Cerulogy

SAFty in numbers

Considerations for setting a 2030 greenhouse gas intensity target to bring alternative fuels to EU aviation

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1. Context

As part of the Green Deal, the European Commission has launched the "ReFuelEU Aviation Initiative" to increase the role of "sustainable aviation fuels" (SAF) in EU aviation, as a way to reduce the climate impact of the aviation sector. The background paper for the second virtual roundtable on ReFuelEU (European Commission, 2020b) discusses the introduction of either a volume-based or GHG-intensity-reduction-based target for SAF use. This report discusses the potential supply of different SAF categories in 2030, and what might be required to deliver a rapid supply expansion. This includes presenting results from a simple bottom-up SAF production model. Based on these potential supply volumes we discuss what an ambitious but potentially achievable level might be for a GHG intensity reduction target for 2030 aviation fuel.

2. Potential supply

2.1. SAF technologies

The technologies to produce SAF can be broadly split into four categories. The most mature technology pathway in terms of commercial production is HEFA (Hydrotreated Esters and Fatty Acids). HEFA fuels are produced by hydrotreating of vegetable oils or animal fats. These might be 'virgin' vegetable oils from crops such as rapeseed, soy or palm or by-products/residues/wastes such as used cooking oil. Both crop-based and residue-based pathways are supported by the RED, but the support is greater for waste or residue feedstocks that are listed in Annex IX of the Directive. This includes used cooking oil and animal fats, which are listed in part B of the Annex, and some oily materials such as tall oil and oil reclaimed from palm oil mill effluent that are listed in part A of the Annex.

The capacity for vegetable oil hydrotreating has grown rapidly in the past decade with large capacity expansions planned for the coming years in Europe and beyond, though to date the main fuel produced at these plants has been renewable diesel for on-road use. Sustainable Aviation 2020) reports that as of 2018 there was already 6.5 million tonnes of vegetable oil hydrotreating capacity globally. Currently most of this capacity is optimised for renewable diesel production, but the renewable diesel process is similar to the HEFA production process, and in principle renewable diesel facilities could be retrofitted to support upgrading of a larger fraction of output fuel to meet synthetic jet fuel specifications. It would therefore be possible to mobilise significant volumes of HEFA jet fuel relatively easily within the 2030 timeframe. According to NLR & SEO Amsterdam Economics (2021) Neste already has 100,000 tonnes of HEFA production capacity globally, while Prussi et al. (2019) identifies 2.4 million tonnes of hydrotreating capacity in Europe and estimates that 360 thousand tonnes of this capacity is already able to produce HEFA.

The drawback of the HEFA technology is that it relies on relatively high value resources (oils and fats) that are generally already being productively used. This applies not only to food grade oils, but in many cases even to lower quality by-product oils including material that might be considered as waste. For example, in the EU used cooking oil is mostly processed into biodiesel. Expanding HEFA production would therefore mean some combination of reducing the supply of on-road biofuels, reducing the availability of oils and fats for applications including food, animal feed and oleochemicals, and expanding oil crop production with associated land use change issues (Malins et al., 2014; cf. Malins, 2017a). The net climate benefits of redirecting waste vegetable oils to aviation fuel use, and the long-term potential of HEFA as a climate solution for aviation, are therefore limited.

The second category of fuel pathways can be grouped as biomass-to-liquids (BtL). Biomass-to-liquids technologies allow a broader range of biomass including cellulosic and ligno-cellulosic materials to be converted into fuel, rather than being restricted to oils and fats that already have fuel-like properties. The main processes being considered in this category are thermochemical, meaning that they involve using heat to break down biomass molecules and catalytic processes to synthesise fuels. The two most developed approaches are using gasification to produce syngas from cellulosic biomass followed by fuel synthesis by the Fischer-Tropsch process, and using pyrolysis to produce low quality oils from cellulosic biomass followed by upgrading to transport fuels, though other technologies (for instance using hydrothermal liquefaction) are under development (U.S. Department of Energy, 2020). To the best of our knowledge there is not yet any commercially operating plant producing SAF with these technologies. While these approaches are less commercially developed than the HEFA process, they have more potential to be delivered sustainably and have much more potential scalability in the longer term. This is because the potential sustainable supply of cellulosic material is much larger than the potential sustainable supply of oils and fats.

The third category of technologies involves synthesis of hydrocarbons using biochemical approaches from some intermediate molecule – more feedstock flexible than HEFA production, but less flexible than the thermochemical technologies. This includes alcohol-to-jet processes to turn ethanol and isobutanol into jet fuel and the ‘SIP’ (hydroprocessed fermented sugar-synthetic iso-paraffins) process to produce jet fuel from sugar molecules. If the sugars or alcohols being processed are based on food crops, then these technologies raise some of the same sustainability issues as HEFA production. If the sugars or alcohols are themselves produced from cellulosic biomass or other low-value waste or residual material, then these pathways have similar sustainability characteristics to the thermochemical pathways. These pathways are currently projected to be relatively high cost to operate (Pavlenko et al., 2019).

The fourth category of technology is referred to as ‘power-to-liquids’ (PtL), e-fuels or RFNBOs (renewable fuels of non-biological origin). In these processes, fuel is synthesised using hydrogen produced by electrolysis, for example using the Fischer-Tropsch process. If the electricity for the system comes from renewable sources these fuels can have a very low GHG intensity. These technologies are also not currently implemented at commercial scale. PtL technologies are generally expected to be more expensive in the near -term than either the HEFA or thermo-chemical pathways, largely because of the cost of sourcing electricity (Malins, 2017b; NLR & SEO Amsterdam Economics, 2021; Pavlenko et al., 2019).

2.2. Development to 2030

The future development of SAF capacity for the EU will be determined by the interaction between high-level policy and targets, the mechanisms used to implement those targets, the success (or lack thereof) of technology developers, and developments in other markets. It will also be dependent on which technologies and feedstocks the European Union and EU Member States make eligible to contribute towards achieving targets. The HEFA technology is the most prepared for expansion at commercial scale, and if HEFA fuel production is given equal incentivisation as other options under EU SAF policy it would be likely to dominate supply in the 2030 timeframe, both because the basic technology has been well demonstrated at commercial scale and because in the short term the levelised production costs for HEFA are likely to be lower than for other technologies (Bullerdiek et al., 2021; NLR & SEO Amsterdam Economics, 2021; Pavlenko et al., 2019).

The European Commission has previously indicated that growth in biofuel consumption should be met by non-food resources, and this is also Transport and Environment's policy position. Food resources are therefore not considered in this assessment. HEFA may also be produced from by-product or waste oils, in particular the used cooking oil and animal fats that are identified in Part B of Annex IX of the recast Renewable Energy Directive. O'Malley et al. (2021) estimates that if hydrotreating plants in the EU were optimised for jet fuel output then 1.5 million tonnes of HEFA jet fuel could be available per year by 2030. Similarly, NLR & SEO Amsterdam Economics (2021) considers supply of 1.4 million tonnes of HEFA in the EU in 2030. Note that the RED II caps the contribution to targets from Annex IX part B oils and fats at 1.7% of transport energy demand, although Member States have some leeway to raise that limit if additional resource is available. There are also some oil and fat resources that could be HEFA feedstocks listed in Annex IX Part A of the RED II, including oil recovered from palm oil mill effluent and some industrial waste oils.

It is Cerulogy's opinion that increasing the production of HEFA jet fuel at the expense of producing less renewable diesel does not provide support for the commercialisation of the technologies needed for the longer-term decarbonisation of the aviation fuel supply, and that including HEFA fuels within EU policy frameworks (such as any targets set under ReFuelEU) would undermine the investment signal for power-to-jet and biomass-to-jet technologies. For the rest of this report we therefore focus on the potential to deliver advanced biofuels from cellulosic and ligno-cellulosic materials, as well as e-fuels.

2.2.i) EU targets

Currently, the RED II includes a requirement for 3.5% of the road and rail transport energy consumed in the EU in 2030 to be "advanced" biofuels produced from renewable feedstocks listed in part A of Annex IX of the Directive. Member States are permitted to double-count energy from Annex IX feedstock towards compliance with this and other targets, so in practice this represents a requirement for 1.75% of physical energy to be from advanced biofuels from Annex IX part A. While Annex IX Part A does include some oils and fats as noted above, it is expected that this target must be primarily met using cellulosic and ligno-cellulosic feedstocks. Meeting this target will require up to 4.5 Mtoe[1] of fuels (if the roll-out of electric vehicles proceeds rapidly the greater efficiency of those vehicles will reduce total energy demand, and therefore reduce the absolute requirement for advanced biofuels). Depending on the technologies used, some of this volume could be produced as SAF.

The consultation on ReFuelEU (European Commission, 2020b) has suggested a potential

1 Million tonnes of oil equivalent.

2030 target for 5% of EU aviation fuel to be SAF (with a suggested split of 4.3% biofuel and 0.7% e-fuels). For this paper, we assume that 2030 jet fuel demand for the EU-27 will be about 54 Mtoe following the analysis presented by Bullerdiek et al. (2021), which includes a consideration of the impact of COVID-19 on aviation demand growth. For that level of total fuel consumption, a 5% target split in that way would require 2.7 Mtoe of SAF – 2.3 Mtoe of biofuels and 380 ktoe of PtL. We have assumed that the ReFuelEU target would be set as a physical fraction of jet fuel supplied within the EU, i.e. that the multipliers in RED II on the contribution of advanced renewable jet fuels would not be applied before assessing compliance with a ReFuelEU target. If the multipliers (double counting for fuels from Annex A feedstocks and a further 1.2 multiplier for jet fuel) were applied *before* assessing compliance with the ReFuelEU target, then the physical volume required would be reduced to 1.1 Mtoe.

These levels of mandated synthetic jet fuel supply are comparable to levels foreseen by policy scenarios in European Commission (2020a), in which the supply of PtL SAF ranges from about 400 ktoe to 1 Mtoe, and the supply of biofuel SAF ranges from about 850 ktoe to 3 Mtoe.

A number of previous studies (de Jong et al., 2018; NLR & SEO Amsterdam Economics, 2021; Sustainable Aviation, 2020) present scenarios under which such a target for ReFuelEU could be met. De Jong et al. (2018) shows cases with 2030 SAF consumption in the EU in the range 3.8 – 6.2 Mtoe (these scenarios rely primarily on HEFA and AtJ technologies). NLR & SEO Amsterdam Economics (2021) suggests a potential for 3.3 Mtoe SAF including 1.2 Mtoe of PtL SAF – though they estimate the levelised cost of PtL SAF at 3,000 €/toe. Assuming a fossil jet fuel price of 560 €/toe, the utilisation of that amount of PtL fuel would represent an additional cost of €3 billion per annum to airlines/passengers. Similarly, Sustainable Aviation (2020) estimates a maximum implied 2030 EU[2] SAF potential of about 3.4 Mtoe. This also includes a significant contribution from HEFA and is predicated on a rapid deployment of several advanced renewable fuel production technologies, all optimised for SAF production at the expense of road fuel yields.

2.2.ii) Capacity deployment model

In order to illustrate what might be required to deliver SAF at scale by 2030, a simple fuel production capacity deployment model has been developed to build a production scenario for 2020 to 2030. The model draws on analysis undertaken by E4tech to support the preparation of a UK Sustainable Aviation Fuels Road-Map (Sustainable Aviation, 2020).

This 'bottom-up' capacity deployment model estimates potential SAF (and other transport fuel) production volumes over time based on assumptions about the rate at which new production facilities may be constructed, their size and how quickly they may reach nameplate capacity. Production may then be summed across these hypothetical facilities, and assumptions made about the fraction of capacity that is utilised for SAF production. The modelling assumptions are detailed in Annex A. As discussed above, the reality of SAF deployment over the coming ten years will be determined by the policies in place and by unpredictable developments and setbacks with the various technologies. The modelling presented here is only a scenario, intended to give some basis to discuss what might be achievable with the correct policy support.

2 The roadmap reports UK potential as a population-based share of potential global production – we have calculated implied EU potential by multiplying the UK value up to correspond to the EU-27's population.

The modelled advanced renewable fuel supply to the EU market is shown by technology in Figure 1, reaching 3.6 Mtoe in 2030. This is based on a total of 134 commercial scale SAF-producing advanced renewable transport fuel plants operational globally by 2030 (Figure 2), and an assumption that two thirds of the fuel output goes to the EU market. The model includes no explicit consideration of where plants might be located. Seventeen of these are PtL plants. Deploying these new plants would require tens of billions of euros of investment. It should be recognised that this would represent an extremely rapid capacity expansion given the lack of existing commercial plants, with annual capacity growth of more than 50% still being delivered at the end of the decade. We believe that an exceptionally clear market signal would be required from EU policy makers for such a rate of deployment to be made a reality.

Biofuels account for 3.2 Mtoe, with a further 450 ktoe from e-fuel plants. If this level of drop-in biofuel production was delivered from Annex IX part A feedstock it would meet most of the advanced biofuel target under the RED II, although up to another1.3 Mtoe of production would still be required from cellulosic ethanol and other Annex IX part A fuels to fully deliver the target[3].

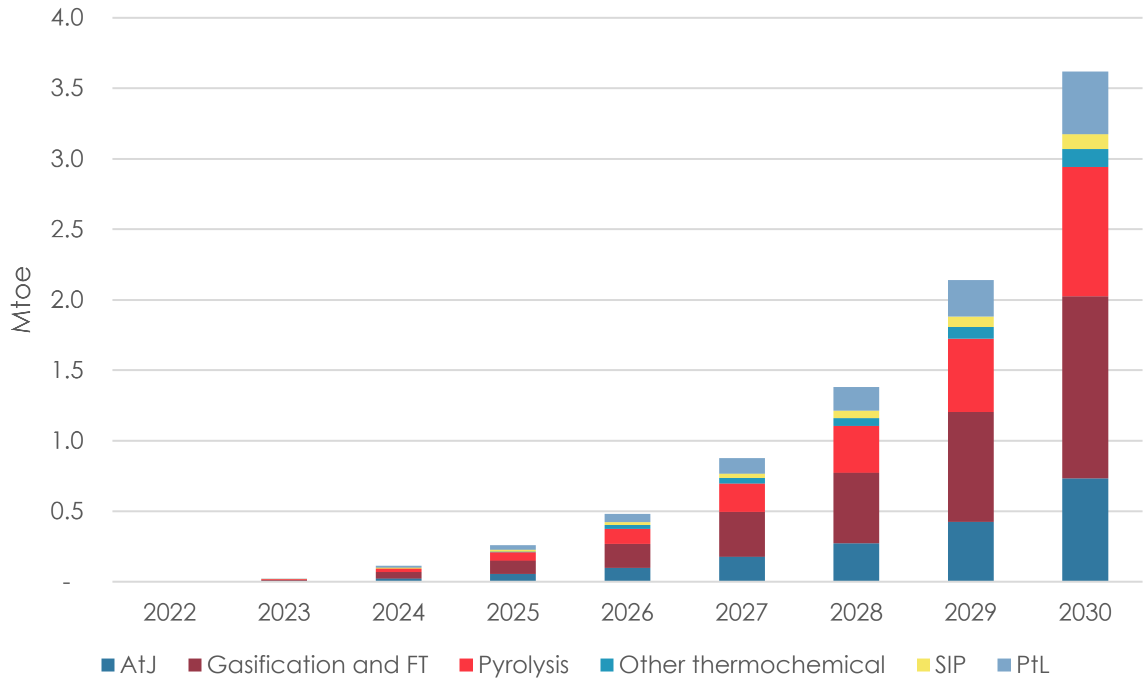

Figure 1. Modelled ramp up of advanced renewable fuel supply to the EU market

3 This could be from a combination of existing and new capacity.

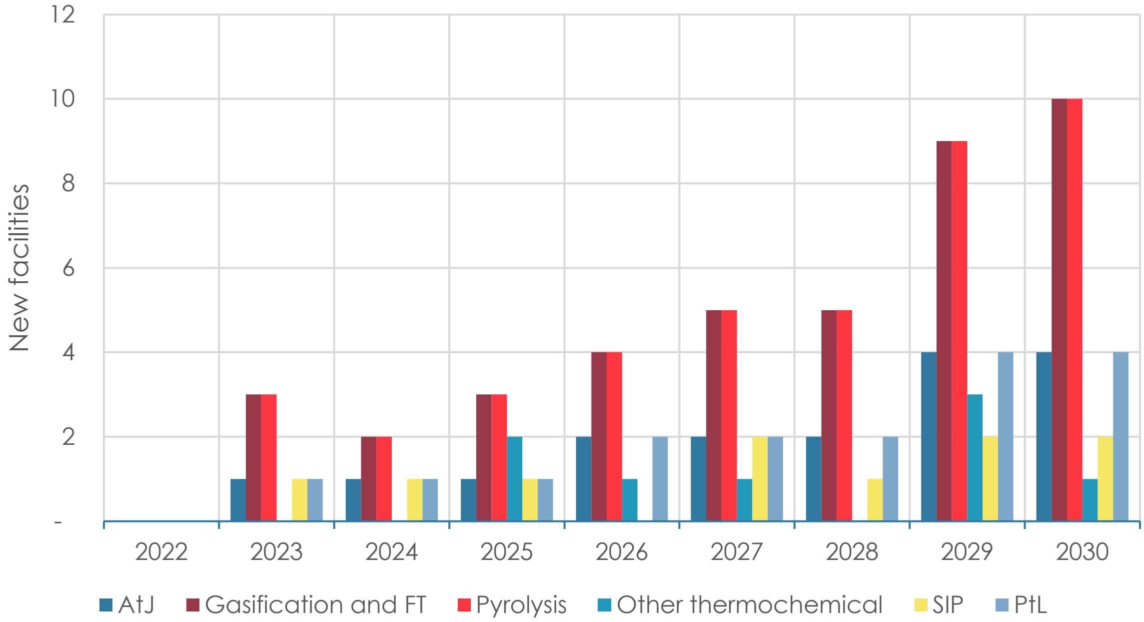

Figure 2. Number of new facilities entering operation each calendar year (global)

While delivering this amount of fuel would represent a major deployment challenge, the quantities of biomass feedstock required would be moderate compared to assessments of EU biomass availability. Delivering 3.2 Mtoe of BtL transport fuels would require of the order of 16 million tonnes of cellulosic biomass globally. This compares to an annual sustainable potential in the EU + UK of over 200 million tonnes, estimated by Harrison et al. (2014). The availability of sustainably sourced cellulosic feedstock is therefore unlikely to represent a constraint on advanced biofuel production in the 2030 timeframe.

Not all this drop-in fuel would be available to the aviation industry. Most drop-in fuel production processes produce a range of molecules, only some of which are suitable for upgrading to meet jet fuel specifications. Each plant has three basic options for SAF output[4]. Firstly, it could choose not to supply SAF at all, focusing on renewable diesel and gasoline. This is the case for most currently operating vegetable oil hydrotreating plants, which generally do not yet have the capacity to upgrade fuel to meet jet specifications. Secondly, it could add SAF upgrading capacity but optimise for total fuel production, rather than targeting SAF production. For most technologies, this might mean up to about a fifth of the output being supplied as SAF. Finally, it could maximise SAF production. SAF-optimised plants may be able to deliver 50% or more of total output as SAF, potentially at the expense of some reduction in overall production quantity.

4 Some plants may supply an intermediate synthetic crude product to existing refineries for upgrading rather than adding upgrading capacity on site, but the same basic options apply in such cases.

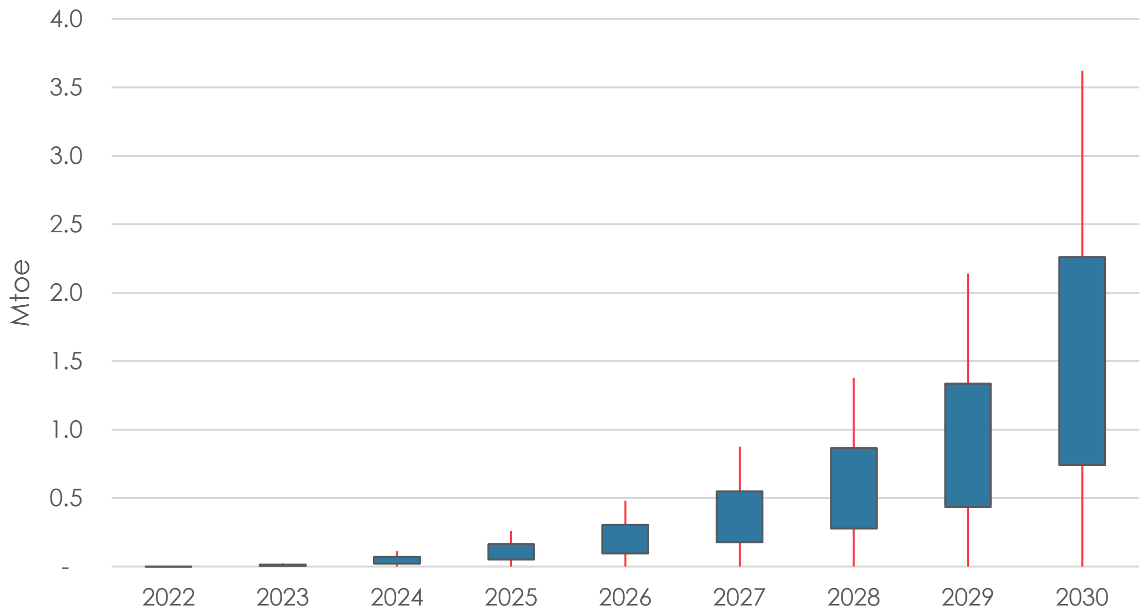

Figure 3. Potential range of SAF output. The box indicates the range between adding SAF production with total output optimisation and fully optimising for SAF. The red line shows total renewable fuel output.

For the total deployment modelled, annual SAF availability (assuming all plants have some SAF upgrading capacity) would be between 740 ktoe and 2.3 Mtoe (Figure 3). Of this, 90 ktoe to 220 ktoe is modelled as PtL SAF. Delivering the higher supply level of 2.3 Mtoe would require full optimisation for jet fuel output at all facilities modelled. Depending on the extent to which facilities were optimised for SAF output, this scenario would be enough to meet between a quarter and four fifths of the target of 5% SAF by volume that has been suggested for ReFuelEU.

2.2.iii) Accelerated PtL scenario

We were also asked by Transport and Environment to consider a scenario for a more rapid deployment of PtL SAF fuels, to explore what would be required to deliver 1% of total EU jet fuel as PtL SAF by 2030. This is about half as ambitious again as the 0.7% PtL SAF target suggested in the ReFuelEU consultation.

In our model, this could be delivered if the first commercial scale plant opens in September 2022, with eight plants becoming operational every year by the end of the decade. Assuming 50% jet fuel output, in 2030 the 37 plants globally would produce a total of 780 ktoe of PtL SAF, and we again assume two thirds of this would be available for supply to the EU market. This would give a total supply of PtL SAF in the EU market of 550 ktoe (Figure 4). Assumed typical plant capacity increases from 44 ktoe for the first few facilities built to 130 ktoe for new plants built from the end of 2029 onwards. Such an aggressive rate of PtL SAF deployment would be difficult to deliver, but with adequately strong government support it might be possible.

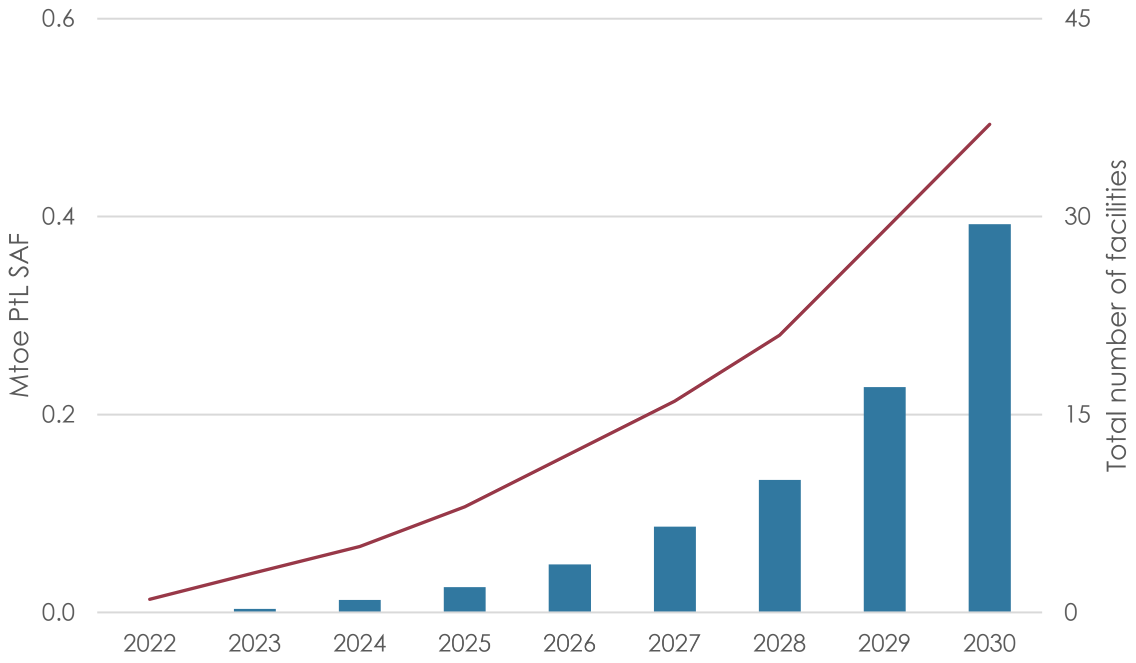

Figure 4. Growth in supply of PtL SAF to meet a target of 1% of EU jet fuel consumption in 2030 (bars, left axis) and associated number of operational commercial scale plants (line, right axis)

2.3. Setting a GHG intensity target for EU aviation fuel

While the potential 5% target for SAF use that has been suggested by the ReFuelEU initiative is framed in terms of supply volume[5], ReFuelEU has also discussed the possibility of setting a GHG intensity reduction target for aviation fuels. The advantage of a GHG intensity reduction target is that it can provide additional incentives for marginal improvements in the CO_2 efficiency of fuel production processes that are not provided by a volume target, and that it favours technologies able to deliver the lowest GHG intensity fuels.

Assuming that biofuel SAF is able to deliver an average reportable GHG emission reduction of 75% and that PtL SAF is able to deliver an average reportable GHG emission reduction of 95%, the level of deployment presented from the main modelling above would be consistent with a GHG-intensity reduction target for aviation in the range 1% to 3%. Of this, PtL SAF could deliver 0.1% to 0.4%. Within these ranges, an overall 2030 GHG reduction target of 2%, of which 0.25 percentage points must be met with PtL SAF, might be considered appropriately ambitious.

Cerulogy does not recommended that HEFA fuels should be included in a SAF target under the ReFuelEU, as at present HEFA producers could be expected to out-compete less mature technologies for market space. HEFA fuels for aviation are already supported through the RED

5 Given that all jet fuel has a similar energy density a 5% target by volume is more or less the same as a 5% target by energy.

II, and including HEFA within a target on an equal basis at this stage would therefore severely inhibit commercialisation of more sustainable and more scalable alternatives. If a political decision is made that HEFA fuels should be included, the assessment presented in O'Malley et al. (2021) suggests that they could contribute an additional 2% GHG intensity reduction.

Target setting for advanced renewable fuel production is an extremely difficult undertaking – a Goldilocks problem if you will (cf. Malins, 2018). Set targets too low and potential producers may not have confidence that they will be able to sell the fuel they produce – that would inhibit investment, and thereby create a self-fulfilling prophecy in which low targets are met with even lower achievement. Set targets too high and you risk creating political instability – if deployment immediately lags behind targets and the gap between the regulatory requirement and what is actually delivered grows wider and wider, producers may expect that targets will be amended down. The moment that producers lose confidence that a high target will be kept in place, it is little more use in driving investment than a low target. An example of the challenges that result from setting targets that are persistently unachieved can be seen in the U.S. Renewable Fuel Standard (RFS). An ambitious mandate for 60 billion litres of cellulosic biofuels was set for 2022, but the associated annual targets were systematically missed in the early years of the programme and now adjusted targets are announced each year. The adjusted target for cellulosic biofuel supply for 2021 is only 2.5 billion litres, and most of this will be met through biogas rather than the liquid cellulosic fuels that the program intended to support. In short, excessively ambitious targets can affect programme credibility and create political uncertainty. With several precedents for targets in advanced biofuels and SAF production being completely missed, that uncertainty can be a major barrier to investment.

Given the difficulty in finding the level to set targets so that they will effectively drive commercialisation of new technologies, we would encourage policy makers at both EU and Member State level, and stakeholders in the SAF community, to look for policy solutions to complement targets that provide the strongest possible value signal for investors. Examples of successful approaches from renewable electricity include feed-in tariffs and contracts-for-difference (cf. Calderbank & Malins, 2021).

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Annex A. Description of bottom-up model

The bottom-up model utilised here can be considered as a simplified version of the modelling framework by E4tech presented in Sustainable Aviation (2020). Seven SAF technologies are considered: alcohol to jet, aerobic fermentation, gasification with Fischer-Tropsch, fast pyrolysis with catalytic upgrading, aqueous phase reforming with catalytic upgrading, hydrothermal liquefaction with catalytic upgrading, and power to liquids. Each technology is associated with a set of parameters: the number of plants to be brought into operation per year once the N^{th} generation is reached; the assumed size of operational N^{th} generation plants; the assumed date for the first commercial scale plant to be brought into operation; and the assumed fraction of fuel output as SAF in moderate and high SAF yield cases.

The assumptions on number of plants per year are based on Sustainable Aviation (2020), with some adjustments (see Table 2). Compared to (Sustainable Aviation, 2020) the assumed rate of deployment of AtJ plants is reduced to reflect the potentially high cost of this technology, while the assumed rate of deployment of FT plants (both BtL and PtL) is slightly increased. Typical plant sizes are taken directly from Sustainable Aviation (2020). The date of opening for first commercial plants is set to 1 January 2023 for all technologies except those considered least technology ready (aqueous phase reforming and hydrothermal liquefaction) for which the first commercial plant opening is assumed to be 1 January 2025. Fractional SAF outputs are based directly on Sustainable Aviation (2020).

The model considers three 'generations' of facilities – 1^{st}, 2^{nd} and N^{th}. With each successive generation, the size of new facilities increases and the rate of new facility deployment increases. In the first generation, the deployment rate is assumed to be a quarter of the N^{th} generation rate and the capacity of facilities is assumed to be half the capacity of N^{th} generation facilities. In the second generation, deployment rate is assumed to be half that of N^{th} generation facilities, and capacities to be two thirds those of N^{th} generation facilities. The parameters used to describe this progression (date of first commercial plant, number of plants per year, size of plants are based on cross-referencing the assumptions documented in (Sustainable Aviation, 2020) with scenario assumptions from other available sources and with Cerulogy's expert judgement. After the first commercial plant opens the model assumes that additional facilities open at regular intervals determined by the technology parameters and the generation. The model does not allow for any plants to fail after becoming operational (although this has not been unusual for advanced biofuel plants in the past) and does not allow for a subset of the technology solutions considered to out-compete the rest.

In the model that producers (as a group) move to the next generation after three years of operational experience with at least one plant of the previous generation – so if the first plant enters operation in January 2023, any plants built after January 2026 would be considered 2^{nd} generation. If the first second generation plant enters operation in March 2023, then any plants entering operation after March 2026 would be considered N^{th} generation, and so on. Finally, after ten N^{th} generation plants have become operational it is assumed that typical capacities for new plants increase by a further 50% on top of the typical capacities suggested in (Sustainable Aviation, 2020).

It is assumed that two thirds of global SAF production is available to the EU market. This is based on the premise that the EU would provide the most appealing market for these fuels, but that strong market signals would also be available in at least North America. The actual rate of global deployment of SAF capacity will be very sensitive to the strength of the policy support available globally, and of course the actual fraction of that fuel consumed in the EU will be determined by a comparison between the value proposition available in the EU (and indeed in specific EU Member States) versus that available from other local SAF policies.

The results are not intended to be taken as predictive. Rather, the assessment presented here provides an indication of what might be possible in the period to 2030, and of what might be needed to deliver it. We believe that the scenario we have constructed would represent an exceedingly successful rollout of SAF technology. Given previous false starts in advanced biofuel deployment, and that significant technology challenges remain before successful commercialisation is delivered, we would recommend readers to treat this scenario as an upper bound on what is likely to be achieved in practice.

Table 1. Key model parameters

Technology	First plant	PPY (Nth generation)	Nth generation plant size (ktoe per year)	Jet output (optimised for total fuel output)	Jet output (optimised for jet output)
AtJ	01/01/2023	4	146	25%	90%
APR with catalytic upgrading	01/01/2025	1	105	20%	60%
Aerobic fermentation	01/01/2023	3	44	0%	100%
Gasification with Fischer-Tropsch	01/01/2023	10	90	20%	50%
Fast pyrolysis with catalytic upgrading	01/01/2023	10	66	20%	60%
HTL with catalytic upgrading	01/01/2025	3	57	20%	60%
Power to Liquid: Fischer-Tropsch	01/01/2023	4	89	20%	50%