Hydrogen Use in UK Aviation

Recommendations for the Jet Zero strategy's hydrogen commitments

June 2023

Executive Summary

Hydrogen is crucial to decarbonising aviation, and this was recognised in the Government's Jet Zero Strategy. That strategy committed to requiring fuel suppliers to provide minimum and increasing levels of power-to-liquid (e-kerosene) fuels (known as the PtL sub-mandate), and "aspired" to have some domestic air routes that used only zero-emission aircraft by 2030. Power to liquid fuels are made by combining hydrogen and captured carbon, and on current market trends the first zero emission aircraft in the UK will be hydrogen fuel-cell planes.

The UK has an established hydrogen strategy that will ensure hydrogen is produced, but there are, as yet, no demand side policies in place. There is a clear hierarchy of needs for hydrogen uses, based on whether existing technologies can be electrified or not. Long-haul aviation is towards the top of this hierarchy. The UK SAF mandate will be the first demand-side policy to be implemented, and therefore will be an important policy in ensuring hydrogen is funnelled towards a suitable sector.

It is anticipated that to fulfil 1% of jet fuel demand in 2030 with PtL fuels would require 0.68 GW, or nearly 14% of all anticipated fossil-free (green) hydrogen production available in 2030: substantial, but eminently achievable. However, this paper recommends that the Government should be ambitious, and that three quarters of 2030 green hydrogen production should be directed towards e-kerosene production. **This paper therefore recommends:**

- **that the 2030 PtL sub-mandate be set at 5.5%.**
- **That strict sustainability guards are implemented: all e-kerosene uplifted in the UK is produced in countries where the local grid is at least 90% decarbonised**

This is far above the unambitious proposed levels in the second SAF mandate consultation. A 5.5% sub-mandate would require 3.74 GW of hydrogen capacity, which would need 37.84 TWh of zero carbon electricity. This would need 1170 offshore wind turbines to produce it.

The Jet Zero strategy also aspired to have zero-emission domestic routes in place by 2030. Analysis, based on market research of expected developments of zero-emission planes and analysis of existing use patterns identified that the route that took the most flights in a small 19-seater turboprop plane was **Glasgow - Barra, with 676 return flights**. The route that carried the most passengers in 80-seater turboprop planes was **Glasgow - Southampton, with 1248 return flights**. Therefore, **the Government should target these two routes to become the first zero-emission routes in the UK**.

Assuming these routes use hydrogen fuel cell planes, then 1085 tonnes of hydrogen would be needed. This would require 64.3 GWh of electricity to create it, and is the equivalent to the electricity produced annually by just two 8MW offshore wind turbines.

1. Introduction

Hydrogen will be a crucial tool when it comes to decarbonising UK aviation. This was recognised in the Jet Zero Strategy and its associated documents that were published in July 2022. These contained a number of hydrogen commitments: the first directly via a commitment to implement an e-kerosene sub-mandate as part of the sustainable aviation fuel (SAF) mandate,[1] and the second implicitly and indirectly, via a commitment to have zero emission routes in the UK by 2030. Subsequently, the Government has proposed, as part of the second SAF mandate consultation, specific e-kerosene sub-mandate levels, but these are based on flawed assumptions. This paper, therefore, suggests what the details should be around these aims, as well as providing evidence as to why we have decided on these details. This evidence encapsulates other commitments already made by the current Government.

The e-kerosene commitment was explicit:

"....the Government can confirm that a PtL subtarget will be included in the SAF mandate. A subtarget still appears to be the most suitable mechanism to accelerate the commercial and technological advancement of PtL and is being considered in other settings such as the EU"

The clear commitment here is in the word 'PtL'. PtL stands for Power-to-Liquid, and is a pathway for producing hydrogen via electricity. This clearly meant that the Government intended that only green

[1] This commitment is to be found in the SAF mandate summary of responses, published at the same time as the Jet Zero Strategy.

hydrogen would qualify under the sub-mandate.[2] This is still the case, however the second consultation has asked if blue hydrogen should be considered under the scheme. Thus far, no other details have been decided and some of these details will be crucial to not only ensuring high sustainability standards, but also ensuring that a British e-kerosene industry is started. This paper will suggest what those details should be.

The next commitment was not as concrete:

"We will ensure the UK is at the forefront of deploying zero emission aircraft, with an aspiration to have zero emission routes connecting different parts of the United Kingdom by 2030"

For a route to be zero emission, then only electric or hydrogen fuel-cell planes could be used. Whilst small electric planes are being developed, the expectation from the Aerospace Technology Institute is that "green liquid hydrogen is the most viable" type of future zero emission aircraft. The leading UK zero emission aviation companies are focussing on hydrogen fuel cell planes, and therefore this paper will focus on those. The question obviously then becomes: what route or routes should be first? This paper will provide suggestions for that.

Finally, for both PtL and domestic routes, one major question is how much hydrogen will be required annually to service them? This paper will provide estimates of the volumes required.

1.1. UK Aviation and Industrial Strategy

British citizens like to fly, and more fly internationally than any other nationality: incredibly one in twelve of all international passengers worldwide in 2018 were British. Pre-pandemic, the UK had the third largest air transport system in the world (behind the USA and China), carrying over 300 million passengers. Furthermore, the UK's aerospace industry is the third largest in the world (behind the USA and France). In 2019, the aerospace sector turned over £34 billion, exported nearly £32 billion worth of goods and employed 114,000 people.

The above demonstrates that the UK already has a leading established position in aerospace, and therefore, all things being equal, it could be expected that the UK would end up being industrial leaders in zero emission aircraft and sustainable aviation fuels (SAF) production. Indeed, in its (April 2022) Destination Zero report the Aerospace Technology Institute stated that the UK could potentially have a 19% share of the future global zero emission aircraft market, which could result in 60,000 extra jobs. However, recent events suggest that simply will not be the case for either hydrogen fuels or zero-emission aircraft. The USA, via the Inflation Reduction Act (IRA), has committed €369 billion to energy and climate change, and growing a domestic industry across a wide range of green sectors, including hydrogen and SAF. This has garnered a response in the EU and some of its member

[2] Note that this does not preclude blue hydrogen being used to produce e-kerosene, however the resultant fuel would not qualify under the sub-mandate.

states, and as a result a *Net Zero Industry Act* has been proposed.[3] This potentially means that, without a UK response, future companies that will have a large share of net zero industries, and could have become "British" will move to other countries. Arguably, this has already started happening in other sectors: electric van producer Arrival announced in October 2022 that it was cutting its UK workforce, whilst developing a factory in North Carolina, USA. This has worried the UK's business groups: Tony Danker, then director-general of the CBI commented to the Financial Times:

"I am genuinely worried that the current government is losing a race for green growth…… It's become a subsidy arms race. We need to come up with our own strategy."

The UK cannot compete across all sectors, but it can, and should, compete in those where it has a large comparative advantage. Aviation and aerospace are such sectors. However, whilst the UK is part of the leading group of nations that are pursuing decarbonisation technologies, it is not the only one, nor is it the outright leader. The EU, via its Clean Aviation research programme has recently offered €137 million in funding towards zero emission aircraft. There is an ecosystem of zero-emission aviation companies forming around Toulouse, which is additionally where Airbus is headquartered. Airbus itself also has the Zero-E programme. Elsewhere, New Zealand has recently launched a zero-emission aviation consortium and there is an ecosystem forming on the west coast of the USA, which is where Universal Hydrogen is based and where Zeroavia recently announced it will open a research facility (partly funded by a €350,000 grant from the US department of commerce).

This call for leadership was echoed in the Science and Technology Committee's recent report *The role of hydrogen in achieving net zero*:

"The Government should use its influence internationally, following its leadership of COP26 and involvement in Mission Innovation, to set standards and timelines for decisions on the role of alternative fuels and hydrogen within aviation and shipping. In these areas the Government should seek to lead the development of standards that can be adopted internationally"

1.2. Paper Considerations

This paper takes into account three distinct considerations in its recommendations: environmental, current UK industrial strengths, and practical limitations. It will then make a series of recommendations. Part of the body of evidence for these recommendations comes from research that T&E commissioned from energy consultancy Element Energy.[4]

[3] In addition, France has proposed an EU-wide fund to boost strategic industries.
[4] The full research is available on the T&E website.

2. Hydrogen

Green, or fossil-free hydrogen is often depicted as a silver bullet for many sectors. Whilst it is true that hydrogen could be used in the power, steel, chemicals, trucking, personal transport, aviation, maritime and other industries, it is also true that it is unlikely to be used in some sectors due to the availability of better options. Furthermore, the UK's low-carbon (both green and blue) hydrogen industry is tiny, and there are no major commercial level plants currently operating.

The Government launched the UK Hydrogen Strategy in August 2021. This strategy committed the UK to producing 5 GW of green hydrogen, and 5 GW of blue hydrogen before 2030. Green hydrogen is also known as electrolytic hydrogen, and there are no associated emissions with producing it, provided renewable electricity is used. Blue hydrogen is produced by capturing the emissions produced during currently-utilised hydrogen production ("grey" hydrogen) and, crucially, there are associated emissions with this pathway.[5] Environmentally therefore, the aviation industry should focus on only using green hydrogen for fuel.

There are two major currently planned clusters: HyNet, in the North West, and the East Coast cluster, around Humberside and Teesside. Both are located close to the CLH pipeline system that serves some of the main country's main airports (including Heathrow, Gatwick, Stansted and Manchester). This means it makes sense to locate any future e-kerosene plants either in these clusters (which is in direct contrast to the planned flagship projects there, which are all currently blue hydrogen plants), or relatively close to other parts of the pipeline.

2.1. Current UK Hydrogen Production

The UK already produces hydrogen, but the vast majority of this is 'grey' hydrogen - (usually) made from natural gas using steam methane reformation. Crucially, the greenhouse gases emitted as part of this process are not captured. UK hydrogen production is currently approximately 683 kilotonnes per year, distributed across 30 production sites. Around 45% is used in refineries, with another third used to create ammonia, which is used in a diverse range of goods (including fertilisers[6]).

As mentioned, the Government has committed to 10GW of low carbon hydrogen production by 2030, with at least 5GW of this being green hydrogen. The world's (current) largest electrolyser factory is in Sheffield, and has a 1GW capacity. The owner, ITM Power, also has plans to open a second site in Sheffield that will have a 1.5 GW capacity. Large scale green hydrogen production sites are planned, including Protium's 70 MW site on Teesside (due to produce in 2026) and Scottish Power's 20 MW site at Whitelee, Glasgow (due to produce in 2023).

[5] The Government has defined blue hydrogen as low carbon when it meets a greenhouse gas emission intensity of 20gCO2e/MJ or less.

[6] Recent research suggests that the amount of fertiliser needed can be cut quite dramatically, simply by using it more efficiently.

2.2. Additionality and Alternative uses of UK-produced Green Hydrogen

Currently, any additional (marginal) electricity demand from the UK's electricity grid will be met by burning fossil fuels. Whilst the share of low-carbon electricity is growing (in 2021 it made up 57% of all generated electricity), in 2022 unabated fossil gas was burnt in a UK power station somewhere every single hour, and, all things being equal, any new source of electricity demand attached to the grid right now would essentially obtain its electricity by burning yet more fossil fuels.

Green hydrogen plants would be additional sources of demand, but there is not likely to be a large-scale plant until towards the end of the decade by which time the grid should look very different.[7] The current electricity grid is a 60-65 GW system. There are also 130 GW "contracted": projects that are going through the planning and building process (not all of these will actually be built). Furthermore, the Government has targeted an additional 40 GW of offshore wind, which equates to over 5000 additional 8MW turbines,[8] and has recently announced a £700 million investment into Sizewell C, the new 3.2 GW nuclear power station in Suffolk that is due to come online by 2035. Finally, the Government has already committed to having a fully decarbonised electricity grid by 2035.

This means that large-scale green hydrogen plants *should* arrive at roughly the same time as the grid becomes decarbonised.[9] However, should this not occur, the Government has already introduced measures to ensure there will not be a problem: it has already defined what low carbon hydrogen is, and to qualify as such producers have to prove that the hydrogen has been produced using renewable electricity.[10]

In short, additionality of renewable electricity should not be a future issue, in the UK, due to good progress being made on grid decarbonisation. However, it is an inconvenient truth for the aviation sector that the emissions savings from using a unit of renewable electricity elsewhere are more than the savings made by creating e-fuels with DAC. This is amply demonstrated by the below graph, taken from Bellona's June 2022 report "*Effective Use of Renewables to Reduce Emissions*"

[7] It is also likely that future green hydrogen plants will be directly connected to their own renewable generation sources, which should be built at the same time as the plant is constructed. This follows the example of the recently announced Megaton Energy Park in Denmark, which will use (yet-to-be-built) on-and-offshore wind and solar generation to power 2 GW of electrolysers by 2030.

[8] Hornsea 2, the current largest wind farm in the UK, uses 8 MW turbines. However, future turbines may be larger: the China State Shipbuilding Corporation is currently building an 18 MW turbine.

[9] This isn't to suggest that more policy work isn't needed: it is. Indeed, the Climate Change Committee has suggested a number of actions the Government can take. However, it is clear that both Government policy and renewable installation are proceeding at pace.

[10] Specifically, producers must use actual data to demonstrate that electrolysers are operating at the same time as the electricity input source is low carbon, and that producers have exclusive ownership of the electricity used. Correlation must occur over 30-minute consignments.

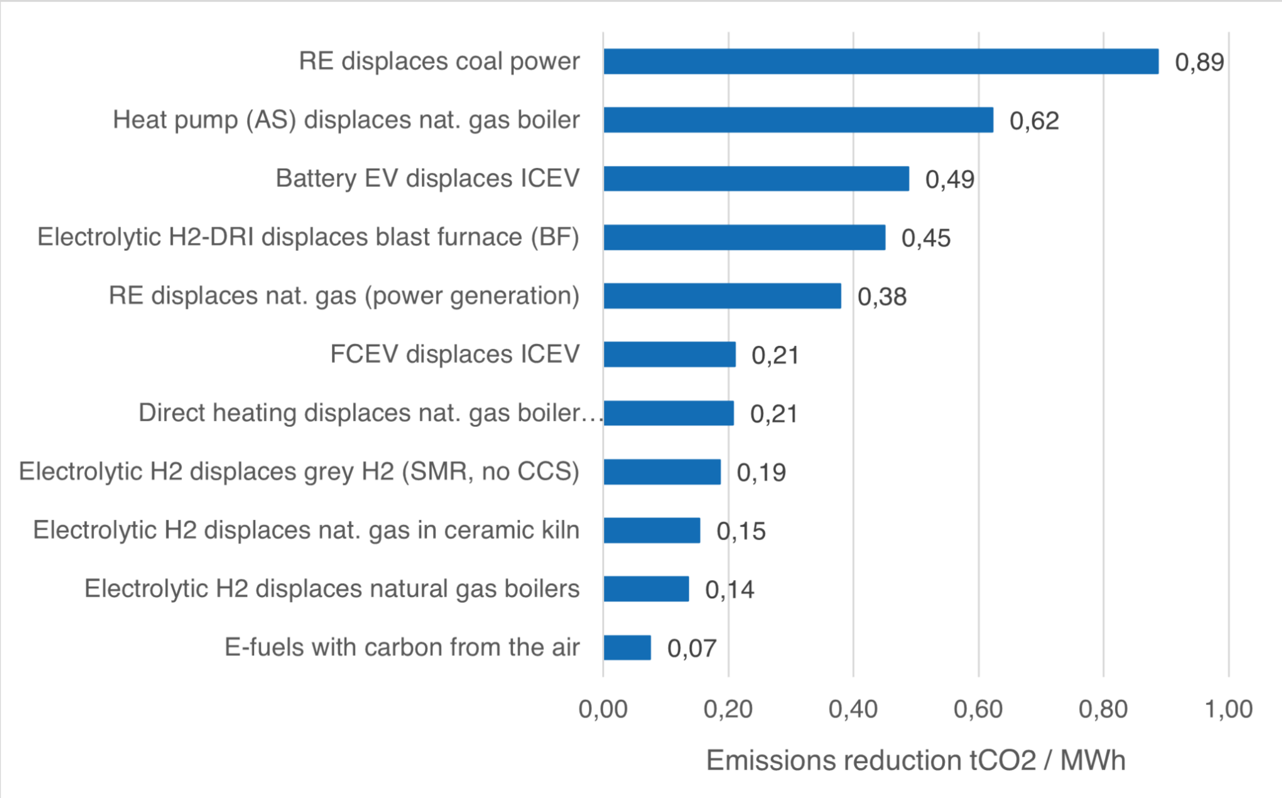


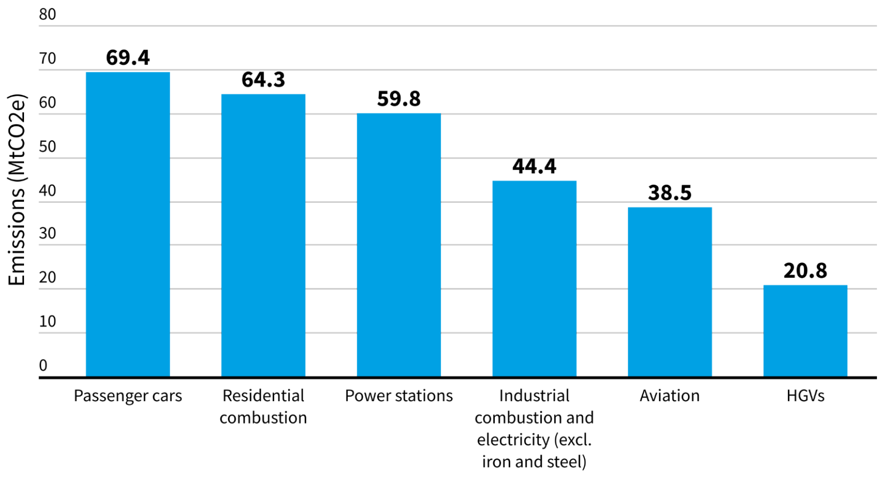
Chart 1: Emissions Savings from using 1MWh of renewable electricity for various applications

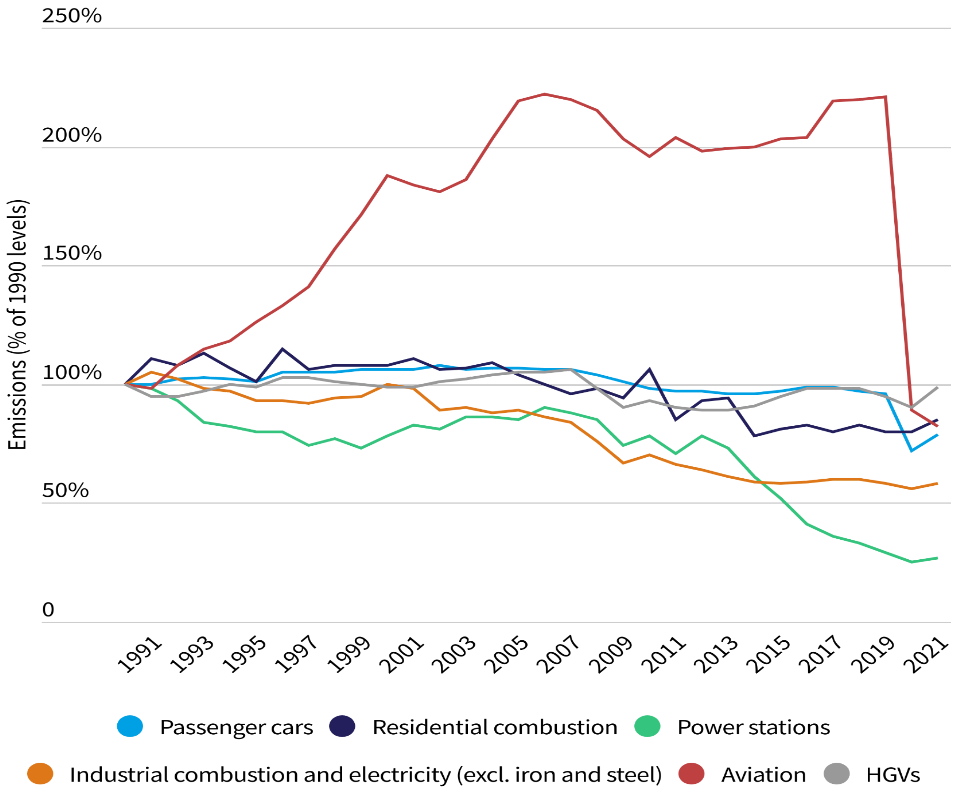
As can be seen, from an environmental perspective, any additional zero carbon electricity supply should be directed to uses that achieve the most “bang for the buck”: those that can reduce emissions the most. Similarly, alternative uses for produced hydrogen should be a consideration. Clearly there will be competing demands for hydrogen in 2030, and using green hydrogen in other areas - notably replacing grey hydrogen used in fertiliser manufacture - would have a significantly greater decarbonisation impact. Balanced against this is the argument that, in the long-term, all sectors need to fully decarbonise, and policies should be enacted that ensure that all sectors start decarbonising as quickly as possible. Since it is highly unlikely that long haul aviation will be able to decarbonise without the use of hydrogen (which is the exact opposite of the situation in some other sectors that are trialling hydrogen), the Government should implement measures to ensure that some hydrogen is diverted to this sector.

The below bar chart shows the sectors of the UK economy that emitted over 20 million tonnes in 2019.[11] [12]

[11] At the time of writing, data is available for both 2020 and 2021, but those figures are skewed by the effects of the pandemic, hence why 2019 data is being shown.
[12] Overall emissions from some sectors that are likely to require hydrogen in the long-term are: Iron and Steel (combustion and electricity) - 9.4 MtCO2e; glass production - 0.4 MtCO2e; cement production - 4.4 MtCO2e

UK Economy Sectors that emitted more than 20 MtCO2e in 2019[13]





[13] 'Residential Combustion' includes all emissions from domestic gas boilers, stoves, and fireplaces. 'Aviation' covers both domestic and international emissions.

As can be seen from the above two graphs, some sectors currently clearly emit more greenhouse gases annually than others, and deserve more urgent attention. However, as shown above, due to existing policies power sector emissions are already on a downward trajectory. Industrial emissions have fallen to just over 50% of 1990 levels, so are in the same category.[14] Emissions from cars have stayed broadly flat, but the Government is about to impose a zero emission mandate on car manufacturers.[15] This will require manufacturers to sell increasing numbers of zero-emission vehicles, rising to 100% in 2035, and, crucially, means that a major policy will shortly be in place to reduce emissions from the sector. Similarly, the Government is currently consulting on the Clean Heat Market Mechanism which will place an obligation on the manufacturers of heating appliances to meet increasingly higher targets for the proportion of low-carbon heat pumps they sell each year (relative to fossil fuel boilers). However, no date has been given for when new replacement gas boilers will be banned from being installed in homes.

There are therefore two sectors that stand out in terms of needing attention, due to both the absolute size of emissions, and the lack of progress in decarbonising the sector: HGVs and aviation.[16] For this reason, this paper suggests that Government focus should be applied to both sectors. However, when it comes to the technologies that will decarbonise these sectors the UK is only likely to be able to gain a competitive advantage in one: aviation.[17]

INFO BOX: Curtailed Electricity

It is a common assumption that hydrogen will be made by using curtailed electricity (electricity that could have been produced from non-dispatchable renewables, but isn't, usually to ensure that the grid is balanced). However, on closer inspection this does not stand up to scrutiny.

Firstly, curtailed electricity is not free. Generator owners would expect to be compensated for the electricity they produce, even at times of low demand: National Grid has to compensate generators for not producing electricity when they could now. The future grid will have various demand-side consumers that will be able to ramp up demand if required: notably, the UK's fleet of electric cars will charge when electricity is cheap and will take that 'surplus' electricity. Excess supply may also be

[14] It is acknowledged that "industry" covers many smaller sub-sectors, which are performing differently viz-a-viz each other.
[15] This will also apply to van manufacturers.
[16] Aviation emissions plunged during the pandemic, but are now rising back to pre-pandemic levels. Consultancy firm OAG estimates that 2023 UK summer capacity is now just 2.5% less than it was in 2019.
[17] Despite the lack of a firm future ban on new boiler installations, it is highly likely that home heating will be decarbonised by the mass rollout of heat pumps. However, heat pumps are not new, and are widely used already globally (about 190 million are in use worldwide). This existing lead from other heat-pump-producing nations suggests the UK will not be able to gain a future competitive advantage. This does not mean that none will be manufactured here: there are currently heat pump manufacturing sites in Cornwall, Derbyshire, Northern Ireland and Scotland. The market for HGVs is similar. Electric HGVs are in development, but the UK does not have a competitive advantage in the design, development and manufacture of them.

absorbed by other storage technologies that can operate cheaply and efficiently too.[18] Some electricity is curtailed due to grid congestion and constraints, but grid improvements are already planned. Additionally, previous academic work suggests that electrolysers need an annual load factor of at least 30% to sufficiently bring down the production cost of electrofuels.

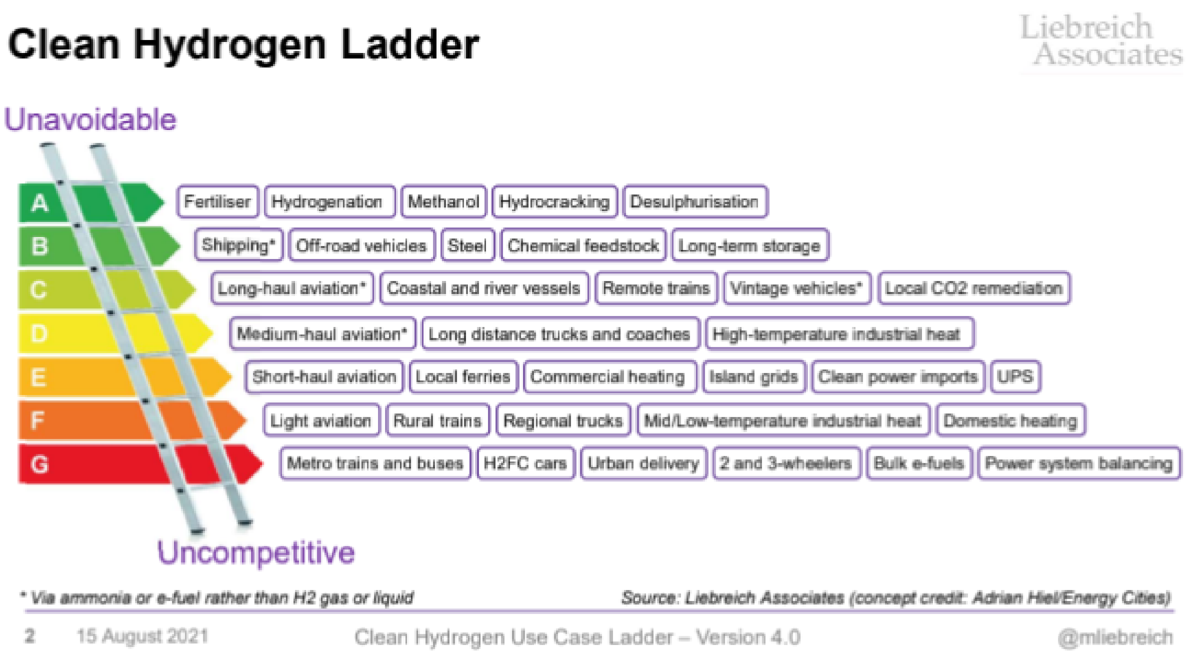
Secondly, although electrolysers can operate with some degree of flexibility, the overall plant efficiency suffers when there is an inconsistent supply of power. A plant owner will therefore want a steady supply of electricity, instead of just operating from excess electricity, unless the incentives for providing grid services are very large. BEIS (now DESNZ) previously assumed that using future curtailed electricity only would result in a plant load factor of 25%: that is, the plant would be producing 25% of the time. The advantage of building such a plant would be that the owners do not have to pay to build a dedicated electricity source, however the clear disadvantage is that the plant would sit idle for 75% of the time.

Potentially a more realistic scenario is 'anti-curtailment'. Grid-connected hydrogen / e-kerosene plants could (should?) be built with their own renewable generators attached. Should national electricity prices spike upwards, the plant could ramp down hydrogen production and supply electricity to the grid. This would only happen when the value of the electricity is greater than the value of the forgone hydrogen, although it should be noted that electricity prices would rise as renewable generation falls - and plants are likely to be connected to renewable generation.

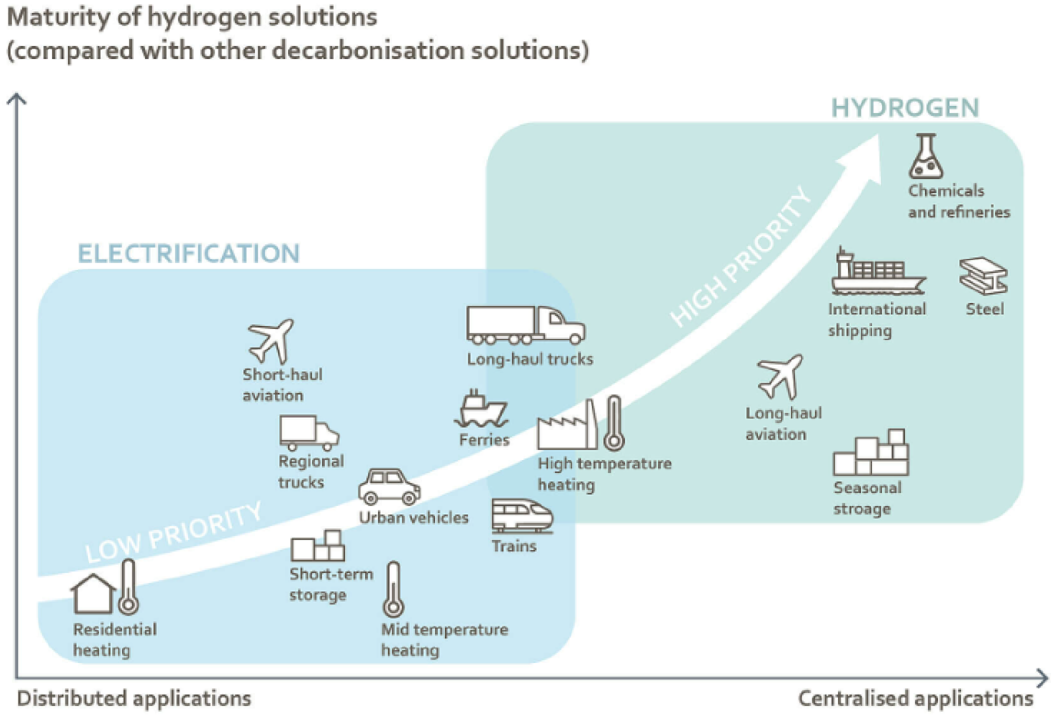
2.3. Hydrogen Demand

Whilst all published hydrogen strategies have focussed on the supply side of hydrogen, none, including the UKs (yet) have significant demand side policies in place. The July 2022 Hydrogen Strategy Update to the Market[19] showed that the Government either has or will shortly support trials for hydrogen use in home heating and in various fuel cell road vehicles (including 124 buses[20] and trucks). However, for both home heating and road vehicles there is an obvious other solution that is cheaper and more likely, and that is using electricity via a heat pump or a battery. This is amply demonstrated by Micheal Liebrich's Clean Hydrogen ladder:[21]

[18] There are conversion losses in creating hydrogen from electricity: in energy terms, the conversion process is between 60% and 80% efficient depending on technology type and load factor, according to the IEA. In contrast, batteries can operate at over 90% efficiency for a full power-storage-power cycle.
[19] These were confirmed in the December 2022 hydrogen strategy update to the market.
[20] The 124 buses will take to the streets in the Midlands. At the same time, the Department for Transport is also funding a project to provide 50 battery electric buses to the Midlands.
[21] This is version 4. Details as to why which sectors are where they are can be found here: https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich



And backed up by the International Renewable Energy Agency (IRENA):



The e-kerosene sub-mandate would be a clear demand side policy, and would be significant as this would ensure that UK-produced hydrogen goes to a sector that is not only towards the top of Michael Liebrich's ladder, but is also a sector that the UK is already an established leader in, and - crucially - is expected to become a core sector in the net zero future.

Government policy does not currently explicitly rule out hydrogen use in any areas.

2.4. Hydrogen Transport

The core cost component of hydrogen is the renewable electricity cost, which is lowest in sunny places. This has led many commentators to declare that we should just wait for hydrogen to be produced in these places, and import it for its various uses. However, there is an inherent problem in that: by itself, hydrogen is extremely difficult to transport.

The physical properties of hydrogen mean that investment will be needed. There are three main options: pipelines, liquid hydrogen shipping, and bonding the hydrogen with something else to make it easier to carry (such as ammonia). Pipelines are the cheapest option, but existing gas pipelines will need to be upgraded if they are used and it may be cheaper to simply build out a new network. Shipping liquified hydrogen will be very expensive as a) the hydrogen would need to be kept at -253 degrees, and b) liquid hydrogen ships are still at the testing stage. Ships that are able to carry ammonia do exist, but converting hydrogen to ammonia, shipping it and then reconverting it back to hydrogen is energy intensive.[22] [23]

However, if looked at environmentally, then the question of whether hydrogen *should* be shipped from certain places should be considered. If produced using electricity then the local grid should already be decarbonised, otherwise UK hydrogen demand would actually increase emissions by displacing renewable electricity use in other countries - a form of reverse carbon leakage (ideally, if the hydrogen is to be made into e-kerosene in the foreign country, then a large proportion of the local jet fuel demand should also already be SAF - otherwise you are needlessly using energy to move e-kerosene between places for no net environmental benefit).

This means that some of the countries that have the potential for good solar resources should currently be excluded from supplying hydrogen-derived products to the UK. According to Our World in Data, in 2021 there were 19 countries where over 90% of their electricity came from low-carbon sources.[24] No country anywhere uplifts a significant amount of SAF (let alone e-kerosene) to its

[22] The Jacques Delors Centre has published a detailed interactive model on hydrogen transportation costs in the EU, available here: http://hydrogen-model.eu/#model

[23] There is research into powering aircraft with ammonia. More details can be found in this article.

[24] Nearly all of these countries get a lot of their electricity from either hydropower and / or nuclear power (eg Norway and France respectively). Many of these countries also have a less extensive grid than the UKs. For example, 90.48% of Sierra Leone's grid is derived from low carbon sources, but only 26% of its population have access to electricity. Major oil exporting nations - that have expertise in handling and exporting kerosene - tend

departing planes.[25] Applying this criteria suggests that the UK should only use UK-produced hydrogen until the electricity grids and jet fuel systems of other countries are substantially decarbonised. This is the opposite of what is being applied elsewhere: the German Government has approved the use of €900 million to buy green hydrogen from elsewhere and sell it within the EU, with minimal environmental considerations.[26]

2.5. Other Countries

Far from going it alone on this, the UK is actually behind other countries when it comes to green hydrogen production. Indeed, the UK was only the 12th country to release a hydrogen strategy. In the USA, as part of the Inflation Reduction Act, clean hydrogen will be subsidised via tax credits by the federal Government.[27] The EU approved €5.2 billion state aid subsidies in September 2022.

Furthermore, a recent report from France Hydrogène (the association of French hydrogen companies) recently showed that there were more than 250 declared planned hydrogen production projects in France alone, and that the vast majority of these would produce green hydrogen. It also suggested that almost 40% of the hydrogen produced would go to e-fuels projects (including kerosene and methanol), but did not specify sites.

3. Sustainable Aviation Fuel (SAF)

Broadly, SAF can be split into two sorts: waste-based SAF, and synthetic SAF (also known as e-kerosene). Currently, most UK focus has been on waste-based SAF, and there are eight ongoing UK projects that have been awarded public money so far, although all of them are still being designed and therefore none of them have started producing any SAF yet.[28] Crucially, all of them are waste-based, and *ICF / Sustainable Aviation* analysis shows that these projects would only be able to meet half of the committed 10% in 2030. Furthermore, previous T&E analysis of future European jet fuel concluded that waste-based SAF would only account for 11% of total jet fuel demand in 2050. There is no reason why the numbers would be significantly different if analysing the UK, and therefore it is clear that the long-term focus should be on e-kerosene.

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to have relatively dirty grids. For example, 98.8% of Saudi Arabia's grid is derived from fossil fuels. Energy Monitor has written about this in more depth.

[25] There is currently an upper blending limit for SAF of 50% due to the low aromatic content of SAFs, meaning that is the current ceiling limit.

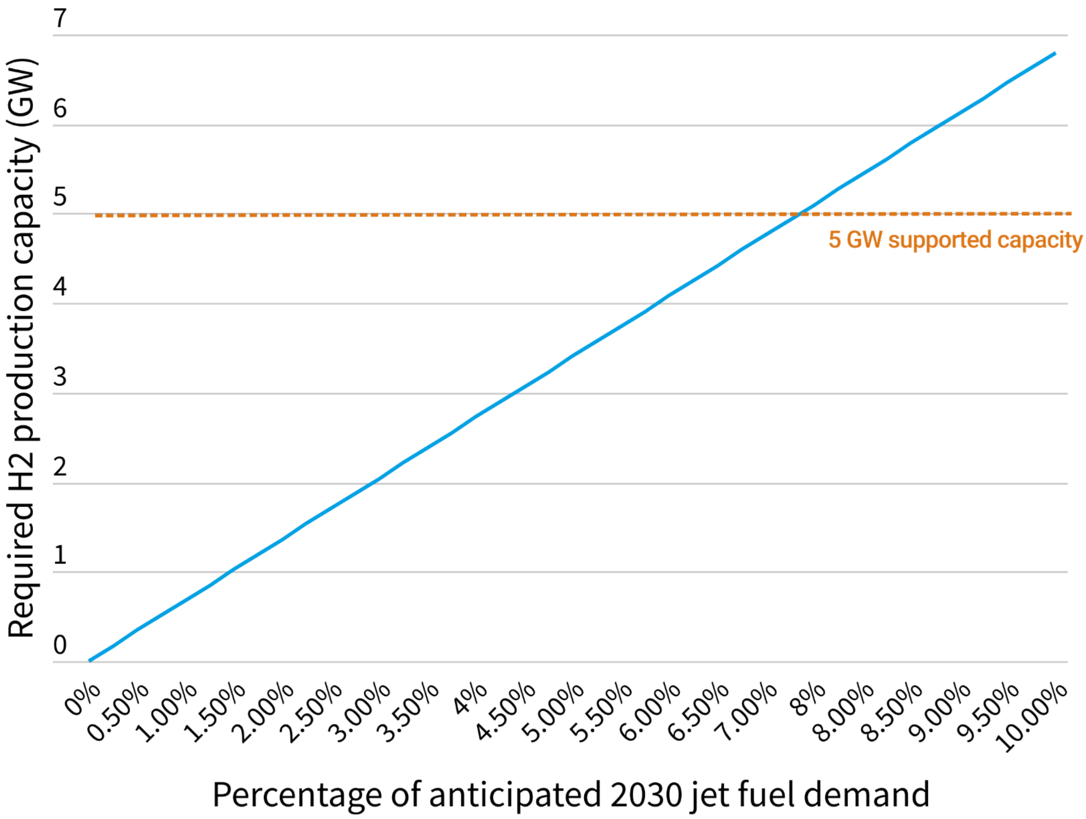
[26] This scheme was also approved by the European Commission.

[27] The Inflation Reduction Act provides a ten-year tax rebate per kilogram of green hydrogen worth €3.

[28] The projects use municipal solid waste, sewage sludge, woody residues, and flue gas waste. More details can be found on page 13 of the Jet Zero Investment Flightpath.

E-kerosene is produced by combining hydrogen and carbon[29] via a number of routes. T&E commissioned Element Energy to model the ongoing electricity requirements needed to produce e-kerosene.[30] The energy needed is significant: if e-kerosene is produced using the lowest cost carbon, then 5.9 TWh of electricity is needed to produce enough fuel to equal 1% of 2030 jet fuel demand. If e-kerosene is produced using direct air capture, then 6.9 TWh is needed. To put this in context, the UK's current largest windfarm, Hornsea 2, is expected to provide 5.32 TWh annually. Total wind generation in 2021 was 49 TWh.

As previously mentioned, the Government has pledged to support 5GW of green hydrogen capacity. To generate 1% e-kerosene would require 0.68 GW, or nearly 14% of all anticipated green hydrogen production in 2030. Every extra 0.25% increase in the sub-mandate target would require an extra 3.4% of all planned 2030 green hydrogen generation.

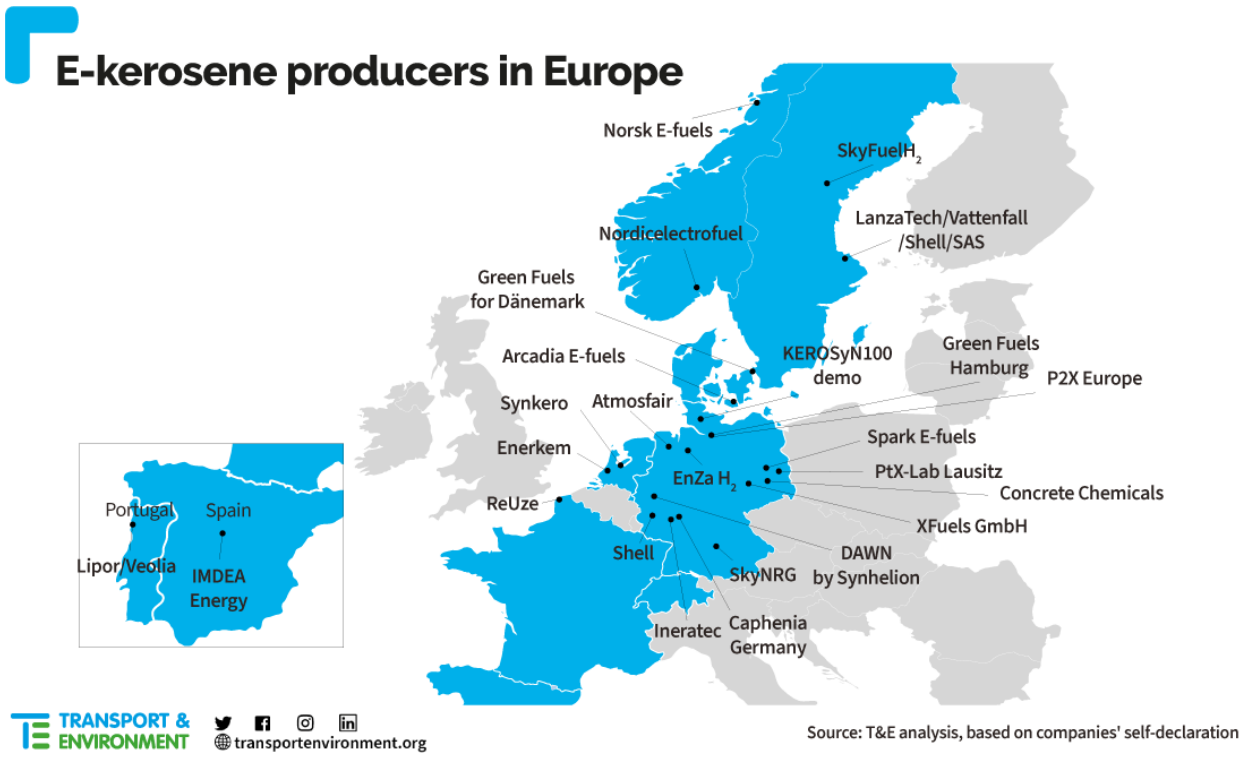


[29] The cheapest source of carbon would be captured from plants that currently combust fossil fuels. This is likely to be a relatively short-term solution as these plants are phased out, however there will also be carbon available from biogenic waste sources.
[30] These figures do not, therefore, include any energy requirements for transport, storage of hydrogen or carbon, nor the handling of the resultant fuel.

The UK already has two e-kerosene companies: [Zero Petroleum](), and the recently-launched [OXCCU](). However, both companies are small and fuel volumes are currently tiny. In theory, current UK refineries could take hydrogen and captured carbon, however they would need adapting to do so, and none do so yet.

3.1. Other Countries

[Recent T&E analysis of the EU market]() suggests there will be 12 companies producing e-kerosene by 2025, and 28 producing by 2030 (see the below map).



This is driven by the EU's near-finalised SAF mandate, which will require an average of 1.2% e-kerosene uplift over 2030 and 2031. This would then rise linearly to 15% in 2045, before jumping to 35% in 2050.

3.2. PtL sub mandate recommendation

The Government has committed to an overall mandate level of 10% in 2030. The question now becomes what level should the 2030 PtL sub-mandate be set at? The previously mentioned statistics show how much green hydrogen will be produced by the end of the decade, and this paper has demonstrated that aviation should be one of the natural homes for green hydrogen. Furthermore, due to the fact that the UKs aviation and aerospace industries are already world-leading industries there are strategic industrial strategy considerations in ensuring that e-kerosene R&D and production companies are attracted to the

UK via robust policies. Finally, since aviation is already one of the highest emitting sectors it makes sense to enact policies that target this sector.

T&E believes the Government should be ambitious, and that three quarters of 2030 green hydrogen production (3.74 GW) should be directed towards e-kerosene production. **This paper therefore recommends:**

- **that the 2030 PtL sub-mandate be set at 5.5%.**
- **That all e-kerosene uplifted in the UK is produced in countries where the local grid is at least 90% decarbonised**[31]

This is far above the proposed levels in the second SAF mandate consultation. This is because those levels are predicated on analysis that constrains e-kerosene uptake to only those fuels made using direct air captured carbon. This is strange, as other, cheaper, more plentiful carbon sources are available. Removing this constraint removes the main blockage to increasing the UKs e-kerosene ambition. However, what the SAF mandate consultation does show is what 'sub-sub mandate' levels are achievable should the Government decide to try and kickstart a DAC industry via the SAF mandate.

A 5.5% sub-mandate would require 3.74 GW of hydrogen capacity which would need 37.84 TWh of zero carbon electricity. This would need 1170 offshore wind turbines.[32]

INFO BOX: Contracts for Difference

This paper focuses on the 2030 sub mandate level should be, but also calls for environmental rules to be put in place which would effectively mean that e-kerosene has to be mostly home-grown for years. This paper has also demonstrated that the UK has some good building blocks to ensure a home-grown e-kerosene industry.

However, it would be remiss not to briefly discuss the current industry calls for a contract for difference (CfD) scheme to be used to 'de-risk' SAF, thus ensuring its production. Currently, the only financial incentive for SAF is via the Renewable Transport Fuels Obligation, but this incentive has failed to start a market (there is more support being provided for SAF, through both financial incentives and more developed policy, in both the EU and USA). The SAF mandate will ensure minimum levels of SAF are uplifted to UK planes, but does not ensure that the SAF is produced in the UK. It is not a given that the UK mandate by itself would provide the policy certainty needed to ensure production facilities are built. However, the EU SAF mandate is more developed, and has

[31] With a 90% zero-carbon grid, even if the last 10% of the grid is coal-fired power generation, then the carbon footprint of the resultant fuel would still meet a 70% GHG LCA saving. This correlates with the EUs rules on RFNBOs, and the UK Government's literature on anticipated average lifecycle savings from SAF.
[32] Assuming each turbine is an 8MW turbine operating at 46% capacity factor

resulted in 28 companies planning to build e-kerosene production facilities on the continent. There is no inherent reason why a UK SAF mandate, once law, would not do the same, and therefore there are question marks as to if a CfD scheme is, in fact, needed.

Regardless, there are advantages to using CfDs. They would guarantee a stable price for all SAF produced by a plant for a minimum length of time. This in turn should ensure that private finance and capital flow to proposed SAF plants, and thus a crucial future UK industry is started. However, the design of the CfD scheme is crucial, and, *should* CfDs be adopted, T&E makes the following recommendations:

- **Only UK produced SAF should qualify for the scheme.**
- **The CfD should be funded by a levy on jet fuel suppliers.** This is identical to how the electricity CfD is funded (by a levy on electricity suppliers). This ensures that the costs of decarbonisation is funded by industry, which is exactly the same as happens in other sectors. If and when the strike price is above the reference price, money would flow from SAF producers to jet fuel suppliers.
- **CfDs should give preferential treatment to e-kerosene**, possibly through the use of pots (which is again identical to how the electricity CfD works). Using pots would mean that different SAF producers that use common feedstocks would only compete against each other (eg waste-based SAF in one group, hydrogen+DAC in another, hydrogen+recycled carbon in another). This would result in different strike prices from the different pot auctions.

There have been many calls for a CfD to be funded by ETS revenues from aviation, partly justified by “the polluter pays principle”. However, this is a fundamental misunderstanding of the principle. The UK Government has recently passed legislation that defines it:

“The polluter pays principle means that, where possible, the costs of pollution should be borne by those causing it, rather that the person who suffers the effects of the resulting environmental damage, or the wider community”

This means that the aviation sector should pay for the damage that their emissions and non-CO2 impacts cause: in the UK, examples include enhanced flood barriers, increased health costs due to excessive heating, etc. These costs will be directly borne by the taxpayer.

However, the polluter pays principle is not uniformly applied to the aviation sector. Carbon emissions from flights to the European Economic Area, Switzerland, Gibraltar and domestic UK flights are part of the UK ETS. Flights elsewhere - which account for approximately 70% of emissions - are not. No airline is charged for any of the non-CO2 impacts they cause. In direct contrast to road fuel (which all British drivers have to pay), no tax is applied to jet fuel.

4. Zero Emission Aircraft

The other hydrogen related 'commitment' made in the Jet Zero Strategy was an 'aspiration' to have zero emission routes connecting different parts of the UK by 2030. T&E commissioned Element Energy to conduct market analysis on the nascent zero emission aircraft sector to determine a) how many passengers zero emission aircraft (ZEA) are likely to be able to carry in 2030, and b) how far these planes are likely to be able to fly. These results were then to be overlaid with existing demand, to determine which routes would be best.

The first ZEA to market are likely to be small turboprop planes, however it was expected that larger turboprop planes, with an 80 seat capacity and a 800 km nautical range, would be available towards the end of the decade. As a small country, all domestic routes fall under 800km, but many are served by planes that carry more than 80 passengers.[33]

The UK Government has already started thinking about how airports will need to adapt. The Connected Places Catapult leads the zero emission flight infrastructure programme. This programme recently (December 2022) received £1.2 million in funding for the next stage of its work.[34]

4.1. Other Countries

As with hydrogen and e-kerosene production, the UK is in a good position, but is not the outright leader in zero-emission aircraft design, development and uptake. Other countries also have nascent ZEA industries and aspirations. IcelandAir recently announced that it wants all its domestic flights to be zero-emission by 2030. Air New Zealand has an ambition to start replacing its domestic fleet with zero emission alternatives from 2030. The German Aerospace Centre (DLR) is working on fuel -cell powered demonstrator projects. The ATI has previously detailed other countries' zero-carbon aircraft technologies capabilities.

However, whilst there is lots of research in other countries into the planes, there is no commitment anywhere else in the world for entire routes to go zero emission yet.

4.2. ZEA Route Recommendation

In 2019, the route that took the most flights in a small 19 seater turboprop plane was Glasgow - Barra, with 676 return flights. The route that carried the most passengers in 80 seater turboprop planes was

[33] It should be noted that many of the planes operating some domestic routes have more than 80 seats, but operate considerably below full capacity. These were considered 'out of scope' for Element's recommendations, but could also be considered viable early routes in the future.

[34] The ATI has also published a review of how to integrate hydrogen into the UKs air transport system.

Glasgow - Southampton, with 1248 return flights.[35] Glasgow - Barra is a public service obligation flight, which is therefore already subsidised. Glasgow - Southampton is a long internal flight. Importantly, all three airports are likely to be well served by future hydrogen availability due to their physical locations.

Recommendation: the UK should target Glasgow-Barra as the first route to only use 19-seater hydrogen fuel cell planes, and Glasgow-Southampton to only use 80-seater hydrogen fuel cell planes.

To cover these routes with hydrogen fuel cell aircraft would annually require 1085 tonnes of hydrogen, with the majority of this - 1000 tonnes - needed for Glasgow - Southampton. This would require 64.3 GWh of electricity to create, and is the equivalent to the electricity produced annually by two 8MW offshore wind turbines.

Crucially, aiming to ensure that these routes are fully zero emission by 2030 does not preclude other domestic flights on other routes using zero emission aircraft. In recent months there have been two notable announcements, both involving Zeroavia, which has partnered with AGS to explore hydrogen opportunities at either Aberdeen or Glasgow, whilst also partnering with Birmingham airport to do the same.

To further stimulate the ZEA market, consideration should be given to mandating the use of ZEA on domestic flights post-2030. T&E previously called for this policy in its January 2022 paper *Reducing UK Aviation's Climate Impacts*.

INFO BOX: How much hydrogen and electricity Is needed to replace all domestic turboprop flights?

Element Energy calculated exactly how much hydrogen would be needed to switch all domestic flights that are currently undertaken by turboprop planes to hydrogen fuel cell planes: it calculated that up to 200 tonnes of hydrogen would be needed daily. This would need 4.3 TWh per year. For context, this is the equivalent of approximately 80% of the anticipated output of Hornsea 2, or the same as the typical use from 1.5 million homes.

[35] Glasgow to Southampton can obviously be done by train. Currently the journey takes approximately seven hours and involves at least two changes. This paper has not focussed on the question of *should* the journeys take place, but has, more pragmatically, accepted that they do and therefore there is commercial demand for the flights.

5. Conclusions

The UK is an aerospace and aviation leader. The number of flights undertaken from the country dwarves all other European nations, and its aerospace sector is the third largest in the world. The UK should build on this existing capability, by implementing policies that will ensure that future aerospace is still based here. This future industry will not involve fossil fuel, but will involve lots of hydrogen. The UK has a hydrogen strategy, but this is very supply-side focussed and there are no major demand side policies in existence. Aviation is one of the sectors that will need hydrogen, and therefore the Government should build on the hydrogen commitments already committed to in the Jet Zero Strategy by applying the above recommendations. These recommendations will result in large domestic e-kerosene and hydrogen fuel-cell plane industries.

This report has explained why the 2030 e-kerosene mandate should be set at 5.5%. Furthermore, it also recommends that imports of e-kerosene should be restricted, for environmental reasons, only to countries whose electricity grids are (at least) nearly decarbonised.

It also recommends that work starts immediately in preparing two distinct routes to be zero emission only by 2030: Barra - Glasgow and Southampton - Glasgow.

Crucially, these should be seen as the minimum levels of ambition, and the aviation sector should be encouraged to go beyond a 5.5% sub-mandate and a handful of domestic flights.

This demand comes with renewable electricity implications. A 5.5% sub-mandate would require 3.74 GW of hydrogen capacity which would need 37.84 TWh of zero carbon electricity. This would need 1170 offshore wind turbines. The proposed domestic routes would need 85 and 1000 tonnes respectively, which would require 5 and 59.3 GWh of renewable electricity. This would need just two additional wind turbines.

Whilst outside the scope of this report, it is also clear that green hydrogen demand will outstrip supply in the near future (and potentially for decades). This report has been explicit: aviation should be near the top of the sectors that logically should get that hydrogen. At the other end, consideration should be given to banning hydrogen use in some other sectors (for example all surface transport), which would provide additional policy certainty, needed to ensure international capital is attracted to the UK.

Further information

Matt Finch
UK Policy Manager
Transport & Environment
matt.finch@transportenvironment.org
Mobile: +44(0)7881 812 398