Cerulogy

Scrutinising the future role of alternative fuels in delivering aviation decarbonisation

Part 3 – the pathway to decarbonised aviation

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Disclaimer

Contents

Glossary

Alternative aviation fuel – aviation fuels not produced from crude oil, including aviation biofuels (biojet) and aviation e-fuels (e-jet).

Biofuels (including biojet) – fuels produced from biomass.

Carbon footprint – see GHG intensity.

Carbon intensity – see GHG intensity.

CCS – carbon capture and permanent storage.

CORSIA – ICAO's Carbon Offsetting and Reduction Scheme for International Aviation.

Direct emissions – when we talk about direct emissions in the context of alternative fuels we are talking about the emissions that are within the control of operators somewhere in the supply chain for a given alternative fuel pathway. Note that this differs from the way that direct emissions are defined in company accounting under the GHG protocol, where direct include only emissions within the control of the company being assessed, and emissions under the control of third parties in the supply chain are characterised as indirect.

Downstream – processes that occur later in the supply chain (i.e. closer to the point at which a product is delivered to an end user).

E-fuels (including e-jet) – fuels produced from electricity be generating electrolytic hydrogen and synthesising it into hydrocarbons (or other fuel molecules).

Embedded emissions – the GHG emissions associated with the production of a material or energy stream used as an input for another process.

GHG – greenhouse gas.

GHG intensity – the GHG intensity of a fuel or of a process is a characterisation of the amount of carbon dioxide and other greenhouse gases that are released due to the production and use of the fuel or the application of the process. For fuels, in this report we express GHG intensity in terms of grams of carbon dioxide equivalent emissions (on a GWP100 basis) per megajoule of chemical energy in the fuel on a lower heating value basis. This unit is abbreviated to gCO_2e/MJ.

Indirect emissions – when we talk about indirect emissions in the context of alternative fuels we are talking about emissions that are generally outside the control of operators within the supply chain. This includes emissions from land use changes that are market driven and do not generally occur at the farms on which feedstock batches are actually produced and emissions (or GHG reductions) associated with displacement of materials out of existing markets. Note that this differs from the way that indirect emissions are defined in company accounting under the GHG protocol, where these sorts of market-mediated indirect emissions are normally treated as outside even Scope 3.

IPCC – Intergovernmental Panel on Climate Change.

LCA – lifecycle analysis, the practice of assessing the full set of emissions associated with production, use and disposal of a product or service.

LCA score – for LCA of climate impacts, the LCA score is an indicator of the GHG intensity, determined not only by the characteristics of the fuel or process but by the rules of the LCA framework.

Physical CO_2 emissions – in this series of reports, when we talk about 'physical CO_2 emissions' we mean the CO_2 emitted from a specified process ignoring lifecycle considerations and conventions such as zero accounting of biogenic CO_2.

REFuelEU – the EU's regulation setting targets and rules for alternative aviation fuel use out to 2050.

Renewable Energy Directive (RED) – the EU's framework for supporting renewable energy, including renewable fuels in transport.

Renewable Transport Fuel Obligation (RTFO) – the UK's framework for supporting renewable fuels in transport.

Sustainable aviation (SAF) – see alternative aviation fuel (AAF).

Synthetic aviation fuels – hydrocarbon fuels certified for aviation use produced from non-oil resources (e.g. biomass, electrolytic hydrogen, natural gas, coal).

True emissions – when we say 'true emissions' in this report we mean the change in total global emissions (associated with a given action) that we could identify if we were omniscient and had perfect foresight – in practice, the true emissions are not known.

Upstream – processes that occur earlier in the supply chain (i.e. closer to the point of raw material extraction).

Summary

Both the aviation industry and European governments have committed to an ambitious ramp up in alternative aviation fuel production as a key measure to reduce the climate impact of aviation. By 2050 the EU has set a target for 70% alternative aviation fuel use under REFuelEU, and the UK Jet Zero strategy anticipates at least 50% alternative aviation fuel use. The International Civil Aviation Organisation (ICAO) has made alternative fuel use a compliance option under its CORSIA[1] programme. Currently, the only alternative aviation fuel technology that is operational at commercial scale is hydrotreating of vegetable oils and animal fats, but the availability of these resources is limited, even if including crop-based vegetable oil production, and therefore this technology is not scalable. Achieving significant penetration in the aviation fuel mix will require the deployment of biomass-to-liquids technologies for the conversion of cellulosic material to biojet, and power-to-liquids technologies for the conversion of electrolytically produced hydrogen to e-jet. The EU and UK targets together imply consumption of about 37 million tonnes of oil equivalent (Mtoe) of alternative fuels, and this would require a rapid and sustained ramp up in alternative fuel production capacity from now to 2050.

Based on cost assumptions that are documented in the impact assessment for REFuelEU, this would require annual capital investments averaging about $1 billion per year throughout the period. The growth trajectory in REFuelEU implies annual capacity growth rates in the 2030s of 25-30% for both biomass-to-liquids and power-to-liquids production technologies, which is similar to the growth achieved in U.S. corn ethanol production in the period from 2000 to 2010. While this parallel shows that capacity growth at these rates is precedented, it is important to recognise that the context for these two industries is not identical. When the corn ethanol industry expanded in the 2000s, it was deploying a technology that had been in commercial use for decades, with a well understood cost structure and a single homogenous feedstock. The capital costs for corn ethanol plants were significantly lower than those for advanced alternative aviation fuel facilities, and corn ethanol was well supported by U.S. policy and politics and was either at or close to cost competitiveness with U.S. gasoline. Delivering similar growth rates will be very challenging for advanced alternative fuel technologies that are relatively unproven, that use a much broader set of feedstocks, and that will be entirely dependent on continuous policy support for the foreseeable future due to higher capital costs and with high production costs. This support can be provided 'directly' in the form of tax breaks or subsidies, but can also be provided through mechanisms such as supply mandates or carbon pricing.

One significant hurdle in the path of the development of advanced alternative aviation fuel technologies is competition with the existing vegetable oil hydrotreating industry. While these technologies are not scalable in the long term, there is currently an ongoing boom in production capacity and producers will seek support for hydrotreated biojet in government policy. Given that hydrotreating has lower capital costs than more advanced technologies and that the technology risk is much lower for investing in these plants than in approaches that have not been proven at commercial scale, hydrotreating is currently able to out-compete other technologies in the short-term and it will be extremely difficult to drive investment in the more advanced approaches without well-targeted government support. The UK has recognised this and proposes to strictly limit the contribution of hydrotreated fuels under a UK

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[1] Carbon Offsetting and Reduction Scheme for International Aviation.

SAF mandate, but EU policy is less firm in this regard and it seems likely that the strong expansion of cellulosic biojet production in the period to 2030 that is foreseen in the impact assessment on REFuelEU will not materialise, and instead that the EU biojet supply will be dominated by hydrotreating of used cooking oil and animal fat resources that were previously being used for road biodiesel.

While there is a considerable range in estimates of the future cost of alternative aviation fuel production, it is generally agreed that these fuels are very unlikely to become cost competitive with fossil jet fuel by 2050 without government support. The production cost for cellulosic biojet could easily remain double the price of fossil jet fuel, and e-jet is expected to cost even more than that unless it is possible for producers to buy renewable electricity for much less than current average wholesale electricity prices. At the moment, the aviation industry is willing to take these higher costs as a necessary corollary of reducing its climate impact, but as the consumption of alternative aviation fuels increases this can be expected to become a very significant cost for airlines. Based on costs used in the REFuelEU impact assessment we estimate that by 2050 fuel costs could be increased by 60%, which would have a noticeable impact on the price of flights to passengers. These costs would in fact be expected to lead to reduced demand for aviation – for example the Jet Zero strategy estimates that increased costs associated with reaching net zero could contribute a 27% emission reduction through lower demand. It seems safe to anticipate that high costs associated with alternative aviation fuels will start to erode the current political support for alternative aviation fuel use, and that at least some airlines will start to call for targets to be reduced or delayed if costs cannot be brought down further. Even if such calls for policy change are not successful, the fact that a policy argument is even happening will inject further uncertainty into the investment climate and could make it even more difficult to deliver the mandated volumes on time. It can also be expected that airlines will look to taxpayers to bear some of the cost burden of deploying alternative aviation fuels in order to reduce the cost burden on passengers, and to try to minimise impacts on demand. Given that aviation is used predominantly by wealthier members of society, it is the opinion of the author that it is appropriate for the cost of reducing aviation's climate impacts to be borne by its users.

While the relatively high cost of decarbonising aviation through alternative aviation fuels could in principle be handled through an increased cost of flying, scaling up alternative fuel production also has implications for the rest of society due to the very significant renewable resources that would need to be committed. The EU + UK alternative aviation fuel goals imply that by 2050 aviation would consume about 100 million tonnes of biomass and about 350 TWh of electricity. These are resources that could otherwise be used elsewhere in the economy – or in the case of biomass crops, land resources that could otherwise be given over to nature restoration and carbon sequestration. E-jet production is also not the most efficient way to use electricity, and the UK Climate Change Committee has noted that a single unit of electricity could deliver about twice as much CO_2 benefit if used to run a direct air capture unit than if used to produce synthetic fuels, and there is a serious question to be answered about whether it could make more sense to use direct air capture of CO_2 with permanent storage to offset emissions from continued use of fossil aviation fuel than to use the same captured CO_2 to produce e-jet.

It is currently *en vogue* to believe that alternative aviation fuels will replace all or most of the fossil aviation fuel supplied in Europe by 2050, but in reality there are major challenges to overcome to deliver that future. Even with concerted government support for the current aviation industry vision, delays to fuel capacity deployment could render these targets exceedingly difficult to achieve. It seems likely, however, that as the reality of competition for renewable resources and the urgency of the climate challenge become unavoidable that governments may conclude that very high levels of alternative aviation fuel production will not be sensibly achievable, and that alternatives such as the introduction of demand management measures and offsetting through CO_2 capture will increasingly become part of the policy conversation.

1 Introduction

For many years, the aviation industry has had a somewhat totemic place in the hearts of climate activists, alongside such GHG generating activities as lone occupancy of SUVs and beef-based diets. Aviation is a high-climate-impact activity that is largely leisure oriented, and where there are simple lower-climate-impact alternatives available for many flights – in the case of long-haul flights, going on holiday somewhere closer; in the case of short haul flights, travelling by train or coach. Decisions to take shorter flights, take fewer flights or not to fly at all could be taken by many people without an undue welfare impact. Starting in Scandinavia, the idea of individuals being unwilling to fly whenever and wherever they would otherwise like to gained a name, 'flygskam'.

Having customers feeling ashamed to use your service is rarely good for business and, confronted by grassroots individual action on the one hand and the looming inevitably of increasingly intrusive regulatory engagement on the other, the aviation industry is trying to renew its social licence to operate by developing a vision for net zero aviation by 2050[2], which builds on the previous commitment to carbon neutral growth from 2020[3]. There are four legs to the stool of the net zero commitment – the improvement of aircraft efficiency including hydrogen and electric planes, improved infrastructure and operational efficiency, offsets and carbon capture, and the use of alternative aviation fuels (a potential fifth leg, namely measures to address demand, are rarely acknowledged in industry and ICAO circles). Of these, alternative aviation fuels are the largest contribution, identified in the 'Fly Net Zero' strategy as delivering 65% of GHG reductions by 2050. This interest from industry is echoed in government policies. The EU has just finalised the REFuelEU mandate for the use of renewable fuels in aviation, the UK is developing a 'sustainable aviation fuel mandate'[4], and the U.S. has announced an alternative aviation fuel 'Grand Challenge'.

The reason that alternative fuels have been given this outsized role in the plan to reduce the net CO_2 emissions from aviation is simple – there are really no other options available that don't either require completely overhauling existing business models, the use of technologies like electric commercial airliners that may not be viable by 2050, or a massive upscaling of the use of offsets. Alternative aviation fuels are in the sweet spot that allows the industry to continue business as usual for the time being but that have more innate credibility than the offsetting model of simply paying for emissions reductions by other people. Notwithstanding the conceptual issues involved in treating alternative fuels as aviation in-sector emission reductions even though the physical CO_2 emissions from planes are not reduced, which we discussed in more detail in Part 1, there is a common understanding that alternative fuels represent a real effort – and investment – by the industry in a way that offsets would not. Some environmental groups support alternative fuel mandates for aviation because they are seen as perhaps the only way to deliver deep reductions in net CO_2 emissions without levels of demand reduction

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[2] https://www.iata.org/en/programs/environment/flynetzero/

[3] We note in passing that various exemptions in CORSIA mean that the carbon neutral growth commitment will not be achieved for a while yet, even on its own GHG calculation terms which allow extensive use of offsets.

[4] https://www.gov.uk/government/consultations/pathway-to-net-zero-aviation-developing-the-uk-sustainable-aviation-fuel-mandate

that are not currently politically popular, and because it would impose the cost of decarbonisation on the industry in a way that offsetting might not.

In this report, we discuss some of the practical and economic implications of the scale up of alternative fuel production for aviation, including considering the rate of capacity deployment that would be needed to deliver target volumes of fuel and the costs and resource allocations that this would imply.

1.1 SAF vs AAF

Readers who are used to the discussion of alternative aviation fuels might have noticed that in the text above, and in parts 1 and 2 of this series of reports, we have studiously avoided using a term that has become standard in the industry in recent years – SAF, standing for Sustainable Aviation Fuel. Instead, we prefer to say 'alternative aviation fuel' (we have not abbreviated this to AAF in the rest of the document!). The reason that we prefer not to use the term SAF is because sustainability is a characteristic of a fuel pathway that is at least somewhat subjective (i.e. it depends on which sustainability criteria are considered important), that may change over time (sustainability can be affected by variables outside the control of a fuel producer such as deforestation rates), and that is at least somewhat scale-dependent – one might feel differently about devoting a couple of farms to bioenergy cropping than devoting half of the agricultural area of Europe.

The endemic use of the acronym SAF has both a positive aspect for the industry and a negative aspect. The positive aspect is that putting the word sustainable front and centre makes it clear that sustainability issues are going to be a central feature of fuel support schemes. It is hard to argue against a SAF mandate including at least some form of sustainability oversight. The use of the abbreviation SAF was initially adopted to signal a firm commitment to sustainability principles – for example, in 2008 the 'Sustainable Aviation Fuel Users Group' (SAFUG) was formed by 25 airlines plus other industry players and adopted a progressive set of sustainability principles. Sadly the SAFUG website lapsed and now hosts someone's blog, but the Way Back Machine allows us to go back in time and recall the core pledges[5]:

1. Fuels should not compete with food and biodiversity impacts should be minimised;
2. Lifecycle emissions should be significantly reduced;
3. Projects in developing economies should improve the socio-economic conditions of small-scale farmers and should not involuntarily displace local populations;
4. High conservation value areas and native eco-systems should not be cleared.

The group also committed to work with the Roundtable on Sustainable Biomaterials. These principles (in particular non-competition with food) made SAFUG's position on sustainability stronger than regulatory requirements in major markets.

When SAFUG stated its principles, it was a way of setting a marker to indicate the intention to go above and beyond current regulatory norms to ensure aviation fuel sustainability. Fast

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[5] https://web.archive.org/web/20091222062343/http://safug.org/docs/sustainability-pledge.pdf

forward 15 years, and the term SAF is used generically for any fuel delivered under the CORSIA[6] regulation. Elements of the SAFUG principles have made it into the CORSIA rules:

- there is a lifecycle emissions assessment (that includes estimated indirect land use change emissions), though at present the LCA score must only be a minimum of 10% below a fossil fuel comparator, not necessarily 'significantly' below;
- production of fuels by clearing high carbon stock areas is forbidden, and from 2024 this prohibition is extended to high conservation value areas;
- from 2024 there are various requirements for fuel production to respect human rights and land rights, seek to improve local food security and socioeconomic conditions, and other environmental conditions.

Notable by its absence, however, is the principle of not competing with food production, and there are various issues (beyond the scope of this paper) with the way that indirect land use change emissions have been characterised (cf. Malins et al., 2014).

To give credit where it is due, the sustainability criteria adopted under CORSIA are quite broad – they go beyond any criteria in place under North American or European on-road biofuel mandates. But there is still a fundamental difference between a fuel 'that meets a set of sustainability criteria' and a fuel that 'is sustainable'. And this brings us to the negative aspect of the term SAF being normalised for any fuels meeting a regulatory standard. When SAFUG first talked about being committed to sustainable fuels, it was aspirational. It represented a group of airlines saying out loud that they wanted to go beyond legal minimum standards in place for biofuels at the time and were interested in how to make alternative fuels work best for the world. When fuel producers state that their fuels are sustainable because they meet a set of defined rules, it is no longer aspirational – it implicitly rejects the possibility that the existing ruleset may have any inadequacy or should be extended. It is common for suppliers in Europe to say categorically that their fuels 'are sustainable' because they meet the minimum standards of the Renewable Energy Directive – standards much more limited than the CORSIA requirements. There are very clear arguments to be made that some of those fuels are not very sustainable at all. Even where biofuels are produced in line with broader requirements set by voluntary schemes such as the Roundtable on Sustainable Biomaterials[7], it is better to say that a biofuel was produced in a way that met the sustainability requirements of a particular standard than to say that the biofuel 'is sustainable'. Any standard could be strengthened further, and the audit processes for standards are not flawless – there will always be some producers certified who should not have been. As the alternative aviation industry grows, many new fuel suppliers will say categorically that their fuels are sustainable because they are listed as SAF, and because SAF *means* sustainable. As with the fuels supplied under the RED, we can expect that some of these fuels labelled as 'SAF' will not actually meet a very high standard for sustainability. By using the term 'alternative aviation fuel' in this report we are reminding the reader that 'sustainable' is not a label but a question, a question that needs to be answered continuously and actively, rather than an answer that can be put on the table and left static.

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[6] Carbon Offsetting and Reduction Scheme for International Aviation.

[7] https://rsb.org/

2 Scaling up alternative aviation fuel production to 2050

In 2030, the EU's jet fuel demand is expected to be about 46 million tonnes of oil equivalent (Mtoe), and EASA[8] expects this total demand to be fairly constant to 2050 (efficiency improvements offsetting growth)[9]. EUROCONTROL (2022) presents scenarios with 50 to 88% alternative aviation fuel – for total aviation fuel demand of 46 Mtoe this implies alternative aviation fuel demand of between 23 and 40 Mtoe. The recently finalised REFuelEU proposes a mandate in the middle of this range, reaching 70% by 2050, implying 32 Mtoe of alternative aviation fuel demand.

Table 1 Alternative aviation fuel shares under REFuelEU

	All alternative aviation fuels	Minimum e-jet share
2025	2%	
2030	6%	1.2%
2035	20%	5%
2040	34%	10%
2045	42%	15%
2050	70%	35%

The UK also sees alternative aviation fuel as a key emission reduction technology. The UK Jet Zero Strategy (Department for Transport, 2022c, 2022b) lays out a 'high ambition' aviation emission trajectory predicated on the use of 50% alternative aviation fuel by 2050, which would represent a further 5 Mtoe of alternative aviation fuel demand.

If this is added to the REFuelEU target it brings the EU + UK total to 37 Mtoe by 2050. This is a large amount of alternative fuel production. It is nearly double current total biofuel consumption in Europe across all transport modes; if produced using the HVO/HEFA[10] technology it would consume over three times more vegetable oil than the EU + UK currently consume for food (based on consumption data from OECD-FAO, 2021). There is no way that that level of vegetable oil demand could be met with used chip fat! Recognising that it would not be sensible to try to produce such volumes from vegetable oils, or even from other more available biomass, REFuelEU calls for half of this to be e-jet, and therefore in the discussion below we consider 18.5 Mtoe of e-jet and 18.5 Mtoe of biojet.

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[8] The European Union Aviation Safety Agency.

[9] https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/current-landscape-future-saf-industry

[10] Hydrotreating vegetable oils or animal fats to produce hydrocarbon fuels. HVO stand for hydrotreated vegetable oils, while in the context of aviation the initialism HEFA for hydroprocessed esters and fatty acids is also often used. For our purposes these terms may be considered interchangeable.

Currently, EU capacity for alternative aviation fuel production is estimated at about 0.24 Mtoe[11] – i.e. less than one hundredth of the minimum 2050 capacity that would be needed. If the vision of an aviation industry running predominantly on alternative fuel is to be realised, it will require a dramatic expansion of fuel production capacity – and a dramatic mobilisation of biomass and/or of renewable power generation to accompany it.

2.1 The energy intensity of aviation

The reality of climate change poses a fundamental challenge to aviation's social licence to operate. CO_2 emissions from aviation are high because travelling long distances in the air is a fundamentally energy intensive practice. Per kilometre travelled, the energy intensity of flying in economy class on a passenger flight is comparable to that of driving a car as the sole occupant, but the difference is that flying allows people to go much longer distances than most people would ever want to drive. Based on the typical fuel consumption values reported by Brandon Graver & Dan Rutherford (2021) and flight distances reported by www.airmilescalculator.com, flying from London Heathrow to Amsterdam Schiphol and back takes about 50 litres of fuel per passenger, about the same as an average petrol car owner in the UK consumes in three weeks[12], generating about 120 kg of CO_2 emissions. To fly from Heathrow to San Francisco International and back takes about 560 litres of fuel per passenger, roughly equivalent to the fuel consumed by the average petrol car owner in eight months of driving, and generates about 1.4 tonnes of CO_2 emissions per passenger. You can do an awful lot of driving the kids to school for the same carbon footprint as one long return flight. You could also do a lot of other things. You could provide two thirds of the heating for a year for an average house[13], wash 670 loads of laundry[14] or brew 20,000 cups of tea[15].

We can also compare the emissions from a return flight to total average annual emissions per capita. Based on data from World Bank (2023), a return flight from London to Amsterdam releases about the same amount of CO_2 as the annual per capita emissions of Sierra Leone. The return flight to San Francisco releases a comparable amount of carbon to the per capita annual emissions for Samoa, a bit more than a quarter of UK per capita annual emissions. For most people in the UK, if they decide to take a long-haul flight it will be the highest carbon footprint decision they take during the year. Many people in the world are never given the opportunity to make such a high-carbon decision even once.

This context is relevant not only to highlight that flying has a significant CO_2 impact, but because the fuel intensity of aviation means that if it is to run on alternative aviation fuel a lot

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[11] https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/current-landscape-future-saf-industry

[12] Average fuel consumption for petrol vehicles reported as 175 UK gallons by https://www.nimblefins.co.uk/largest-car-insurance-companies/average-cost-petrol-car

[13] Data from CCC taking average of 2014 and 2030 heating emissions values https://www.theccc.org.uk/wp-content/uploads/2016/07/5CB-Infographic-FINAL-.pdf

[14] From 'How bad are bananas?' by Mike Berners Lee via https://honestmobile.co.uk/2021/08/05/carbonfootprint/

[15] https://www.goodbyecar.uk/blog/emissions-of-daily-activities

of resources will need to be devoted to making it possible. In the following sections, we try to provide an indication of the scale of these resources.

2.2 Production capacity

Reaching 37 Mtoe of alternative aviation fuel consumption within 30 years will require a very rapid deployment of capacity. Work undertaken to support the impact assessment for REFuelEU (Giannelos et al., 2021) provides an estimate of the number of alternative aviation fuel plants that would be needed to deliver 63% of EU jet fuel, 28 Mtoe, by 2050[16]. The results of this work are presented for four specified technologies: vegetable oil hydrotreating; biomass gasification and Fischer-Tropsch synthesis (FT); cellulosic alcohol to jet (AtJ); and e-fuels. While modelling such as this can give a sense of precision about forecasting future technology splits, it is impossible to know confidently in advance which precise set of alternative fuel production technologies will be the most successful. Within the overarching category of 'biomass-to-liquids' (technologies that can convert cellulosic or ligno-cellulosic material into hydrocarbon fuels) there are several other possible approaches (e.g.; hydrothermal liquefaction and upgrading; pyrolysis and upgrading; aqueous phase reforming). Some roadmaps for alternative aviation fuel deployment (e.g. Sustainable Aviation, 2020) identify a wider range of possible technologies, and model all of these delivering continuous growth to 2050. Others such as the REFuelEU work make a technology choice – in this case including gasification with FT and alcohol to jet, but not considering pyrolysis etc. In practice, it seems reasonable to anticipate that by 2050 one or two technologies will prove to be the most successful, that some technology options will be deployed but then suffer capacity stagnation, and that some will never reach commercial scale in the first place. It is beyond the scope of this paper and the predictive power of this author to assess which technologies will win out, or indeed which will reach commercial scale first.

From the point of view of highlighting the required rate of capacity deployment it does not matter whether FT, AtJ or some other biomass-to-liquids technologies will commercialise fastest, the point is that whichever of them scale up will have to do it aggressively. The expectation of competition between technologies is, however, a reminder of the very considerable investment risks associated with being a first mover in the development of these new technologies. Not only must project developers worry about the economics of their specific implementation of a given technology as compared to their competitors (cf. N. Miller et al., 2013), but they also risk having their whole technology approach being made redundant by a different development path. Developers of new fuel production systems are not interested only in the potential of their first commercial facility to be profitable, the real opportunity lies in either building further plants or in licensing the technology for others to do so. The risk that a successful fast pyrolysis project in the UK could be superseded by the development of a more-economical FT technology on the other side of the world is unavoidable, but adds to the challenge of achieving rapid deployment of these technologies in the next few years.

Disclaimers aside, the minimum capacity requirements to meet targeted EU + UK alternative aviation fuel demand in 2050 are illustrated in Figure 1, based on the results of the REFuelEU

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[16] The REFuelEU proposal suggested a 63% target for 2050, in the final version this has been increased to 70%.

impact assessment (Giannelos et al., 2021)[17]. The capacity values have been adjusted upwards to reflect the final adopted value for the 2050 target, to include 5 Mtoe of demand from the UK and to include capacity for production of the fuel that Giannelos identifies as imported[18]. Delivering the targeted levels of fuel production for the EU + UK for 2050 would require 145 dedicated alternative aviation fuel plants, 46 of them producing e-fuels and 97 making biomass-to-liquids fuels, plus 6 HVO/HEFA plants. Based on the plant capacities assumed in Giannelos[19] that would require an average of about five new commercial scale plant openings a year from 2025 through to 2050, and based on plant costs given in the report[20] would require capital investment of over $30 billion, more than $1 billion per year[21] through the period. This capacity might be developed in the EU, but could also be developed elsewhere for export to the EU. Giannelos et al. (2021) models about 2.4 Mtoe being supplied as biojet imports, and the rest as domestic production.

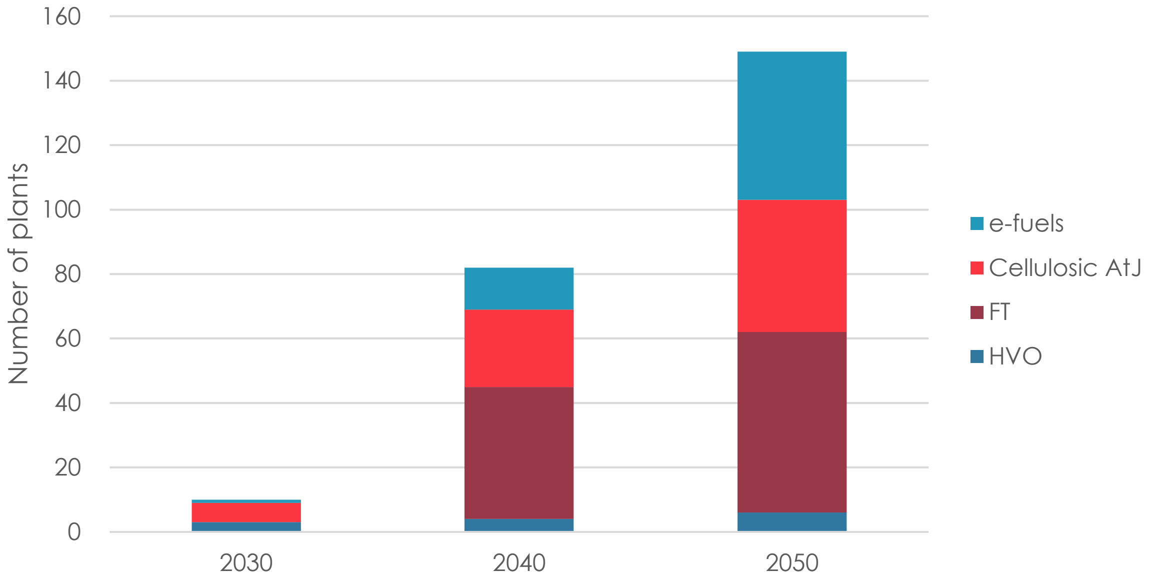

Figure 1 **Number of plants required to deliver targeted 2050 alternative jet fuel production for the UK + EU**

Source: Based on Giannelos et al. (2021).

This rate of deployment will certainly be challenging to deliver. For the period 2030 to 2040, it requires equivalent annual production growth of 25% for the biomass-to-liquids technologies

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[17] The fuel deployment results for the policy scenarios that assume 28 Mtoe of alternative aviation fuel consumption in 2050 are fairly similar, we have referred to the results for their scenario A1.

[18] Production quantities and plant numbers discussed below are all scaled up on this basis, and therefore are slightly different than the numbers quoted in the source material.

[19] Giannelos assumes relatively large facilities, and does not assume increasing commercial-scale plant capacities over time, and therefore these facility numbers may be on the low side. This is discussed further below, around Figure 3.

[20] These costs are taken from analysis by Soubly et al. (2020).

[21] In today's dollars, i.e. not adjusted for possible inflation.

taken together, and 29% for e-fuels[22]. These growth rates are not without precedent in the biofuel industry – for example in the period 2000-2010 U.S. corn ethanol production delivered equivalent annual growth of about 26% (Malins et al., 2015) – but they are very ambitious.

The comparison with corn ethanol is interesting not only for the *prima facie* similarity (an industry rapidly expanding under strong government support) but for some of the underlying differences in the context:

- In the year 2000, the U.S. corn ethanol industry was well established with decades of experience of the technologies involved – making ethanol from corn is similar to making whiskey, and the origins of the more recent boom in corn ethanol for fuel lie as far back as the oil crisis of the 1970s. The technologies required were well understood and had been observed in operation at commercial scale for decades, and their costs were well known.
    - In contrast, while some of the building blocks for biomass-to-liquids technologies have been used in other contexts for many years (e.g. FT synthesis in gas-to-liquids and coal-to-liquids plants) there are no operational commercial scale facilities producing jet fuel by these pathways, and there is considerable uncertainty about what the costs will be for the first generation facilities and how those costs may evolve over time.
- Corn is a relatively homogenous feedstock with an established supply chain. Requirements for material handling were well understood.
    - Cellulosic biomass can be very varied, and there are different challenges associated with handling different types of biomass. Limiting a biomass-to-liquid plant to a single type of biomass reduces flexibility and could leave the operator more exposed to feedstock price variation, but trying to be feedstock neutral means having to handle a broader variety of materials and chemical contaminants. The cheapest feedstocks (like refuse derived fuel) are also the least homogenous and the most difficult to handle.
- The price and production cost of corn were well understood, and the corn price was fairly stable through the 90s (notwithstanding that prices rose and became unstable later, after 2007 (Malins, 2017a)).
    - The likely price of cellulosic material remains contested, with significant differences in feedstock price assumptions between studies, and in the absence of established supply chains may be vulnerable to price spikes if rapid deployment of facilities leads to strong demand growth.
- The capital cost of corn ethanol facilities was estimated at about 300 $/toe in the year 2000 (McAloon et al., 2000)(adjusted to 2023 dollars).
    - The 2025 capital cost of biomass-to-liquids facilities is estimated by Soubly et al. (2020) to be three times higher than this for AtJ plants and five times higher for FT plants.

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[22] It is not really useful to consider equivalent growth rates for the first few commercial plants in 2020-2030, as the percentage growth would be enormous given the tiny volumes currently produced.

- Corn ethanol was a product that had a market on its own merits as a fuel oxygenate (octane enhancer) as well as benefiting from firm government support in the U.S. (through tax credits and the Renewable Fuel Standard). Some analysts have argued that the value of ethanol as an octane enhancer was enough on its own to support blending at nearly 10% by volume given the relative prices of ethanol and gasoline in the U.S. (Irwin & Good, 2012).
    - The use of alternative aviation fuel does not provide any financial benefit to airlines in the absence of supportive policy or options to pass costs to consumers directly. While alternative aviation fuels have some nice properties compared to fossil equivalents (e.g. reduced sulphur) these properties are not needed by airlines to meet non-climate regulatory requirements. Soubly et al. (2020) anticipates that in 2030 alternative aviation fuels will cost at least twice and possibly as much as five times as much as fossil jet fuel (depending on pathway).
- Ethanol costs less per litre than gasoline (although more per unit of energy) so that ethanol blending reduced the apparent cost of fuel to motorists (though it also caused increased fuel consumption), reducing consumer opposition.
    - The additional cost of supplying alternative aviation fuels will cause increased ticket prices unless the costs are socialised and imposed on taxpayers.

At present, there is no significant commercial production of alternative aviation fuel using either biomass-to-liquids or e-fuel technologies, and only modest production as HVO/HEFA. Whereas the U.S. corn ethanol industry headed into the 2000s after a decade of steady growth (at a more moderate rate), the alternative aviation fuel industry will need to have five years of rapid capacity deployment from 2025 to 2030 if it is to get to the point where ‘only’ 25% annual growth would be enough to reach the 2040 milestones.

To put all this another way, if it is to deliver the trajectory outlined for REFuelEU the alternative aviation fuel industry would need to deliver remarkable success in first deploying and then scaling up a set of technologies that developers have spent the last couple of decades failing to commercialise for on-road applications (despite strong government support), and would then need to deliver a decade of sustained expansion comparable to the expansion of corn ethanol in the 2000s despite the fact that the technologies required are less well understood, less commercially viable, significantly more capital intensive and dependent on much more difficult supply chains. Not an easy task.

The REFuelEU work may also make the task sound a little easier than it is by understating the number of plants likely to be needed. The analysis implies six operational commercial scale AtJ plants in 2030 and one operational commercial scale e-fuel plant, but these numbers are based on very large facilities – producing 200 thousand toe a year for the AtJ plants and 400 thousand toe a year for the PtL plant. These assumed plant sizes are 40% and 130% larger than those suggested by Sustainable Aviation (2020), for example. The suggested e-fuel plant size in particular seems very large compared to what we would expect to see in the next few years. An annual output of 400 thousand toe would require about 660 MW of power[23]. This is more than the output of the Stalowa Wola gas power plant in Poland, which was the largest gas

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[23] Assuming that the electrolysers are active 80% of the time.

plant that opened in Europe in 2020[24]. Simply arranging a connection to deliver that much power would be challenging.

These sizes are also based on considering the jet fuel output only. In practice, alternative fuel plants are likely to deliver a mix of fuel outputs including renewable diesel, renewable gasoline and renewable ‘light ends’ (shorter-chain hydrocarbons that can be used as chemicals feedstock, in LPG or in other industrial applications). Sustainable Aviation (2020) suggests that an e-fuel plant optimised for aviation would produce about 50% jet fuel and 50% other outputs. That implies that in order to deliver 400 thousand toe of jet fuel capacity you might need a total e-fuel capacity of 800 thousand toe. Short of setting up next door to a nuclear power station, this level of concentrated power consumption sounds unlikely to us. Even if the plant sizes could be realistic in the long run, it is very likely that the first commercial plants will be rather smaller. For comparison, a recent announcement for the ‘first ever commercial scale e-fuel plant’ suggested a production capacity of a fifth of this quantity, about 78 thousand toe per year. The UK has stated an ambition to see at least five commercial scale alternative aviation fuel plants under construction by 2025 (Department for Transport, 2023) supported by the Advanced Fuels Fund[25], but none of the initial grantees proposes a capacity greater than 90 thousand toe per year.

In order to provide an alternative view on the number of plants that might be required by the REFuelEU trajectory we have developed our own version of the capacity deployment modelling, using a modelling framework similar to that described by Malins (2021), which is itself based on the modelling described by Sustainable Aviation (2020). This modelling framework is based on a gradual scale up of facilities from smaller first commercial plants to larger Nth-generation plants based on the plant sizes from Sustainable Aviation (2020) – 146 thousand toe for AtJ, 90 thousand toe for FT and 89 thousand toe for e-fuels.[26] As shown in Figure 2, we have calibrated our model to give results as close as possible to the EU + UK trajectory implied by REFuelEU and the Jet Zero strategy. This gives a good match in 2050 and 2030, but lower biomass-to-liquids capacity in 2040 than the REFuelEU version.

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[24] https://www.iea.org/reports/electricity-market-report-december-2020/2020-global-overview-capacity-supply-and-emissions

[25] https://www.ricardo.com/en/news-and-insights/campaigns/aff

[26] The model assumes that the first generation of plants are half this size, and eventually the ‘optimal’ plant size is one and a half times the size given by (Sustainable Aviation, 2020).

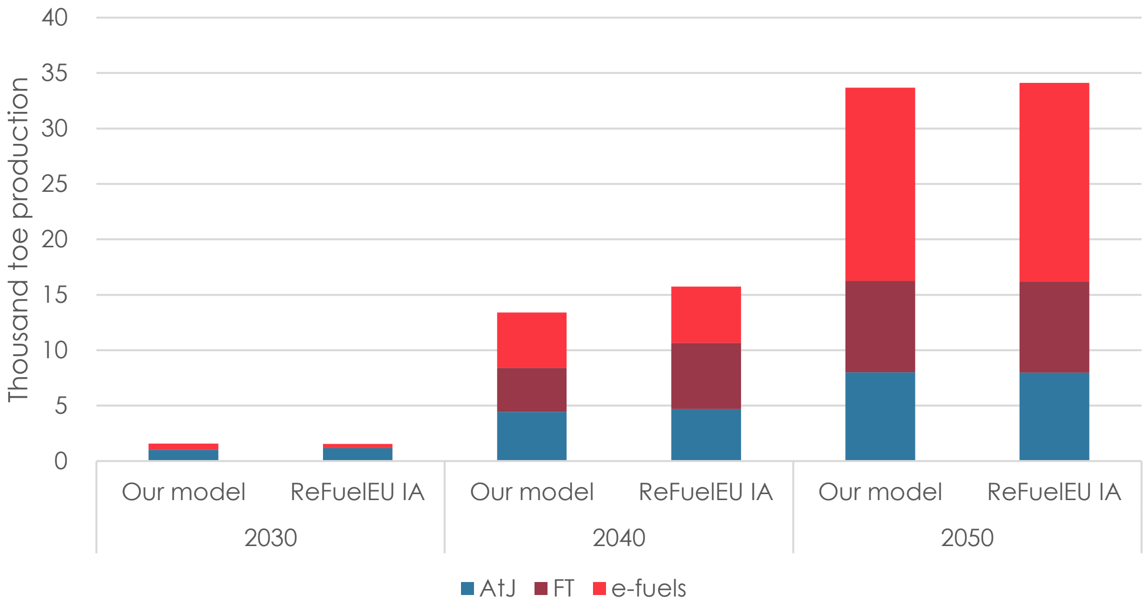

Figure 2 **Comparison of alternative jet fuel capacity deployment in REFuelEU modelling against our modelling framework**

While total capacity deployment is matched up between the models, assuming smaller plants obviously means that more plants are needed. As shown in Figure 3, with the alternative plant size assumptions over three times more plants are needed by 2050 in order to deliver the target volumes. In 2030 with our model's assumption of smaller first-generation plants the discrepancy is even more striking – 7 times more plants in our modelling, implying that we would need six plant openings a year from now to 2030 rather than less than one a year. This rate of plant deployment is not impossible, but it is certainly not easy to achieve, and given the previous false starts of the biomass-to-liquids industry it surely cannot be guaranteed that the introduction of policies like REFuelEU will make it happen.

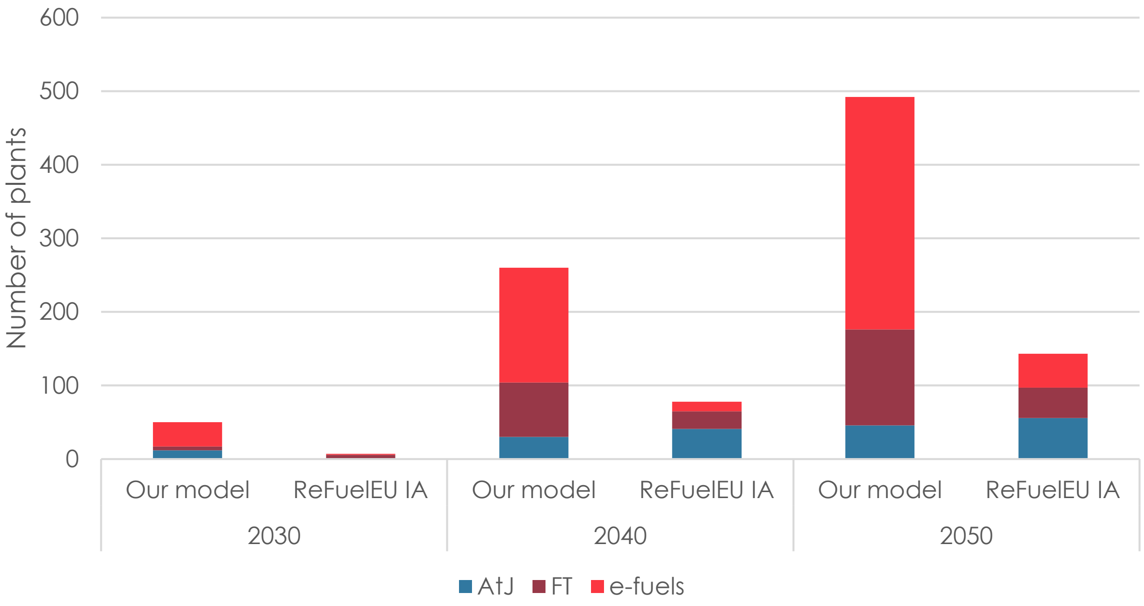

Figure 3 **Number of plants required to meet REFuelEU deployment targets in the two modelling approaches**

2.2.1 *HVO/HEFA – head start or distracting cul-de-sac?*

One key question for the development of the alternative aviation fuel industry is what role (if any) hydrotreated 'HEFA' fuels ought to play. Two points about HEFA are generally agreed:

1. HEFA fuel production is the only alternative aviation fuel pathway that is already operative at commercial scale[27].
2. HEFA fuel production is not scalable to meet a significant fraction of aviation fuel demand because vegetable oils (either virgin or waste oils) are not available in adequate quantities or at low enough prices.

Combining these two observations, HEFA is a fuel pathway that we could expand relatively rapidly in the near term, but that has little role to play in aviation decarbonisation in the long term. There is also a third point on which there is continuing disagreement in the community – whether increasing production of HEFA fuels actually delivers any net GHG savings, or whether the benefits of reducing fossil fuel use are probably offset by indirect emissions.

This leads to two contradictory positions in the community regarding near term actions:

1. The 'pro-HEFA' camp argues that including HEFA fuels in alternative aviation fuel mandates now will allow a more rapid expansion of production, can therefore deliver immediate GHG benefits instead of waiting for other technologies to be commercialised, and will pave the way for other more scalable fuel options.

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[27] Though most of the fuel output is currently sold for diesel applications.

2. The ‘anti-HEFA’ camp argues that including HEFA fuels in alternative aviation fuel mandates now will undermine investment in the more scalable and more sustainable options, will therefore delay the introduction of fuels that truly deliver net GHG benefits while failing to deliver any net GHG benefits itself, and will have deleterious impacts on existing businesses producing road biodiesel.

It is the opinion of the author that the narrative that HEFA fuel deployment now can accelerate the deployment of other technologies later is unconvincing. There is a kernel of truth in the idea that getting used to handling and using HEFA fuels will help airlines and airports be prepared to use other alternative aviation fuels in future, but the challenge of building capacity for e-jet and cellulosic biojet production (which could be delayed by growing the HEFA industry) seems much greater than any challenges involved in fuel handling that could be resolved by expanding the HEFA industry.

The UK proposal for an alternative aviation fuel mandate includes a strict cap on the amount of HEFA that could be supplied to meet requirements, effectively creating a two-tier compliance market. The New Report (New, 2023) observes that limiting the use of HEFA to meet obligations will allow the UK to send a strong value signal in support of biomass-to-liquids technologies that may be lacking in other jurisdictions. Under REFuelEU there is no distinction drawn between biomass-to-liquids fuels and HEFA fuels (though e-fuels are given a sub-target), and therefore it is plausible that HEFA fuels will dominate the EU market for some years to come. In its response to the REFuelEU consultation, the industry organisation of the EU waste-based biodiesel industry EWABA argued that,

> *“By establishing a blending mandate that mostly relies on HEFA using limited waste lipids from the onset, the ReFuelEU Aviation proposal is breaking the existing level-playing field between transport sectors and technologies. If adopted as currently drafted, the proposal will create a protected market for the single technology processing waste lipids for aviation and to the detriment of the waste lipid processes for road and maritime use.”*

It further argued that including HEFA fuels alongside biomass to liquids fuels,

> *“Thwarts investments in much needed SAF developing technologies such as alcohol-to-jet, Fischer-Tropsch and e-fuels.”*

This idea that a short-term uptick in HEFA supply will be deleterious to the longer-term development of alternative aviation fuels should be taken seriously. Most economic analyses of the costs of alternative fuel production (see also section 4) agree that in the near term HEFA fuels can be produced more cheaply than biomass-to-liquids fuels or e-fuels, due to the much lower capital costs involved. This hierarchy of costs creates something of a chicken and egg problem – while ongoing research and development has some potential to allow costs to be reduced, an existing market tends to be a powerful driver of learning and efficiency improvements. That means that without an operational biomass-to-liquids industry to learn from it will be harder to make improvements. The more that competition with HEFA delays this learning process, the longer HEFA producers will be able to argue that HEFA is needed because other pathways are still not mature. The longer HEFA is allowed to compete against biomass-to-liquids in the market the longer biomass-to-liquids technologies will remain immature, and so it will go on. In the meantime, the aviation industry will register emission reductions that could otherwise have easily been delivered in road transport in order to claim to be meeting its decarbonisation targets, while adding pressure to global vegetable oil markets, and while the technologies that are actually needed get more and more delayed.

Other jurisdictions would do well to follow the UK's example by strictly limiting the role of HEFA fuels in the expanding alternative aviation fuel industry.

2.3 Biomass feedstock

2.3.1 HEFA

The production of biomass to liquids or HEFA fuels will require large quantities of biomass as feedstock. In the case of HEFA, this means oils and fats – and given that there is fairly limited scope to increase the available supply of waste oils and fats that either means shifting resources from road biofuels to aviation biofuels, or it means directly or indirectly increasing consumption and production of virgin vegetable oils (cf. Malins & Sandford, 2022). Delivering the REFuelEU trajectory as laid out by Giannelos et al. (2021) would require 3.3 million tonnes of vegetable oils and/or animal fats in 2050 (1.3 million tonnes in 2030). This quantity is slightly less than the quantity of used cooking oil plus category 1 & 2 animal fats currently processed for EU biofuels according to SHARES. This is not a coincidence – the REFuelEU impact assessment is predicated on using these RED Annex IX B feedstocks for HEFA production.

While the REFuelEU impact assessment assumes that the use of HEFA fuels is limited and is gradually superseded by biomass-to-liquids, this outcome is far from guaranteed by the proposed legislation, and indeed it seems extremely likely given the current framing that we will discover that the impact assessment has significantly underestimated the amount of HEFA that will be used to meet the targets and overestimated the amount of AtJ fuels from cellulose. In 2030, this could mean up to double the predicted demand for oils and fats, implying a much more rapid displacement of used cooking oil and animal fat resources out of road biodiesel use.

In the UK, in contrast, the consultation on a sustainable aviation fuel mandate proposes to strictly limit the amount of HEFA that will be eligible to be used towards targets.

2.3.2 Biomass to liquids

By 2050, delivering 18.5 Mtoe of biomass-to-liquids jet fuel for the EU + UK as described above (about 30% of assumed 2050 jet fuel demand) would require around 100 million tonnes a year of biomass. This is about half the amount of biomass currently consumed for stationary bioenergy in the EU, and is within the sustainably available technical potential of about 160 million tonnes for biomass wastes and residues identified by Searle & Malins (2015).

Delivering an additional 100 million tonnes a year of sustainable biomass is achievable in principle, but would represent a massive mobilisation of biomass resources. In addition to waste and residual resources, it could (and probably would in the absence of regulatory limitations) also be supplied from biomass cropping, such as grass crops and/or short rotation coppicing. Searle & Malins (2014) anticipates that achievable biomass yields from these cellulosic crops on low quality marginal land could be in the region of 10 tonnes per hectare, so delivering 100 million tonnes of biomass could take about 10 million hectares of land (less if grown on higher quality areas, more if grown on very low-quality areas or in colder climates). That is comparable to the total area of barley currently harvested every year in the EU.

It should also be recalled that alternative fuel production technologies produce a mixture of molecules, not all of which are appropriate for jet fuel use, and therefore total biomass consumption by these facilities would be higher. Following the Sustainable Aviation (2020) assumptions on optimised jet yields (50% for FT and 90% for AtJ) would imply total cellulosic biomass demand for fuels of 150 million tonnes. It should also be recognised that transport fuels will not be the only draw on biomass resources in 2050 – there is likely to also be demand for power generation, for biogas and potentially for biochemicals and bioplastics.

2.4 Electricity for e-fuels

The REFuelEU impact assessment calls for about half of the alternative aviation fuel consumed in 2050 to be e-fuel (therefore about a third of all aviation fuel). The UK is also targeting e-fuels with a dedicated sub-target proposed for its SAF mandate. Delivering 18.5 Mtoe of e-fuels for aviation in 2050 would require 350 TWh of electricity generation – if the e-fuels are to be delivered at low GHG intensity this must all be from additional renewable[28] power generation capacity. Based on 2021 statistics, 350 TWh is equivalent to about an eighth of EU power generation, double total EU solar power generation and a bit less than total EU wind power generation[29]. It would therefore represent a large but not entirely implausible commitment of renewable generation capacity.

We can provide an indication of how much renewable electricity capacity would be needed to supply this much power by considering typical 'capacity factors' for renewables. Capacity factors express the ratio between the actual power production of a renewable facility in an average year and the maximum possible power output if it ran at full capacity 24-7. Badouard et al. (2020) report a typical capacity factor for utility scale solar in the EU of about 15%, and a capacity factor for onshore wind of 32%. This means that generating 350 TWh a year would require about 260 GW of solar power capacity or about 120 GW of onshore wind capacity.

Solar farms have a typical capacity density of between 0.5 and 1 MW per hectare, so 260 GW of solar panels would require up to 520 thousand hectares of panels. This is a large area, but much smaller than the area of land potentially required to grow biomass crops for biomass to liquids fuels, as solar panels have a much better areal energy efficiency than crops. The typical power rating for an onshore wind turbine at the moment is about 3 MW[30], so 120 GW would require about 40 thousand onshore wind turbines, more than three times the current number installed in the UK.

These numbers, based on delivering about a third of aviation fuel in the EU + UK as e-jet by 2050, are already large. Some analysts have suggested much more ambitious pathways, with e-fuels accounting for close to 100% of the aviation fuel supply – that would triple these renewable electricity requirements.

Another way to think about these levels of electricity demand is to make a (very rough) comparison to the amounts of electricity consumed by households. We can take the UK as an example, considering 53 TWh of electricity demand associated with our hypothetical 2050 UK

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[28] Or possibly nuclear.

[29] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview

[30] https://www.nationalgrid.com/stories/energy-explained/onshore-vs-offshore-wind-energy

e-fuel consumption. A 2012 survey of owner-occupier household electricity consumption (Zimmermann et al., 2012) reported an annual average household electricity consumption of 3,867 kWh. Our 2050 electricity consumption for e-fuel is therefore equivalent to the total electricity consumption of about 14 million 2012 households. This would also make e-fuel production a larger electricity consumer than any single category of domestic appliance – the UK would be using more electricity to produce e-fuels for aviation than it would to run every fridge-freezer in the country, or every domestic lightbulb, or every electric hob, or every electric washing machine, or every home computer etc.

Before committing these levels of renewable electricity to e-fuel production, policy makers should reflect on the opportunity cost implied by using electricity in a process with relatively high losses. The Committee on Climate Change (CCC, 2020b) has argued that direct uses of electricity can deliver several times greater GHG benefit than e-fuel production (Figure 4) and therefore that, "synthetic fuels are relatively inefficient uses of electricity and should be lower priority than direct use of electricity for decarbonisation".

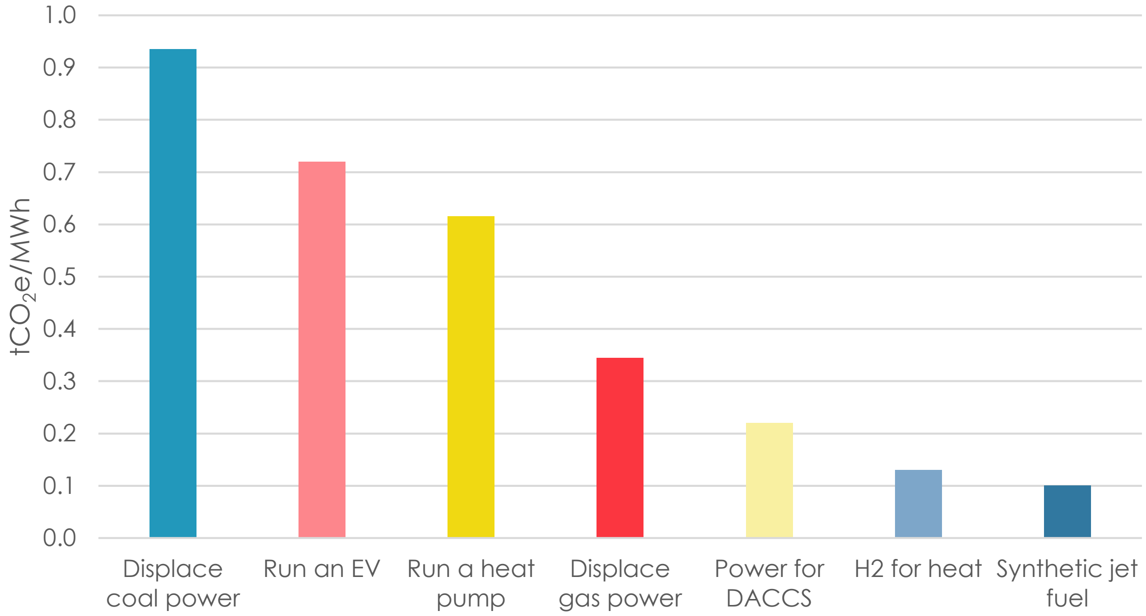

Figure 4 **Emission avoidance with 1 MWh of zero carbon electricity in example applications**

The way that we think about opportunity cost when using renewable electricity for e-jet production relates to the question of the additionality of renewable power generation for e-fuels, which we discussed in Part 1 of this series of reports. If the power generation for e-fuels is truly additional then it implies that extra generation has been supported by the aviation industry, and therefore in one sense the choice is not about how a given amount of renewable electricity capacity is used, but about whether that additional capacity would ever be brought online in the first place. Even so, if that additional renewable electricity capacity could have been used much more efficiently in other ways, it suggests a potential policy misalignment.

3 Co-benefits from alternative fuels

While the production of alternative fuels imposes externalities through resource competition, there is also an upside from alternative fuel use because the fuels are cleaner burning than their fossil fuel counterparts. Most aviation fuel is burned at altitude away from people and therefore the air pollution requirements on aviation fuels are not as strict as on road fuels (in particular, the sulphur limit on aviation fuel is 3000 parts per million, versus 10 parts per million for road diesel). Aviation fuel use in taxiing, take-off and landing does, however, affect local air quality around airports. There is also (as mentioned in Part 1 of this series of reports) an additional climate benefit from alternative fuel use in aviation, as alternative fuels have fewer 'aromatic' molecules and produce less soot when they are burned, which reduces aviation-induced cloud formation.

3.1 Sulphur

Alternative fuels are naturally low in sulphur, as there is very little sulphur in biomass and no sulphur involved in the production of e-fuels. In contrast, fossil jet fuel typically has about 600 parts sulphur per million. Work for EASA (M. Miller et al., 2010) suggests that globally reducing sulphur in jet fuel from 600 ppm to 10 ppm (like road diesel) would reduce mortality associated with particulate matter emissions from aircraft take-off and landing, delivering a monetised health benefit of the order of $1 billion per annum[31]. Alternative aviation fuel blending will deliver marginal reductions in fuel sulphur content proportional to the amount blended[32] – achieving 10ppm on average would require all but eliminating the use of fossil jet in the fuel mix.

The health benefits of lower sulphur fuels could also be delivered by desulphurising fossil jet fuel, using the same 'hydro-desulphurisation' technology used to remove sulphur from fossil diesel. M. Miller et al. (2010) estimate the costs of global aviation fuel desulphurisation to 10 ppm at about €300 million per annum. It would therefore be considerably cheaper to remove fuel sulphur by additional refinery processing than by switching to alternative fuels[33]; but the potential health improvement from reduced sulphur is a significant co-benefit if alternative fuels are adopted anyway for climate reasons.

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[31] Note that there is also a likely additional health benefit from reduced aromatics content (Jasper Faber et al., 2022).

[32] In the case of on-road alternative fuels, there has been a long running debate about how to characterise the air quality benefits of biofuel addition because fuel suppliers are expected to change the composition of fossil blendstocks to take advantage of the characteristics of the biofuels, thereby reducing any potential air quality advantage. In aviation, however, average sulphur levels are already well below the regulatory maximum so we would not expect that fuel refiners would take advantage of the low sulphur in alternative fuels by using higher-sulphur fossil components.

[33] In section 2.2 we noted an estimated capital cost of over $1 billion a year to deliver slightly more than half of aviation fuel as alternative aviation fuel, not to mention potentially much higher operational costs.

3.2 Aromatics

Aromatic molecules are a type of hydrocarbon containing a ring structure (as opposed to paraffinic molecules that have a straight-line structure) and which are associated with particulate matter emissions. Modern jet engines and associated fuel systems are designed on the assumption that jet fuel contains some quantity of aromatic molecules and cannot function properly on zero-aromatic synthetic fuels, and therefore the current alternative fuel blending standards limit the allowable blending ratio to ensure at least 8% aromatics content and at most 25% (Zheng et al., 2021). In the longer term, these blend limits can be overcome by designing new engines capable of using low-aromatics fuels, or by producing synthetic aromatics as part of the alternative fuel mix.

Everything about aviation induced cloudiness and the relationship between fuel formulation and cloud formation is subject to considerable uncertainty, but it is believed with some confidence that reducing aromatic content in jet fuel reduces the number of ice crystals that form in jet exhaust and that this will reduce the rate of contrail formation. There is experimental evidence that a 50% alternative fuel blend can reduce soot emissions by 50% compared to a conventional jet fuel, and that this may be associated with a 50-70% reduction in ice crystal formation (Voigt et al., 2021)[34], but to the best of our understanding there it is not yet known with confidence precisely how much such ice formation reductions will reduce radiative forcing by contrails, and Faber et al. (2022) notes that it is extremely difficult to gather direct evidence of changes in persistent contrail formation and associated radiative forcing would be very difficult to detect due to natural variation in ambient cirrus.

Just as sulphur could also be reduced in fossil jet by refinery operations, aromatic content could also be reduced with further fuel hydrotreating. Faber et al. (2022) estimate that the combined cost of processing conventional jet fuel to halve aromatics content, reduce sulphur to 14 ppm and nearly eliminate a specific class of aromatics called naphthalenes would be about 1 €cent per litre – much less than the additional cost of entirely replacing fossil jet with alternative jet fuel.

Faber et al. (2022) argues that given that aromatics reduction in fuel imposes costs on refineries and typical fuel aromatics content is relatively close to the regulatory maximum there is some risk that fuel blenders would offset aromatics reductions offered by alternative fuels by using higher-aromatics fossil blendstock, and therefore calls for a system of aromatics monitoring if the potentially air quality and contrail benefits of reducing aromatics with alternative fuels are to be guaranteed.

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[34] The strongest results in this study came from a fuel blend in which the type of aromatic molecules included in the fossil component was also managed.

4 The cost of decarbonisation

At present, alternative aviation fuels are very much at the top of the hype cycle. Many aviation industry representatives proclaim the industry's commitment to use them, some environmental groups call for greater ambition in mandating them and several governments seem willing to prioritise alternative aviation fuels over other transport fuels. This seeming commonality of cause has led to the adoption of roadmaps for aviation fuel deployment that rely on the aggressive scaling up of relatively expensive climate change mitigation approaches.

4.1 Cost of alternative aviation fuels

The cost analysis by McKinsey that is referenced by the REFuelEU modelling (Soubly et al., 2020) provides an example of anticipated costs for alternative aviation fuel production.[35] McKinsey presents costs in dollars, and therefore we also present dollar costs in this section – a dollar is currently worth 0.9 Euro or 0.8 UK pounds. A recent quote for the price of fossil jet fuel is $717 per toe[36]. McKinsey's estimated current production costs for several types of alternative aviation fuel are significantly higher than this. McKinsey's 2020 production cost estimate for HEFA was about twice this price, the estimate for AtJ from bagasse[37] was three and a half times this price, the estimate for FT fuels from municipal waste was two and half times this price and the estimate for e-fuels was five and a half times this price. For 'typical' values for the GHG intensity of these fuels[38] these prices imply costs of carbon abatement from 230 $/t$CO_2$e for a HEFA fuel achieving an 80% GHG reduction up to 920 $/t$CO_2$e for e-fuels (or for a HEFA fuel delivering only a 20% GHG reduction due to indirect emissions). UK work underlying the Jet Zero strategy anticipates needing an effective carbon price in aviation of 480 $/t$CO_2$e[39] in 2050. These costs are significantly above the highest prices recorded up to now in the EU ETS market (about 110 $/t$CO_2$e in February 2022) or under the California Cap and Trade programme (about 30 $/t$CO_2$e, also at the start of 2022). They are between twenty-five and a hundred times above the highest price recorded for CORSIA eligible credits to date (9 $/t$CO_2$e).[40] It would seem based on current costs that supplying alternative aviation fuels

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[35] Note that McKinsey estimated costs in dollars, and for consistency we have also used current dollars (rather than pounds or euros) to describe all of the costs/prices in this section. Given the considerable uncertainty in future fuel prices (and exchange rates) and that the euro is in any case close to parity with the dollar (at the time of writing 1.1 dollars to the euro) we suggest to the reader that for the first approximation dollars and euros can be considered interchangeable.

[36] https://www.iata.org/en/publications/economics/fuel-monitor/, 5 May 2023.

[37] A cellulosic residue of sugarcane production.

[38] In part 1 of this series of reports we noted that there are methodological issues associated with treating the difference between the LCA score for a fossil fuel and an alternative fuel as the amount of GHG emissions avoided by using the fossil fuel, but as it is a standard analytical approach in the field we have used it in calculating the implied carbon prices reported in this section. The GHG savings fractions assumed are: HEFA, 80% or 20%; AtJ and FT, 85%; e-fuels, 95%.

[39] Converted from £ based on 1.27 $ to the £.

[40] https://carboncredits.com/carbon-prices-today/

might be a much more expensive way to deliver emissions reductions than most other decarbonisation activities that will be part of the transition.

Part of the answer to this is that those 2020 estimated costs should reduce over time. Both the capital and operational costs associated these facilities should reduce with experience. Feedstock costs are more difficult to reduce, especially if growing demand causes increased competition for limited resources. Figure 5 shows the cost reductions that McKinsey anticipate being achievable for the pathways mentioned above. The cost reductions are significant, but still none of the pathways is identified as likely to become cost competitive with fossil jet fuel production before 2050. The biomass-to-liquids pathways never fall below $1,400 per toe, and while McKinsey model e-fuels reaching a cost of ‘only’ $1,300 per toe this is predicated on aggressive reductions in the price of electricity. It is beyond the scope of this paper to provide a detailed discussion of the argument for and against long-term reductions in industrial electricity prices – on the one side are potentially low levelised production costs[41] for renewable electricity, on the other side are the increased costs involved in managing variable power output from distributed renewables and the potential for strong growth in electricity demand across the economy to push prices up – but in order to highlight the importance of low cost electricity in making e-fuel production more competitive we have also included a ‘stable cost electricity’ line, which never falls below $2,000 per toe.

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[41] Levelised costs refers to the cost averaged over a given period, so as to include both the cost of building and installing a renewable power facility and the (generally quite low) costs of running it.

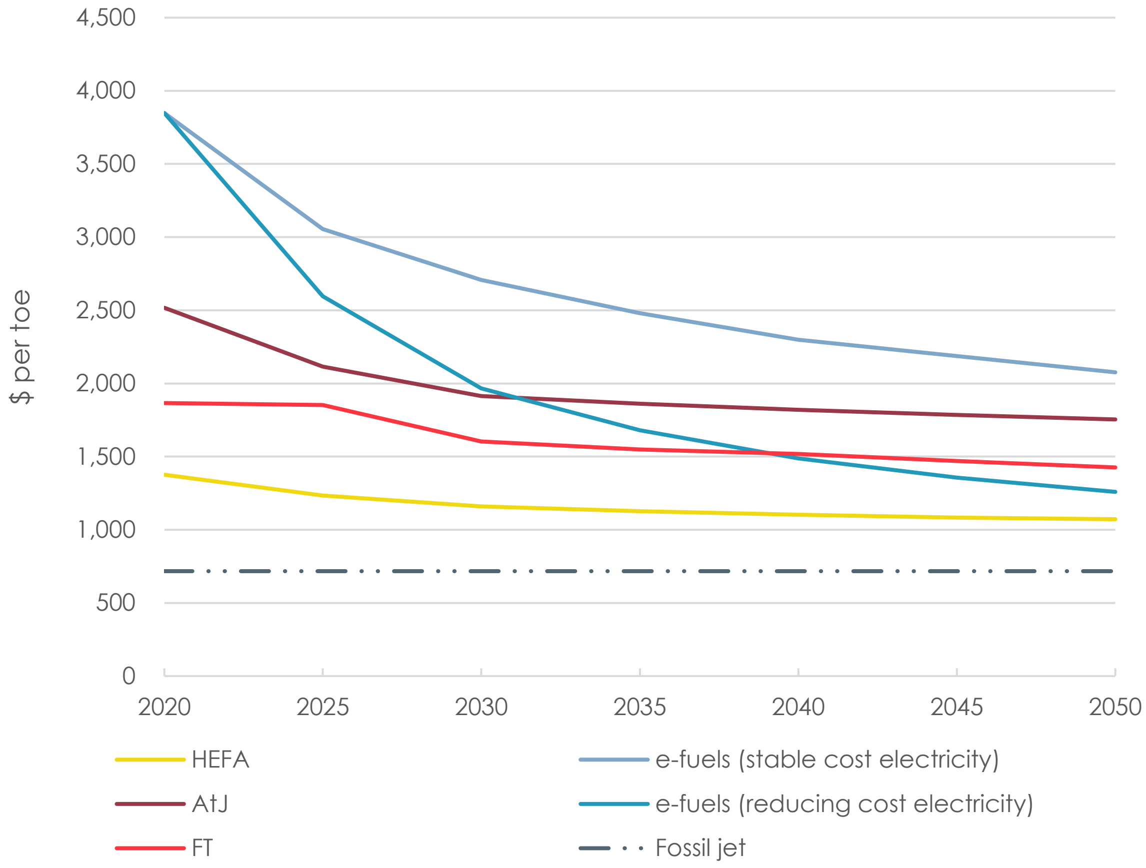

Figure 5 **Potential for cost reductions in alternative jet fuel pathways, 2020 to 2050**

Source: Soubly et al. (2020), with line added for 'e-fuels (stable cost electricity)' based on calculated data.
Notes: The e-fuel pathway is based on the use of captured point source carbon dioxide rather than on direct air capture of carbon dioxide – requiring direct air capture would further increase the cost of e-fuels. Jet fuel price is set constant at the current price. Predicting future oil prices is notoriously difficult – oil demand reduction in the energy transition could reduce oil prices and therefore jet fuel costs, but changes in the cost of refining and action by OPEC to manage supply could offset those effects. We do not consider the imposition of a carbon price on jet fuel here – we would understand carbon pricing as one of a number of mechanisms available to close the illustrated price gap between fossil and alternative fuels.

Delivering REFuelEU and the UK alternative aviation fuel mandate would therefore impose significant additional fuel costs on the European aviation industry. Based on the McKinsey fuel prices[42] and the fuel mix identified in the REFuelEU supporting analysis the average price of jet fuel in the EU + UK would be increased by about $440 per toe, at a total annual cost to aviation users in 2050 of $24 billion.[43] This would of course add significantly to the cost of flying. If fuel currently makes up roughly a third of airline operating costs, and fuel prices rise by about 60%, this could increase the cost of an average flight by about 20%: a noticeable increase. Past

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[42] Including using McKinsey's low assumed 2050 cost of electricity.

[43] This implicitly includes the cost of investments in alternative fuel production facilities.

research by IATA (Smyth & Pearce, 2008) suggested that the elasticity of EU aviation demand to price was about -1 (i.e. a 1% increase in price would cause a 1% reduction in demand) and therefore a 20% increase in flight costs might be expected to drive a demand reduction of up to 20%. Reducing the number of flights by increasing costs would of course represent a co-benefit in climate mitigation terms, even if it is not considered desirable in terms of costs to passengers. This result is comparable to a result in the UK Jet Zero strategy consultation estimating that carbon pricing consistent with the strategy would drive demand reduction that would deliver 27% of the modelled GHG emission reductions (Department for Transport, 2022a). The REFuelEU impact analysis assumes a more modest 6% reduction in air transport activity compared to the 2050 baseline due to the cost of alternative aviation fuel use

There is a range of alternative fuel cost estimates in the literature, both higher and lower than the McKinsey estimates, and it should be understood that the estimates given here are specific to a certain set of technology and feedstock assumptions. The McKinsey numbers are not dissimilar to estimates by the EU's 'Sub group on advanced biofuels' (Sustainable Transport Forum sub group on advanced biofuels, 2017) or by the ICCT (Pavlenko et al., 2019). There are commentators out there who have high hopes for low cost e-fuels, which are generally predicated on the idea of being able to access very low cost renewable electricity by placing facilities in remote locations with no easy connection to local grids (and therefore no option to sell electricity directly) and plentiful low-cost renewable energy potential, or on being able to take advantage of cheap electricity during periods of excess renewable generation. It is the opinion of the author that predictions of very low electricity prices to e-fuel producers do not adequately reflect the likely level of competition for electricity in an increasingly electrified economy. While it is true that electricity can be produced from renewables at a relatively low cost, low-cost electricity will attract other industries as well and this should be expected to raise the price that electricity generators can charge. It is therefore considered unlikely by the author that the low electricity price (3 cents per kWh) assumed in the McKinsey scenario marked as 'reducing cost electricity' in Figure 5 will be achievable for large volumes of e-fuel production in the 2050 timeframe.

It is not only renewable electricity generation that might experience a gap between cost (the amount of money spent to produce a unit of energy) and price (the amount of money that can then be charged for that unit of energy); competition could also further inflate the cost of alternative aviation fuels. It is not only Europe that is interested in developing a market for alternative aviation fuels but also countries in North America and the rest of the world. IATA has made a global net zero GHG emissions pledge for 2050, and this is predicated on massive substitution of fossil fuels with alternative aviation fuels (rates of substitution higher than the 70% foreseen by REFuelEU). We discussed in section 2.2 that delivering the capacity rollout required for REFuelEU will already be difficult. It is quite likely that there will end up being competition between nations and airlines for available volumes of alternative aviation fuels, and that this will drive up the price of alternative aviation fuels during parts of the transition, further burdening aviation users.

4.2 Direct air capture

Carbon dioxide is not only a climate pollutant; it is also an input for the production of e-fuels. Carbon from CO_2 is chemically combined with hydrogen from electrolysis to produce synthetic hydrocarbons. For now it should be fairly obvious that excess CO_2 is not a resource that is in immediate danger of running out, but in the longer term as the world goes toward net zero CO_2 emissions there will be fewer and fewer CO_2 generating processes remaining, and the

CO_2 from biomass and from processes that cannot be readily eliminated from the economy will be in demand for synthetic fuels, synthetic chemicals and for capture and storage. It has therefore been argued that it is important that e-fuel production should shift over time from using point source CO_2 to CO_2 captured directly from the atmosphere – EU rules for e-fuels currently require that after 2040 the CO_2 must be from direct air capture (DAC) or from biomass combustion.

The downside of the use of DAC CO_2 is that because the concentration of CO_2 in the air is much lower than in various industrial flue gases, producing a pure CO_2 stream by DAC will always be more energy intensive and therefore expensive than capturing point source carbon. Malins (2017b) suggests a mid-range cost of between 10 and 50 € per tCO_2 for various industrial streams (streams that are already more concentrated and less contaminated are cheaper to capture and concentrate), versus a mid-range cost of 140 € per tCO_2 for DAC. Similarly, IPCC (2022) suggests a potential DAC cost range of 100-300 € per tCO_2 and Williams (2022) suggests a cost between 137 and 412 € per tCO_2. The use of DAC CO_2 could make a significant difference to the cost of e-fuels, depending on how the costs of DAC evolve. For example, Schmidt et al. (2016) estimate that using DAC instead of point source CO_2 could add nearly 500 € per toe to the cost of produced e-fuels, a significant difference. Like electrolysis, the main long-term cost for DAC will be the cost of energy, and therefore in a world where e-fuel plants are able to source electricity cheaply they will also be able to reduce the costs of DAC CO_2 capture – and conversely if e-fuel producers are unable to access low prices for electricity, the cost difference between DAC and point source carbon will remain more significant.

4.3 CCU versus CCS

The production of e-fuels for aviation or on-road use is a form of ‘carbon capture and utilisation’ – CO_2 captured from an industrial source, from biomass or from the atmosphere is reacted with hydrogen produced by electrolysers to produce hydrocarbon molecules which will mostly be burned rather than stored. Creating a large-scale e-fuels industry therefore requires not only developing fuel synthesis capacity and electrolysis capacity but also carbon capture capacity. An obvious question that arises when we recognise carbon capture as the first step in e-fuel production is whether carbon capture and *utilisation* actually delivers any benefit compared to carbon capture and *storage*.

Mathematically speaking, the implications for atmospheric CO_2 levels are similar whether a given amount of captured CO_2 is used via e-fuel production to avoid the release of fossil carbon into the atmosphere or whether that amount of CO_2 is injected underground for permanent CO_2 storage. This is illustrated schematically in Figure 6.

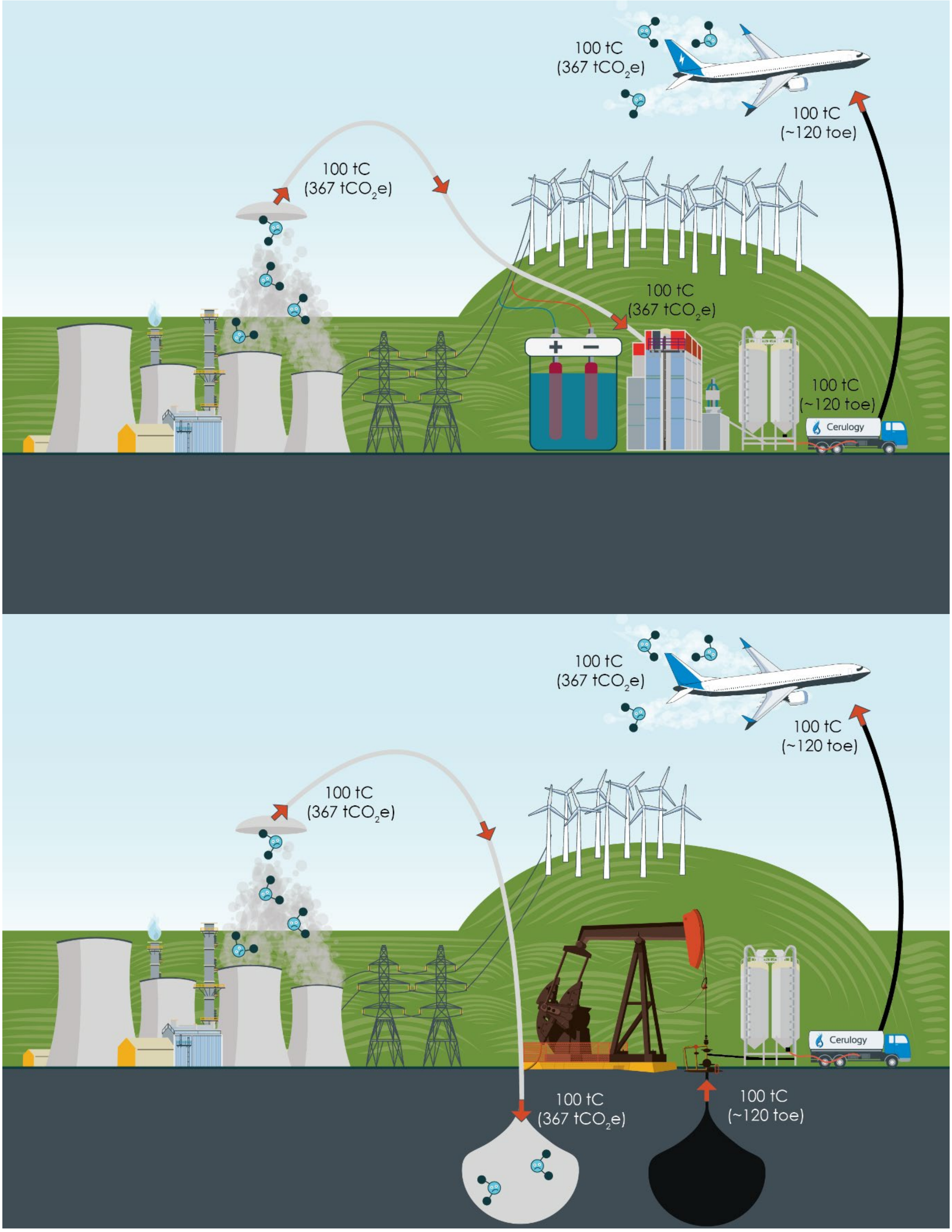

Figure 6 **Schematic of carbon flows for e-fuels (top) and fossil jet fuel with CCS (bottom)**

Note: this schematic is simplified and ignores CO_2 leakage, carbon in co-products, difference in carbon:hydrogen between crude oil and jet fuel, and CO_2 from process energy.

In the first case, the e-fuels case, captured carbon is used to produce fuels and is then re-emitted, with no net change in CO_2 in the atmosphere, and no use of fossil carbon. In the second case, the CCS case, fossil carbon is used to produce conventional jet fuel leading to CO_2 being released into the atmosphere, but this is exactly offset by capturing an equivalent amount of carbon from the atmosphere and injecting it underground. In both systems power is needed for carbon capture, but in the e-fuel system a much larger amount of power is needed for electrolysis, whereas the energy in the fossil jet fuel comes from oil. While oil extraction and refining require some energy input, it is much less than is required to produce renewable hydrogen by electrolysis.

The conventional jet fuel production system certainly has some downsides. Oil extraction is clearly associated with a number of potential environmental issues at the point of extraction, and oil refining is associated with local air pollution. Fossil jet fuel also has a higher sulphur content than e-fuel as discussed in section 3, and the aromatics in conventional jet fuel are associated with induced cloudiness. In principle, however, these problems could be addressed at the oil refinery. The technology exists to remove most of the sulphur from jet fuel (the regulatory limits on sulphur in road fuels are currently much tighter), and it would be possible to add additional processes to reduce aromatics content. Even adding these additional processing steps, the amount of heat and power required to process the fossil fuel would be much less than the amount of power needed to produce the e-fuel. There are also questions about the delivery of permanent CO_2 storage, whether there is a risk of leakage and what the full cost of injection and storage will be.

The downside of the e-fuel production system is cost. Both approaches need to add new carbon capture capacity (whether from point sources or using direct air capture), but the oil extraction and refining infrastructure is largely already in place while the electrolysers and fuel synthesis units for e-fuels would need to be built new. Because of the cost of all the extra electricity, the operational cost of e-fuel production is much higher than the cost of producing oil and refining it into jet fuel.

If there are two options that would deliver the same net CO_2 emissions outcome, and one is significantly cheaper and allows existing facilities to be utilised and existing jobs to be retained, it seems reasonable to assume that there will be voices advocating to go with the cheaper option. At present, this option of using CCS to offset the emissions from conventional aviation fuel is firmly in the background. The environmental community is understandably cautious of supporting an option that would extend the life of the fossil fuel industry that has been responsible for much of the climate change problem. Airlines see alternative fuels as a way to deliver emissions reductions that can be characterised as ‘in-sector’ and that will seem more credible to the public than paying for CCS elsewhere. The development of the CCS industry has certainly not been characterised by runaway success, and governments are probably cautious of relying on CCS to meet their climate goals any more than they need to. Nevertheless, while the aviation industry is happy to talk about alternative fuels, the instrument that supports alternative fuel use at the ICAO level is CORSIA – which is explicitly an offsetting scheme. The only reason that airlines are not already using CCS offsets to meet their CORSIA obligations is that far cheaper credits are available from other types of project! It would be unsurprising if, as the cost of alternative fuel mandates starts to bite, some airlines start questioning whether a full switch to alternative fuels is really the best way to manage aviation’s net CO_2 emissions.

4.4 Socialising costs?

Aviation use is not equally distributed in society. Despite the increase in the availability of low-cost flights over recent years, the overwhelming majority of flights by UK citizens are taken by people in relatively wealthy households. Research by Büchs & Mattioli (2021) using data from the 'Living Costs and Food Survey' (2006 to 2018, excluding business travel[44]) found that 72% of UK households in the top income decile take at least one flight a year, while this number is only 18% for the lowest income decile. The average person in the lowest decile takes one non-business flight every three years while the average person in the top decile takes a non-business flight every five months. Overall, households in the top income quintile are responsible for seven times more flights than households in the bottom income quintile (42% versus 6% of total flights). The Gini index[45] for the distribution of flights by UK households was calculated at about 73% – if a country had its wealth distributed like use of aviation is distributed among UK households then it would be the most unequal country in the world. Access to aviation in the UK has become more equal over the last twenty years, but only slightly – the Gini index in 2001 was 76%. Similarly, analysis from France has shown people from wealthier households are more likely to take longer flights (Demoli & Subtil, 2019), implying that there is even more inequality in consumption of aviation fuel than in number of flights taken.

None of this should be particularly surprising – many people still understand flying on holiday to be a luxury – unless you were to spend a lot of time listening to representatives of the aviation industry arguing that any measures to manage aviation demand growth are intrinsically unfair. It is not at all unusual at conferences discussing aviation decarbonisation to hear people waxing lyrical about how aviation growth will allow people to fly who have never flown before, allow greater connectivity for poor families living spread out across island nations, that it is ethically outrageous for wealthy people in the west to consider a measure that could prevent new entrants to the middle classes in the developing world from flying on their first foreign holiday. There is a kernel of truth to these claims. Increasing the cost of aviation, or reducing access to aviation, would inevitably affect some less wealthy travellers. Certainly the middle classes are expanding in many less wealthy nations and some of these people will start to use flights. The rate of aviation growth is faster in Asia Pacific than in Europe or North America[46]; but aviation use is still growing in Europe, and the high growth scenario from Eurocontrol (Figure 7) is based on 1.8% annual growth to 2050[47] while the UK government assumes 53% growth in passenger numbers between 2023 and 2050 in the 'high-SAF' scenario of the Jet Zero analysis. The broader truth, however, is that increases in the cost of aviation would be overwhelmingly borne by wealthier people and by frequent travellers. In terms of imposing climate change related costs on the population, charges on aviation are one of the more naturally progressive measures you could imagine – and that's before you start thinking of options like frequent flyer levies that target costs towards the regular fliers, and introducing growth management measures in regions that already have higher rates of aviation access first.

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[44] We exclude business travel from the discussion of equity of access to aviation, as in general business travel is presumed to be considered necessary for business reasons rather than a 'perk' to employees.

[45] The Gini index is a measure of inequality.

[46] https://www.aviationbusinessnews.com/low-cost/asia-pacific-region-airline-activity-aviation/

[47] About half the global average.

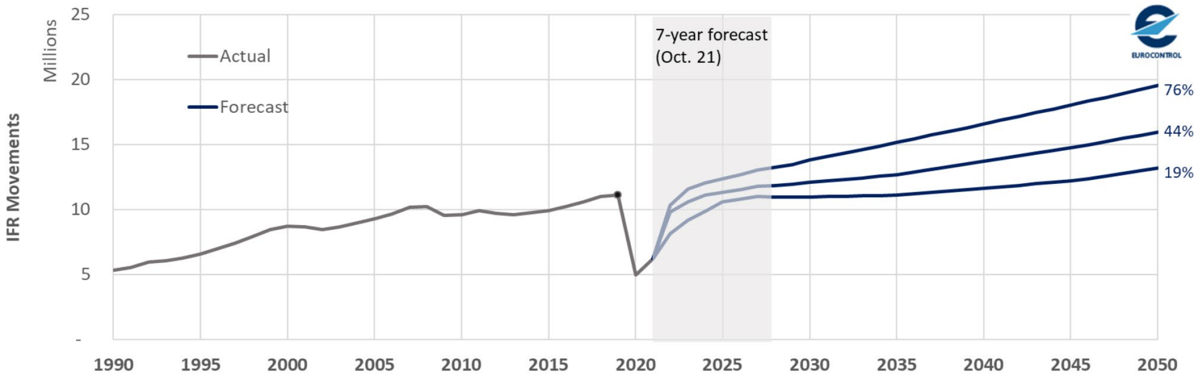

Figure 7 **Scenarios for European aviation growth to 2050**

Source: Eurocontrol

This context is important, because as part of the energy transition government policies will be introduced that impose costs on polluting sectors at various rates, with a mix of complementary policy support being offered and additional charges being borne. Both the UK and the EU have adopted the 'polluter pays' principle in environmental governance, which says that all things being equal the costs of pollution should be imposed on those who cause the pollution[48], but this is not likely to stop some polluters in every sector from arguing that the costs imposed on them for their GHG emissions should be minimised.

The aviation industry is certainly not above this, and up until now the airlines have been successful at allowing most of the costs of alternative aviation fuel deployment to be borne by others (primarily drivers and other users of road transport, and taxpayers). Existing alternative fuel mandates impose obligations on road transport fuel suppliers, and therefore costs on road fuel consumers, but have allowed alternative fuel use in aviation to generate credits. The CORSIA scheme introduced by ICAO allows airlines to register GHG reductions from alternative fuel use, but as an option alongside offsets rather than as an obligation. This means that airlines have been able in principle to supply alternative aviation fuels that are paid for by road users, and then count the GHG reductions against their CORSIA obligations.

Even if obligations are to be imposed on aviation through mechanisms like the UK alternative aviation fuel mandate and REFuelEU, we can expect continued enthusiasm from airlines for costs to be defrayed by the taxpayer wherever possible. Both the UK and EU offer grant funding for alternative fuel production projects; potential producers of e-fuels for aviation have criticised the idea that they should be made to pay for the deployment of the renewable electricity capacity that they need; aviation fuel is still not taxed like road fuel[49]; in the UK, the New Report (New, 2023) discusses the possibility of supporting e-fuel production by socialising grid connection costs. While the industry has accepted that it is not politically sustainable for the full cost of alternative aviation fuels to be passed on to either road users or taxpayers, it is keen to find ways to minimise the additional costs it faces. For example, the New Report notes

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[48] In the case of aviation, those causing the pollution are the airlines and passengers.

[49] https://www.transportenvironment.org/discover/taxing-kerosene-on-flights-could-raise-6-7-billion-a-year-for-the-treasury/

that the aviation industry is keen for ETS revenues from reduced allocation of free allowances to aviation to be recycled to support aviation alternative fuel projects.

> *"The aviation sector argues strongly that ETS revenues (from reducing free allocation for the aviation industry) will create a new revenue stream that should be used to underwrite a price stability mechanism – the EU has signalled a willingness to utilise aviation ETS revenues to support SAF."*

Parts of the aviation industry seem to feel entitled to, rather than grateful for, governmental support to help it maintain its social licence to operate. At the end of 2022 the Director General of IATA stated that "Given the billions of dollars being spent by the airline industry on Sustainable Aviation Fuels, offsetting, and other decarbonization initiatives, we have no reason to hesitate in calling out governments when they fail to take action to significantly reduce aviation emissions." It turns out that 'failing to take action' meant that governments were considering actions to significantly reduce aviation emissions that he didn't agree with but that the EU had failed to adopt the Single European Sky. This is a policy that has some co-benefits in terms of reduced operational emissions but that is primarily intended to allow Europe "to cope with sustained air traffic growth".

Just as the aviation industry has long fought against fuel taxation and is now fighting against the narrative that demand management may be necessary, we can safely assume that as the costs of alternative aviation fuel deployment start to mount we will start to hear pleas for volume ramp-up to be delayed until costs can be brought further down, or for new forms of government subsidy to reduce the impact on passengers. . As this new phase of the discussion becomes active, it would be pertinent to bear in mind that if the data in Büchs & Mattioli (2021) is broadly characteristic of Europe as a whole, then if the $22 billion of extra costs in 2050 we identified in section 4.1 were passed through in direct proportion to the money spent by each passenger, we would expect that at least $9 billion would be borne by the richest 10% of households, and less than $1.3 billion by the poorest 10%. If costs could be passed through differentially to different types of passenger this gap could be further widened.

4.5 Alternative investments

Delivering large volumes of alternative aviation fuel will require both large capital investments and significant increases in operational costs for fuel production. In section 4.3 we discussed whether there might be an economic case to focus on CCS-based offsets rather than on alternative fuels. We might also ask whether investment could or should be focused on delivering more fundamental changes to aviation rather than on delivering fuel production capacity. As noted above, the REFuelEU trajectory implies about $31 billion of capital expenditure on fuel infrastructure between now and 2050. How would this amount compare to the potential costs of developing new more efficient airliners, or of hydrogen or electric planes?

We can consider some examples for the development of recent commercial aircraft.[50] The Boeing 787 Dreamliner project had a budget of $5.5 billion but cost $22 billion. The Airbus 350 had a budget of $5.3 billion and cost $10 billion. The Airbus 380 had a budget of $11.3 billion but cost $34 billion. These were all major airframe launches, but none included a truly innovative new aerodynamic design. We might therefore conclude that moving $30 billion

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[50] See https://simpleflying.com/modern-airliners-development-cycle-cost-guide/

from fuel capacity to airframe development should allow the design of at least one new commercial airliner, but possibly not one with a revolutionary new aerodynamic design. We also note in passing that while $30 billion sounds like, and is, a lot of money, it is also significantly below a current estimate for the cost of building a high-speed railway from London to Manchester[51].

While the capital budget for REFuelEU probably would not be enough to revolutionise flying, there is a key difference between alternative fuels and more efficient airframes (or indeed electric or hydrogen powered aircraft) which is that alternative fuels are expected to increase operating costs, but more efficient aircraft would reduce them. It may be more useful therefore to think about the full additional costs of alternative fuel use rather than only the capital expenditures. Using the fuel deployment model calibrated to REFuelEU assumptions (as described in section 2.2) and the McKinsey costs[52] we estimate a potential cumulative cost for alternative fuel use of about $260 billion by 2050. This uses the relatively low electricity costs assumed by McKinsey – for a static electricity price, the cumulative cost would increase by up to a further $100 billion.

These cumulative total cost numbers are on a scale that might be capable of delivering genuinely new ways of flying (or a railway line from London to Aberdeen). It is certainly worth asking before the alternative aviation fuel revolution really gets going whether there could be better ways to expend the very significant resources involved.

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[51] Cf. https://en.wikipedia.org/wiki/High_Speed_2

[52] And ignoring any reduction in aviation activity due to higher costs.

5 Are alternative fuels the future for aviation?

In his report on developing a sustainable aviation fuel industry for the UK, Philip New observes that,

> *"The enthusiasm for SAF extends across the stakeholder community to an extent not seen by the author in other aspects of the energy transition. It offers a clear opportunity for leverage that should not be wasted."*

There is currently much enthusiasm for alternative aviation fuels, seen as an opportunity to green an otherwise deeply problematic industry and also a driver to finally kick start the development of an advanced renewable fuels industry that has been stalled for many years. Arrayed against the (relatively) united community that wants alternative aviation fuel mandates to work are two fundamental challenges: cost and the possibility of project failures.

The first of these, cost, is a problem for the obvious reason – the enthusiasm of the aviation industry and of politicians for alternative aviation fuels may start to wane in the face of sustained high costs for alternative fuel supply, especially as the volumes mandated go from small, to modest, to significant, to representing a meaningful chunk of the overall market. It is the opinion of this author that there are (at least) two constituencies currently supportive of alternative fuels in the aviation industry. One is genuinely committed to delivering decarbonisation and has identified alternative fuels as a way to do that. The other is committed only to defending sales and growth and has identified alternative fuels as something that can be identified today as a future solution to their climate change problem, but that requires them to do very little now. The first constituency should be willing to keep supporting alternative fuels even if costs remain relatively high (as many analysts expect), and will be focused on fuels with real long-term potential. The second constituency is likely to pivot from supporting the principle of alternative fuel deployment to opposing the reality of alternative fuel mandates as costs start to increase – one might expect to hear arguments about allowing more time for technologies to develop, about the need for government support for a financially struggling industry, about the need to lower targets if roll-out is delayed; and if food-based HEFA fuels are cheaper than the more sustainable options, it would be unsurprising to see a renewed push to reopen EU and UK alternative aviation fuel markets to food-based fuels. The higher the costs remain, the more vociferous we can expect this second constituency to become. If the first constituency dominates the market then continued mandates will have a lot of momentum, as it is much harder to argue a regulation is too costly when half of your competitors support it. If the second constituency turns out to be in the majority, it would not be surprising to see a partial reversal of the current drive for alternative fuel production.

At present, while a great deal of the buzz in the aviation industry is on aviation fuels, which are a high-cost option, the majority of the reportable decarbonisation that is actually being delivered is from more efficient planes and – in relation to net emissions – from offsetting[53]. With alternative fuels having a nominal cost of carbon abatement one, two or even three orders of magnitude higher than current offsetting measures, it would seem remarkable if there is not a

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[53] Though we note that there are questions around the robustness of some offsets.

renewed push at some point in the next ten to fifteen years to expand the role of offsets in aviation's long-term vision.

The second challenge identified above was project failures. These would be a problem because, despite extensive evidence that there is a high risk of project failure in the advanced alternative fuel industry, it can feel as if an optimistic community, and an ambitious policy framework, is not prepared for more disappointments. The analysis behind REFuelEU anticipates as few as 7 active advanced alternative aviation fuel plants supplying the EU in 2030. If two of the first three fail for any of the reasons that previous cellulosic biofuel projects have failed, it would set the industry back, make investors even more cautious, and seriously impact the potential to deliver 2030 targets and ambition. This said, we have argued in this report that the REFuelEU analysis probably understates the number of plants that would be needed to meet targets. The bad news is that getting 50 projects successfully greenlit and operational by 2030 sounds even harder than getting nine running, but the good news is that a few plant failures in a larger pool would not have such a fundamental impact on industry development. Still, the rate of plant deployment needed to meet the targets currently proposed is very rapid indeed by any historical standard, and it seems very likely that 2030 targets will not be fully met. If the rate of project deployment falls short of what is needed to meet targets, this implies political uncertainty – will it be considered politically acceptable to penalise aviation fuel suppliers heavily for not supplying fuels that are not being produced? For example, the REFuelEU framework includes requirements for penalties per volume of alternative fuel (per volume not supplied) that are at least twice the cost difference between alternative jet fuel and fossil jet fuel. In the case that the total alternative fuel production in 2030 falls well short of what is targeted then penalties would be applied on the resulting large deficits in alternative fuel supply – and the level of those penalties could be inflated when the price of alternative aviation fuel is pushed up by competition for a small available volume. If the EU has the willpower to stand by those penalties, they could be a powerful driver to invest in capacity. If fuel suppliers come to believe that penalties could be waived when policy makers are confronted with the reality of imposing large costs on airlines and passengers, the effectiveness of those penalties as a driver of action will be substantially reduced. In the past, advanced alternative fuel policies for road transport have often suffered from elements of poor design that have made them less effective as drivers of change (Malins, 2018). The UK in particular is now serious about designing policies that have a good chance of actually driving investment – for example, discussion of contract for difference approaches is positive, both because it seems like a potentially very effective tool to help investors manage uncertainty (cf. Calderbank & Malins, 2021) and because exploring these options is indicative of a more serious interest in good policy design, which has not always been apparent in policy making in this field.

It is clear that if availability of alternative aviation fuels is, for whichever reason, inadequate to the goals being set in current policies, then there will be even greater pressure for aviation to demonstrate reduced climate impact in other ways.

Aside from the question of whether a policy framework will be in place that is able to drive the targeted level of alternative aviation fuel production, there are also broader underlying questions:

- will the aviation industry really be able to achieve its aspiration to make it through the transition to a net zero economy with only minimal reduction in aviation demand growth?
- are the renewable resources that would need to be devoted to aviation in 2050 proportionate to the service that aviation provides?

We suspect that the answer to the first question is no – not only are the increased costs associated with alternative fuel use or other decarbonisation options likely to affect demand, but it is the opinion of the author that some form or forms of demand management in aviation will become politically inevitable as the transition progresses. Given the high climate impact and energy cost of aviation it would seem bizarre if the possibility of simply doing less of it does not gain increasing traction as a policy option. The UK Climate Change Committee has argued that, "Demand management policy should be implemented, as given expected developments in efficiency and SAF deployment, demand growth will need to be lower than baseline assumptions, and likely constrained to 25% growth by 2050 from 2018 levels for the sector to contribute to UK Net Zero" (CCC, 2020a). We would expect that an increasing focus on non-CO_2 climate impacts from aviation will only strengthen the push for measures that directly target demand. This further raises the political question of whether industry enthusiasm for alternative fuels will diminish if the discourse moves from 'alternative aviation fuels *instead of* demand management' to 'alternative aviation fuels *and* demand management'!

As to whether the resources needed to run aviation on renewable fuels are proportionate – it is clear that these resources are very significant and that there is an opportunity cost implied in devoting renewable resources to delivering aviation decarbonisation that could be used elsewhere in the economy. Becken et al. (2023) argues that, "The scaling up of SAF to not only maintain but grow global aviation is problematic as it competes for land needed for nature-based carbon removal, clean energy that could more effectively decarbonise other sectors, and captured CO_2 to be stored permanently," and goes further by arguing that due to this competition, "SAF production undermines global goals of limiting warming to 1.5 °C; a conflict that is neither recognised in the roadmaps nor in the public debate."

We showed above that making even a modest inroad into UK aviation fuel demand using e-fuels would take as much electricity as is currently consumed by about 12 million homes. If we were to go further and think about fuelling the whole of UK aviation in 2050 with e-fuels it would take an amount of electricity roughly equivalent to two thirds of total current UK electricity consumption. People certainly like going on holiday, and business benefits from face-to-face interactions, but that sounds like an awful lot of energy for a service that most people in the UK use only once or twice a year.

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