC,[34] Jacobson,[35] and Sgouridi et al.[36] Therefore,

$$(25\%) * [(38.5\text{ g CO}_2\text{ per MJ}) - (5.8\text{ g CO}_2\text{ per MJ})] = 8.2\text{ g CO}_2\text{ per MJ} \tag{13}$$

That is, emissions from the energy used to drive the carbon captured from the SMR process are themselves an additional 8.2 g CO_2 per MJ (Table 1).

If carbon dioxide is also captured from the flue gases used to generate heat and pressure, we assume the emissions from the energy cost is equal to 39% of the emissions captured, based on Jacobson.[31] That is,

$$(39\%) * [(31.8\text{ g CO}_2\text{ per MJ}) - (11.1\text{ g CO}_2\text{ per MJ})] = 8.1\text{ g CO}_2\text{ per MJ} \tag{14}$$

Therefore, the carbon dioxide emissions from the energy used to drive the carbon capture is between 8.2 g CO_2 per MJ if only emissions from the SMR process are captured or an additional 8.1 g CO_2 per MJ for a total of 16.3 g CO_2 per MJ if emissions from the energy source used for heat and pressure are also captured (Table 1).

As above for Equation 7, one mole of methane is burned for every mole of carbon dioxide emitted from the burning. Therefore, we can estimate the methane burned to produce the electricity required for the carbon dioxide capture as follows, for the case where only the SMR carbon is captured:

$$(8.2\text{ g CO}_2/\text{MJ}) * (1\text{ mole CO}_2/44.01\text{ g CO}_2) * (16.04\text{ g CH}_4/\text{mole CH}_4) * (1\text{ mole CH}_4/1\text{ mole CO}_2) = 3.0\text{ g CH}_4/\text{MJ} \tag{15}$$

That is, 3.0 g CH_4 per MJ are consumed to generate the electricity used for carbon capture if only the reforming process emissions are captured (Table 1). Similarly, if the emissions from the energy used for the heat and pressure are also captured,

$$(8.1\text{ g CO}_2/\text{MJ}) * (1\text{ mole CO}_2/44.01\text{ g CO}_2) * (16.04\text{ g CH}_4/\text{mole CH}_4) * (1\text{ mole CH}_4/1\text{ mole CO}_2) = 3.0\text{ g CH}_4/\text{MJ} \tag{16}$$

Therefore, the quantify of methane used to drive carbon capture when the flue gases from the combustion of the gas used to generate heat and pressure for the SMR process are 3.0 g CH_4 per MJ plus 3.0 g CH_4 per MJ, for a total of 6.0 g CH_4 per MJ when carbon capture is applied both to SMR and exhaust flue gases (Table 1).

If we again assume that 3.5% of the natural gas that is consumed is emitted unburned to the atmosphere (as in Equation 9), then for the case where only carbon dioxide emissions from SMR are captured, upstream methane emissions are:

$$(3.5\%) * (3.0\text{ g CH}_4/\text{MJ}) = 0.11\text{g CH}_4/\text{MJ} \tag{17}$$

For the case where flue gases are also treated for carbon capture, the upstream methane emissions are:

$$(3.5\%) * (6.0\text{ g CH}_4/\text{MJ}) = 0.21\text{ g CH}_4/\text{MJ} \tag{18}$$

Converting these methane emissions to carbon dioxide equivalents:

$$(0.11\text{ g CH4 per MJ}) * (86\text{ g CO}_2\text{eq/g CH}_4) = 9.5\text{ g CO}_2\text{eq per MJ} \tag{19}$$

And

$$(0.21\text{ g CH}_4\text{per MJ}) * (86\text{ g CO}_2\text{eq/g CH}_4) = 18\text{ g CO}_2\text{eq per MJ} \tag{20}$$

Therefore, upstream emissions of unburned methane from the energy used to drive carbon capture are between 9.5 g CO_2eq per MJ if only the SMR carbon is captured and 18 g CO_2eq per MJ if the flue-gas emissions are also captured (Table 1).

3.3 | Total carbon dioxide and methane emissions for blue hydrogen

The total emission of carbon dioxide for the production of blue hydrogen is the sum of the emissions from the SMR process after carbon capture, emissions from the energy used for heat and pressure to drive SMR, emissions from the energy used to power the carbon capture, and the indirect upstream emissions associated with producing and transporting natural gas. The indirect upstream carbon dioxide emissions result from the activity needed to provide the natural gas, and so should be applied as a percentage to the carbon dioxide produced from using natural gas, and not simply the carbon dioxide emitted after carbon capture. Using the approach of Howarth et al,[21] this is 7.5% of the carbon dioxide produced in the SMR process plus energy needed to fuel that process as for gray hydrogen (70.3 g CO_2 per MJ) plus the emissions from the energy needed to drive the carbon capture (8.2-16.3 g CO_2 per MJ depending on whether or not the flue gases from the SMR-energy source is captured). Therefore, these indirect upstream carbon dioxide emissions are between 5.9 g CO_2 per MJ and 6.5 g CO_2 per MJ depending on whether or not the flue-gas emissions are captured (Table 1). For the case where only the emissions from the SMR processes are treated for carbon capture, total emissions of carbon dioxide are:

$$(5.8 \text{ g CO2 per MJ}) + (31.8 \text{ g CO2 per MJ}) + (8.2 \text{ g } CO_2 \text{ per MJ}) + (5.90 \text{ g } CO_2 \text{ per MJ}) = 51.7 \text{ g } CO_2 \text{ per MJ} \quad (21)$$

When the emissions from exhaust flue gases are also treated for carbon capture:

$$(5.8 \text{ g } CO_2 \text{ per MJ}) + (11.1 \text{ g } CO_2 \text{ per MJ}) + (16.3 \text{ g } CO_2 \text{ per MJ}) + (6.5 \text{ g } CO_2 \text{ per MJ}) = 39.7 \text{ g } CO_2 \text{ per MJ} \quad (22)$$

To summarize, when only the carbon from the SMR process itself is captured, total emissions of carbon dioxide are 51.7 g CO_2 per MJ. When efforts are also taken to capture the carbon dioxide from the flue exhaust from the energy driving the reforming process, total carbon dioxide emissions are 39.7 g CO_2 per MJ (Table 1). Treating the exhaust flue gases for carbon capture reduces total lifecycle emissions of carbon dioxide by 23%, less than might have been expected. This is due both to a relatively low efficiency for the carbon capture of flue gases[31] and to the increased combustion of natural gas needed to provide the electricity for the carbon capture.

The methane emissions from blue hydrogen are the same as for gray hydrogen, except for those associated with the increased use of energy from natural gas to drive the carbon-capture process. The emissions for gray hydrogen are 77.4 g CO_2eq per MJ. The additional methane emissions from the gas used to drive carbon capture are given in Equations 19 and 20: 9.5 g CO_2eq per MJ when only SMR is treated for carbon capture and 18 g CO_2eq per MJ when the exhaust flue gases are also captured. Therefore, the total upstream methane emissions for the production of blue hydrogen are:

$$(77.4 \text{ g } CO_2\text{eq per MJ}) + (9.5 \text{ g } CO_2\text{eq per MJ}) = 86.9 \text{ g } CO_2\text{eq per MJ} \quad (23)$$

when only emissions from the SMR process are captured (Table 1). When flue gases are also treated, total upstream methane emissions are:

$$(77.4 \text{ g } CO_2\text{eq per MJ}) + (18 \text{ g } CO_2\text{eq per MJ}) = 95.4 \text{ g } CO_2\text{eq per MJ} \quad (24)$$

Total emissions for blue hydrogen when only the SMR process is treated are the sum of the carbon dioxide emissions and the upstream methane emissions:

$$(51.7 \text{ g } CO_2\text{per MJ}) + (86.9 \text{ g } CO_2\text{eq per J}) = 139 \text{ g } CO_2\text{eq per MJ} \quad (25)$$

See Table 1. When the exhaust flue gases are also treated for carbon dioxide capture, total emissions for producing blue hydrogen are:

$$(39.7 \text{ g } CO_2\text{per MJ}) + (95.4 \text{ g } CO_2\text{eq per MJ}) = 135 \text{ g } CO_2\text{eq per MJ} \quad (26)$$

We are aware of no previously published, peer-reviewed analyses on either total carbon dioxide or methane emissions associated with producing blue hydrogen. Several non peer-reviewed reports suggest that it may be possible to reduce carbon dioxide emissions for blue hydrogen by 56% (when only the SMR process is treated) to 90% (when exhaust flue gases are also treated) relative to gray hydrogen.[1,7] However, no data have been presented to support these estimates, and they apparently do not include emissions associated with the energy needed to drive carbon capture. Our results using a full lifecycle assessment show the 56% to 90% assumptions are too optimistic.

In Figure 1, we compare the greenhouse gas footprint of gray hydrogen with blue hydrogen where only the SMR process is captured and with blue hydrogen where carbon capture is also used for the exhaust flue gases. Because of the increased methane emissions from increased use of natural gas when flue gases are treated for carbon capture, total greenhouse gas emissions are only very slightly less than when just the carbon dioxide from the stream reforming process is treated, 135 vs 139 g CO_2eq per MJ. In both cases, total emissions from producing blue hydrogen are only 9% to 12% less than for gray hydrogen, 135 or 139 g CO_2eq per MJ compared with 153 g CO_2eq per MJ. Blue hydrogen is hardly "low emissions." The lower, but nonzero, carbon dioxide emissions from blue hydrogen compared with gray hydrogen are partially offset by the higher methane emissions. We further note that blue hydrogen as a strategy only works to the extent it is possible to store carbon dioxide long term indefinitely into the future without leakage back to the atmosphere.

4 | COMPARISON OF EMISSIONS WITH OTHER FUELS AND SENSITIVITY ANALYSES

4.1 | Emissions for fossil fuels

In Figure 1, we also compare greenhouse gas emissions from gray and blue hydrogen with those for other fuels per unit of energy produced when burned. The carbon dioxide emissions

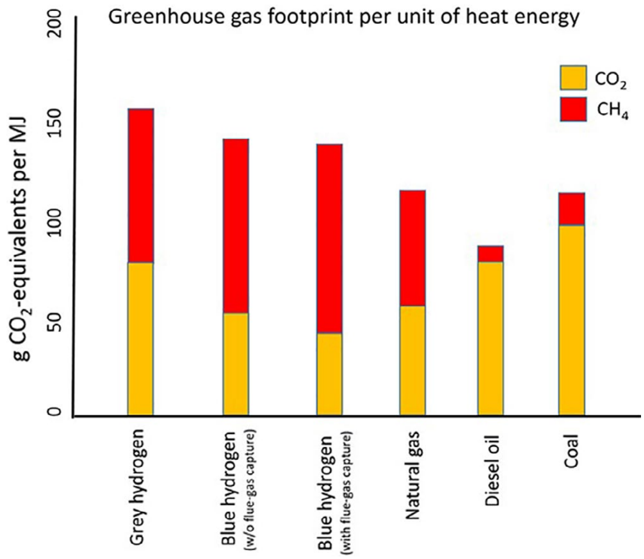

FIGURE 1 Comparison of carbon dioxide equivalent emissions from gray hydrogen, blue hydrogen with carbon dioxide capture from the SMR process but not from the exhaust flue gases created from burning natural gas to run the SMR equipment, blue hydrogen with carbon dioxide capture from both the SMR process and from the exhaust flue gases, natural gas burned for heat generation, diesel oil burned for heat, and coal burned for heat. Carbon dioxide emissions, including emissions from developing, processing, and transporting the fuels, are shown in orange. Carbon dioxide equivalent emissions of fugitive, unburned methane are shown in red. The methane leakage rate is 3.5%. See text for detailed assumptions

shown for coal, diesel oil, and natural gas include both direct and indirect emissions. The direct emissions are based on gross calorific values from EIA.[19] Indirect emissions are those required to develop and process the fuels and are based on Howarth et al.[21] These indirect carbon dioxide emissions are 4 g CO_2 per MJ for coal, 8 g CO_2 per MJ, and 3.8 g CO_2 per MJ for natural gas. Upstream fugitive emissions of unburned methane are assumed to be 3.5% for natural gas, as we have assumed for the hydrogen estimates. Methane emissions for coal and diesel oil are as presented in Howarth[24]: 0.185 g CH_4 per MJ for coal and 0.093 g CH_4 per MJ for diesel oil, corresponding to 8.0 and 15.9 4 g CO_2eq per MJ respectively based on a 20-year GWP of 86.

Combined emissions of carbon dioxide and methane are greater for gray hydrogen and for blue hydrogen (whether or not exhaust flue gases are treated for carbon capture) than for any of the fossil fuels (Figure 1). Methane emissions are a major contributor to this, and methane emissions from both gray and blue hydrogen are larger than for any of the fossil fuels. This reflects the large quantities of natural gas consumed in the production of hydrogen. Carbon dioxide emissions are less from either gray or blue hydrogen than from coal or diesel oil. Carbon dioxide emissions from blue hydrogen are also less than from using natural gas directly as a fuel, but not substantially so. Carbon dioxide emissions from gray hydrogen are somewhat larger than from natural gas (Figure 1).

4.2 | Sensitivity analyses for methane emissions

Given the importance of methane emissions to the greenhouse gas footprints of gray and blue hydrogen, we here present sensitivity analyses on our estimates. We separately consider different rates of fugitive methane emissions and different assigned GWP values.

Our default value for methane emissions used above for gray hydrogen, blue hydrogen, and natural gas is 3.5% of consumption. As noted above, this is based on top–down estimates for emissions from 20 different studies in 10 different gas fields plus a top–down estimate for emissions from gas transport and storage.[16] This is very close to an independent estimate of emissions from shale gas production and consumption estimated from global trends in the ^{13}C stable isotopic composition of methane in the atmosphere since 2005.[37] For the sensitivity analysis, we also evaluate one higher rate and two lower rates of methane emission. The higher rate is from the high-end sensitivity analysis for shale gas emissions based on the global ^{13}C data, or 4.3% of consumption.[37] The lower rates we analyze are 2.54% and 1.45% of consumption. The 2.54% value is based on Alvarez et al[22] who used "bottom–up" approaches to estimate the upstream and midstream methane emissions for natural gas in the United States as 12.7 Tg per year in 2015. This is 2.54% of consumption, based on annual gas consumption for 2015 of 771 billion m^3 of natural gas in the United States,[26] assuming methane comprises 93% of the volume of gas.[38] The bottom–up approach presented by Alvarez et al[22] likely underestimates methane emissions.[24,39,40] We also consider an even lower estimate based on Maasakkers et al.[41] Using an inverse model in combination with satellite data and the US EPA methane emissions inventory, they concluded that methane emissions from natural gas operations in the United States were 8.5 T per year in 2012. This is 1.45% of gas consumption, based on again assuming methane is 93% of gas and a national US consumption of gas of 723 billion m^3 in 2012.[26]

Our baseline analysis is based on a 20-year GWP value of 86.[13] There is uncertainty in this estimate, so here we also explore the higher 20-year GWP value of 105 presented in Shindell et al.[42] Most traditional greenhouse gas inventories use a 100-year GWP, so we explore that as well, using the latest value from the IPCC[13] synthesis report of 34. However, the IPCC[13] noted that the use of a 100-year time period is arbitrary. We prefer the use of 20-year GWP, since it better captures the role of methane as a driver of climate change over the time period of the next several decades, and the 100-year time frame discounts the importance of methane over these shorter time frames.[15,24]

In our sensitivity analyses, we substitute emission rates of 4.3%, 2.54%, and 1.54% for our baseline value of 3.5% in Equations 9, 17, and 18 for gray and blue hydrogen and in our estimate for natural gas presented in Figure 1. We also substitute a 20-year GWP value of 105 and a 100-year GWP value of 34 for the 20-year GWP of 86 used in Equations 10, 19, and 20. The sensitivity estimates are shown in Table 2. Across the full set of assumptions, both gray hydrogen and blue hydrogen without flue-gas capture (where only the carbon dioxide from SMR is captured) always have greater emissions than natural gas. The differences between the greenhouse gas footprint of blue hydrogen with or without the capture of carbon dioxide from the exhaust flue gases are generally small across all assumptions concerning fugitive methane emissions, with the total greenhouse gas emissions without the flue-gas treatment usually higher. The emissions from blue hydrogen with full carbon capture including the exhaust flue gases are higher than for natural gas across all set of assumptions except for the analysis with the 100-year GWP of 34 and low methane emissions, 2.54% or less (Table 2).

We also evaluate the sensitivity of our conclusions to the percentage of carbon dioxide that is captured from SMR and from the flue exhaust from the natural gas burned to power the SMR process. Our default values presented above are for 85% capture from the SMR process and 65% capture from the flue gases, if an effort were made to capture those. Our sensitivity analysis includes a low estimate for SMR capture of 78.8% based on actual data from one commercial blue-hydrogen plant[30] and a high estimate of 90%, the highest yet reported.[31] For capture of the flue gases, we explore carbon dioxide capture efficiencies of 55% at the low end and 90% at the high-end based on actual facility performance for flue gases from coal-burning electric plants.[31-33] Note that the 90% rate is the best ever observed and does not reflect likely actual performance under long-term commercial operations. We present the results of this sensitivity analysis in Table 3. Perhaps surprisingly, our conclusions are very insensitive to assumptions about carbon dioxide capture rates. This is because capture is very energy intensive: to capture more carbon dioxide takes more energy, and if this energy comes from natural gas, the emissions of both carbon dioxide and fugitive methane emissions from this increase in such proportion as to offset a significant amount of the reduction in carbon dioxide emission due to the carbon capture.

These sensitivity analyses show that our overall conclusion is robust: the greenhouse gas footprint of blue hydrogen, even with capture of carbon dioxide from exhaust flue gases, is as large as or larger than that of natural gas.

5 | IS THERE A PATH FOR TRULY "GREEN" BLUE HYDROGEN?

Some of the CO_2eq emissions from blue hydrogen are inherent in the extraction, processing, and use of natural gas as the feedstock source of methane for the SMR process: fugitive methane emissions and upstream emissions of carbon dioxide from the energy needed to produce, process, and transport the natural gas that is reformed into hydrogen are inescapable. On the other hand, the emissions of methane and

TABLE 2 Sensitivity analysis for total emissions of carbon dioxide and methane (g CO_2-equivalents per MJ of heat generated in combustion) for different upstream fugitive methane leakage rates and for either 20-year or 100-year global warming potentials (GWP20, GWP100)

	Gray H_2	Blue H_2 (w/o flue-gas capture)	Blue H_2 (w/flue-gas capture)	Natural gas
Fugitive CH_4 = 3.5%				
GWP20 = 8	153	139	135	111
GWP20 = 105	170	158	155	123
GWP100 = 34	106	86	77	76
Fugitive CH_4 = 4.3%				
GWP20 = 86	171	159	156	124
GWP20 = 105	192	182	181	139
GWP100 = 34	113	94	86	81
Fugitive CH_4 = 2.54%				
GWP20 = 86	133	115	109	95
GWP20 = 105	144	129	124	104
GWP100 = 34	98	76	67	70
Fugitive CH_4 = 1.54%				
GWP20 = 86	110	90	82	79
GWP20 = 105	117	98	91	84
GWP100 = 34	89	67	57	64

TABLE 3 Sensitivity analysis for combined emissions of carbon dioxide and methane (g CO_2-equivalents per MJ of heat generated in combustion) while producing blue hydrogen as a function of the percent carbon dioxide captured from the SMR process and from flue gases for the energy that drives the SMR process

	Total CO_2	Total fugitive CH_4	Total emissions
Blue H_2 w/o flue-gas capture			
85% SMR capture	51.7	86.9	139
90% SMR capture	50.2	86.9	137
78.8% SMR capture	53.5	85.7	139
Blue H_2 w/flue-gas capture			
85% SMR & 65% flue-gas capture	39.7	95.4	135
90% SMR & 90% flue-gas capture	33.3	98.9	132
78.8% SMR & 55% flue-gas capture	43.4	93.2	137

Note: The methane leakage rate is 3.5%. The first row in each case is from the baseline case in Table 1.

carbon dioxide from using natural gas to produce the heat and high pressure needed for SMR and to capture carbon dioxide could be reduced if these processes were instead driven by renewable electricity from wind, solar, or hydro. If we assume essentially zero emissions from the renewable electricity, then carbon dioxide emissions from blue hydrogen could be reduced to the 5.8 g CO_2 per MJ that is not captured from the SMR process (Equation 11) plus the indirect emissions from extracting and processing the natural gas used as feedstock for the SMR process, estimated as 2.9 g CO_2 per M (7.5% of 38.5 g CO_2 per MJ; see section on "total carbon dioxide and methane emissions for gray hydrogen"), for a total of 8.7 g CO_2 per MJ. This is a substantial reduction compared with using natural gas to power the production of blue hydrogen. However, the fugitive methane emissions associated with the natural gas that is reformed to hydrogen would remain if the process is powered by 100% renewable energy. These emissions are substantial: 3.5% of 14 g CH_4 per MJ (Equation 3). Using the 20-year GWP value of 86, these methane emissions equal 43 g CO_2eq per MJ of hydrogen produced. The total greenhouse gas emissions, then, for this scenario of blue hydrogen produced with renewable electricity are 52 g (8.7 g plus 43 g) CO_2eq per MJ. This is not a low-emissions strategy, and emissions would still be 47% of the 111 g CO_2eq per MJ for burning natural gas as a fuel, using the same methane emission estimates and GWP value (Table 1). Seemingly, the renewable electricity would be better used to produce green hydrogen through electrolysis.

This best-case scenario for producing blue hydrogen, using renewable electricity instead of natural gas to power the processes, suggests to us that there really is no role for blue hydrogen in a carbon-free future. Greenhouse gas emissions remain high, and there would also be a substantial consumption of renewable electricity, which represents an opportunity cost. We believe the renewable electricity could be better used by society in other ways, replacing the use of fossil fuels.

Similarly, we see no advantage in using blue hydrogen powered by natural gas compared with simply using the natural gas directly for heat. As we have demonstrated, far from being low emissions, blue hydrogen has emissions as large as or larger than those of natural gas used for heat (Figure 1; Table 1; Table 2). The small reduction in carbon dioxide emissions for blue hydrogen compared with natural gas are more than made up for by the larger emissions of fugitive methane. Society needs to move away from all fossil fuels as quickly as possible, and the truly green hydrogen produced by electrolysis driven by renewable electricity can play a role. Blue hydrogen, though, provides no benefit. We suggest that blue hydrogen is best viewed as a distraction, something than may delay needed action to truly decarbonize the global energy economy, in the same way that has been described for shale gas as a bridge fuel and for carbon capture and storage in general.[43] We further note that much of the push for using hydrogen for energy since 2017 has come from the Hydrogen Council, a group established by the oil and gas industry specifically to promote hydrogen, with a major emphasis on blue hydrogen.[5] From the industry perspective, switching from natural gas to blue hydrogen may be viewed as economically beneficial since even more natural gas is needed to generate the same amount of heat.

We emphasize that our analysis in this paper is a best-case scenario for blue hydrogen. It assumes that the carbon dioxide that is captured can indeed be stored indefinitely for decades and centuries into the future. In fact, there is no experience at commercial scale with storing carbon dioxide from carbon capture, and most carbon dioxide that is currently captured is used for enhanced oil recovery and is released back to the atmosphere.[44] Further, our analysis does not consider the energy cost and associated greenhouse gas emissions from transporting and storing the captured carbon dioxide. Even without these considerations, though, blue hydrogen has large climatic consequences. We see no way that blue hydrogen can be considered "green."

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ORCID

Robert W. Howarth https://orcid.org/0000-0001-9531-4288

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