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Estimating sustainable aviation fuel feedstock availability to meet growing European Union demand

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Summary

If the European Union aviation industry is to meet its long-term goal of decarbonization without curbing traffic growth or relying on out-of-sector carbon offsets, switching to sustainable aviation fuels (SAFs) is one of the few methods of achieving in-sector greenhouse gas (GHG) reductions. Though previous, transport-wide EU fuel policies have done little to stimulate the development of the SAF industry, the recently proposed ReFuel EU initiative could set a clear policy signal for the introduction and expansion of an advanced-only SAF industry producing ultra-low carbon fuels. However, it is critical that policymakers set realistic SAF deployment goals that match the amount of fuel that could be made from available feedstock. This study evaluates the EU resource base to support SAF production from 2025 to 2035, focusing only on the potential volumes available from sustainably available feedstocks.

Without taking into account the political or economic barriers to SAF production, we estimate that there is a sufficient resource base to support approximately 3.4 million tonnes (Mt) of advanced SAF production annually, or 5.5% of projected EU jet fuel demand in 2030. The estimated production potential takes into account feedstock availability, sustainable harvesting limits, existing other uses of those materials, and SAF conversion yields. This assessment does not factor in the economic incentives necessary to drive that level of market demand or to mobilize investment in new biorefineries.-

The commercialization of SAF depends on many factors beyond the resource base for SAF production. Currently, even with some incentives and targeted support in place, SAF production covers less than 0.05% of global jet fuel demand. While producing SAF from waste oils is the most technically mature SAF conversion pathway, waste oils are highly resource-constrained and are already largely consumed by the road sector. High near-term targets for SAF blending may only incentivize the diversion of waste oils from existing uses in the road sector, approaching approximately 2% of 2030 jet fuel demand from waste oil alone. Moving beyond 2% of SAF deployment will require targeted support for more conversion pathways with more challenging economics and uncertain production timelines. To achieve long-term success for the advanced SAF industry, the

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ReFuel EU initiative must first lay the groundwork for these pathways through targeted incentives for individual projects before laying out a sector-wide blending target.

Introduction

As part of the Green Deal framework, the ReFuel EU initiative announced in 2020 is intended to reduce the environmental footprint of the EU aviation sector by building supply and demand for sustainable aviation fuels (SAFs) (European Commission, n.d.). Significant technological barriers to electrification make fuel-switching one of the only methods of reducing aviation GHG emissions without curbing demand. While first-generation biofuels made from food crops account for about 5% of EU road sector fuel consumption and more than 15 billion liters of annual production, the sustainability of these fuels has also been called into question because of high indirect land use change (ILUC) emissions (Valin et al., 2015) and displacement effects across use in other industries (Searle, Pavlenko, Takriti, & Bitnere, 2017). While SAFs made up only 0.05% of global jet fuel consumption in 2019 (European Commission, n.d.), it is possible that their use could expand over the next decade through expanded policy support.

Deploying SAFs requires overcoming even greater economic and technological constraints than deploying alternative fuels to the road sector. SAF pathways require additional testing and certification to demonstrate their safety before commercial use, adding to the expense and difficulty of their commercialization relative to road fuels. Petroleum jet fuel has lower GHG emissions and a lower price than petroleum diesel, making the uptake of alternative fuels costlier on a per-tonne carbon dioxide equivalent basis in aviation than in the road sector. In addition, modifying biorefineries with a mixed product slate to produce a greater share of SAF in place of diesel would be less efficient (Pavlenko, Searle, & Christiansen, 2019). While petroleum refiners have had mandates to blend biofuels in the road sector in the United States and the European Union for more than a decade, there has not been a corresponding policy to spur aviation fuel demand. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the international aviation industry's contribution to the Paris Agreement, is primarily viewed as a carbon offsetting plan rather than one that will promote SAFs (IATA, 2019).

As of 2019, the vast majority of biofuel production in the European Union comes from first-generation, food-based biofuel (Phillips, Flach, Lieberz, & Bolla, 2019). This includes rapeseed, soy, and palm oils as well as wheat, maize, and sugar beet, which are relatively easy to convert using first-generation biofuel production processes. However, the European Union is increasingly supportive of transitioning away from food-based biofuels. Policymakers introduced a cap on the contribution of these fuels to the transport-sector target within the recast Renewable Energy Directive (RED II) and have suggested that policy support within ReFuel EU focus on promoting advanced fuels. These include biofuels produced from feedstocks largely defined in Annex IX of the RED II: primarily lignocellulosic byproducts, wastes, and residues. Other sustainable advanced fuels could be made from renewable electricity or wastes from fossil fuel-based processes if they generate significant GHG savings relative to conventional petroleum-derived fuels.

By targeting the deployment of advanced SAFs from nonfood feedstocks early on, the nascent SAF industry may be in a position to avoid the political controversies around the social and climate consequences of food-based biofuels. However, the contribution of SAFs to aviation decarbonization will be limited by a variety of factors, including economic viability, feedstock supply, and pace of technology deployment. To inform potential policy targets for SAF deployment, this working paper first provides an overview of expected advanced fuel conversion pathways, then assesses the resource base for advanced SAF production. Independent of SAF production costs, we then estimate the quantity of SAF that could be produced from those feedstocks and contextualize availability relative to the projected demand for aviation fuel in 2030. We incorporate multiple factors that constrain overall SAF availability in this analysis including existing uses for feedstocks and anticipated deployment rates for new conversion technologies.

Overview of potential advanced SAF feedstocks and assessment methodology

In this study, we estimate the potential SAF volumes that could be produced from sustainably available feedstocks – the amount of feedstocks that can be used for biofuel production without negatively impacting commodity markets or the environment. We find that in many cases, the availability of feedstocks may constrain advanced SAF production.

While it is generally better from a sustainability perspective to use wastes rather than purpose-grown feedstocks for fuels, the EU Waste Framework Directive (2008/98/EC), provides important context for how to prioritize the recovery and reuse of discarded materials. This directive establishes a waste management hierarchy that prioritizes applications with the lowest impact on human health and the environment and a focus on waste prevention (European Commission, 2019). The hierarchy in fact gives low priority to using wastes and residues for biofuels, ranking it in the second-lowest tier, above landfilling and below recycling and composting. This suggests that biofuel production should not divert feedstocks from other uses, with the ideal feedstocks being those that are discarded or landfilled.

As with food-based biofuels, interactions with existing markets for some SAF feedstocks may lead to indirect emissions that change our understanding of their GHG savings. Feedstocks are rarely pure wastes that are disposed of in the absence of biofuel demand. In most cases, they contain market and ecological value. For example, residues from crops such as wheat are already productively used for livestock fodder and bedding, as well as in other uses such as mushroom production and horticulture (Searle & Malins, 2016). If all wheat straw were instead diverted to biofuels production, the other uses would lack raw materials and require an increase in production of substitutable materials. Understanding a feedstock's displacement effects is critical for ensuring GHG savings as well as determining quantities that can be diverted to biofuels production without reducing its availability for use in other applications.

CORSIA incentivizes countries to develop their own climate policies that may rely in part on domestic biofuel feedstocks. Many countries outside the European Union have climate targets and incentives to maximize utilization of domestic wastes and residues. It may therefore be difficult for EU climate policy to rely heavily on imports. For example, the European Union imports high quantities of used cooking oil (UCO) from Asian markets. As Asian countries seek to meet their own climate targets, this is likely to lead to increased competition for UCO produced in Asia. Rising demand for UCO in the European Union has fueled substantial imports from abroad and even resulted in several cases of fraud ("Fraudulent used cooking oil biodiesel," 2019). Notably, the European Court of Auditors in 2016 found the Commission's monitoring and oversight of waste oil markets to be insufficiently transparent.

Taking these considerations into account, this analysis focuses on EU feedstock availability, the future supply of which may be more certain than imported materials. The European Commission estimated the domestic biomass supply for bioenergy in the European Union at 134.4 million tonnes of oil equivalent in 2016 (European Commission, 2016). For a population of roughly 510 million, this equates to 263.4 kg of oil equivalent per capita. Comparatively, the EU Parliament Greens estimate that an equal distribution of global biomass resources equates to 15 GJ, or roughly 360 kg of oil equivalent per capita (European Free Alliance, 2018). This suggests that the European Union may have access to a limited amount of imported low-carbon feedstock.

Estimated availability of SAF feedstocks

We estimate feedstock availability in 2030 based on previous ICCT analyses assessing physical production of feedstocks and taking into account limits on maximum collection rates including harvesting capability, in situ ecological value, and usage as raw materials in other markets. We also note that diverting available feedstock toward fuel for the aviation sector would reduce its availability for competing uses in other transportation applications such as on-road diesel fuel. While waste fats are easier to process into "drop-in" fuels — or direct substitutes — lignocellulosic feedstocks are more abundant and could theoretically provide greater quantities of SAF. Previous research on lignocellulosic waste and residue availability in the European Union by Searle and Malins (2016) groups sustainable feedstocks into three categories: agricultural residues, forestry residues, and municipal and industrial waste. We supplement those findings by evaluating the potential from three additional potential SAF feedstocks including cover crops, industrial flue gases, and electrofuels produced using renewable electricity, CO_2, and water.

Waste fats, oils, and greases

Waste oils including used cooking oil, animal fats, and other fatty acids offer the cheapest and easiest means for producing SAF with current technology (Pavlenko, 2019). Hydrogenated esters and fatty acids (HEFA) fuels are the most common alternative drop-in jet fuels with about 360,000 tonnes of capacity in the European Union in 2018 (Padella, O'Connell, & Prussi, 2019). HEFA fuels are produced from the hydrogenation of waste and vegetable oils and can be blended up to 50% by volume with petroleum-based kerosene (Pavlenko et al., 2019).

An advantage of HEFA fuels is that infrastructure is already in place to support large production volumes. For example, Neste currently operates two plants that can process approximately 1 million tonnes of waste oils a year with plans to expand its Singapore plant to more than double its current capacity by 2022 (Jaganathan & Samanta, 2019). A fraction of the fuel produced from these refineries could be used as HEFA fuel, while the remainder of the product slate consists of renewable diesel as a drop-in diesel substitute as well as light products such as propane. Although refinery product slates are often optimized for diesel substitutes, optimizing for a higher jet fuel fraction and diverting the product slate from the road to aviation sectors can be done swiftly and less expensively than creating entirely new SAF capacity (Pearlson, Wollersheim, & Hileman, 2013). Pavlenko (2019) estimates that HEFA fuels are likely to be the cheapest source of SAF in the near term. The author calculates production costs as low as €0.88 per liter, twice the cost of petroleum-based jet fuel production, while other conversion processes cost as much as eight times the price of petroleum fuel (Pavlenko, 2019).

Used cooking oil

Used cooking oil is discarded vegetable oil after its use for frying. It can be collected from commercial sources such as restaurants and some households. In the European Union, UCO cannot be used in livestock feed and has no beneficial use outside the biofuels sector, unlike in the United States (Searle et al., 2017). Nearly all recovered UCO in the European Union is already used for on-road biofuel production (Phillips et al., 2019). For this analysis, we assume that UCO availability is equal to the EU-27 baseline of UCO used in the biofuel industry estimated by Phillips et al. (2019), adjusted to subtract 2019 consumption of UCO in the United Kingdom (UK DfT, 2020).

In 2019, waste fats, oils, and greases (FOGs) including UCO, animal fats, and others such as tall oil accounted for 32% of consumed biodiesel and renewable diesel in the European Union and about 2.5% of EU road diesel consumption (Phillips et al., 2019). Of UCO used for EU biofuel production, 62% is currently imported, of which three-quarters comes from Asia (Euractiv, 2019). There is some potential with additional policy support for UCO collection to grow, especially from households. One study estimated that expanded programs for household collection could increase overall UCO collection in the European Union by 11% (GreenEA, 2016). Additional collection would result in a potential maximum of 1.7 Mt of UCO for all uses in the European Union in the 2030 time frame.

Animal fats

Animal fats consist of beef tallow, pork lard, and chicken fat primarily obtained from rendering plants. These byproducts have many uses. Edible fats are used in shortenings and food products while inedible fats have applications in pet food, animal feed, and soap processing (Seber et al., 2014). Animal fats are also used in heat and power production. Although costs of these feedstocks are lower than for vegetable oil (Toldrá-Reig, Mora, & Toldrá, F., 2020), only a portion of them would be eligible under EU biofuel policies. For example, Germany does not support the use of animal fats in its biofuel mandate out of concerns over existing uses of the feedstocks (Phillips et al., 2019) while only certain categories of inedible fats are eligible under the RED II. Because of applications outside the biofuels sector and limited policy support, a substantial increase in animal fat availability for biofuel production is unlikely by 2030. Setting availability estimates at 2019 consumption rates, we estimate 750,000 tonnes of available animal fat feedstocks in 2030 for all uses in the EU-27 (Phillips et al., 2019).

Palm fatty acid distillates

Palm Fatty Acid Distillates (PFADs), made up of free fatty acids and palmitic and oleic acid, are a byproduct of palm oil refining. Apart from their use as a biofuel feedstock, PFADs are used in making soap, in animal feed, and as raw materials for oleochemicals such as candles, cosmetics, and toiletries (Ping & Yusof, 2009). An increase in PFAD usage for the SAF industry is expected to spur increased production of palm oil to meet steady demand across nonbiofuel industry sectors such as the cosmetics and food industries (Malins, 2017). Given the high land use GHG emissions associated with palm oil (Valin et al., 2015), use of PFADs in biofuel production would most likely cause high indirect GHG emissions. We thus exclude this feedstock from our analysis.

Tall oil

Pulp mills produce tall oil by separating crude sulfate soap from “black liquor,” a byproduct of paper manufacturing made up of lignin residues, hemicellulose, and organic chemicals (Malins, 2017). Crude sulfate soap further undergoes acidulation to produce crude tall oil feedstock, which can be converted into SAF via the HEFA process. Current applications of tall oil include the production of rubber emulsifiers, metalworking fluids, printing inks and adhesives, and energy-recovery applications (Malins, 2017). Included in Annex IX List A of the RED II, tall oil is also used at one known facility for on-road biofuel production (European Union, 2018). However, due to low overall availability of this material, further expansion of this pathway through SAF incentives would be likely to divert significant amounts of tall oil from other uses (Malins, 2017). To replace diverted tall oil, additional production of virgin vegetable oil in commercial applications and natural gas for electricity generation would most likely be required, each with significant associated GHG emissions (Pavlenko, 2019b). We thus exclude tall oil from this analysis.

Lignocellulosic wastes and residues

Lignocellulosic feedstocks from agricultural and forestry residues and from municipal and industrial waste are more technically challenging to convert than waste oils due to their physical properties. These materials contain long organic polymer chains that are difficult to break down, requiring extensive pretreatment before thermochemical or biochemical processing (Baldino, 2019). However, these feedstocks are more abundant than waste fats and, when converted to SAF, generally have higher GHG savings than food-based SAF pathways (ICAO, 2019). Feedstock conversion pathways include gasification with Fischer-Tropsch synthesis or by upgrading ethanol or isobutanol derived from these materials into drop-in fuel quality, or alcohol-to-jet fuel. Neither pathway is in operation on a commercial scale, and these feedstocks are largely unused in the road sector. Even achieving low blending rates—on par with the 3.5% advanced biofuels sub-target in the RED II for the road sector—would necessitate strong policy support. In the United States, a high blending mandate for cellulosic fuels within the federal Renewable Fuels Standard was insufficient to stimulate the deployment of appreciable volumes of cellulosic fuel, reflecting a combination of low private investment, insufficient government support, and technological delays (Bracmort, 2020). Delays associated with designing, constructing and deploying compatible biorefineries have slowed the commercialization of lignocellulosic biofuel pathways (Pavlenko, 2018).

Agricultural residues

Agricultural or crop residues include stems and leaves from crops such as wheat and maize and processing residues such as wheat chaff. Modern harvesting techniques allow for most discarded materials to remain in situ, providing nutrients and moisture for enhanced soil quality. If agricultural residues are harvested at levels that avoid displacement impacts, these materials used in production of biofuels could provide high GHG savings relative to petroleum-based fuels (Searle, Malins, & Baral, 2014).

A study by Searle and Malins (2016) estimates the quantity of available agricultural residues, forestry residues, and municipal and industrial waste in 2030 in the European Union. For agricultural residues, estimates are based on the production quantities of the 12 most-produced EU crops as reported by the Food and Agriculture Organization of the United States Statistical Division (FAOSTAT). Searle and Malins estimate residue production based on yields and production area of each crop in each EU member state. The authors then develop a linear model to estimate the optimal in situ retention rates of agricultural residues to maintain soil quality. The model references erosion rates and tillage practices from Eurostat (n.d.) and soil carbon concentration of each member state from the Harmonized World Soil Database (FAO, n.d.). The study also applies a harvesting constraint that assumes one-third of residues cannot feasibly be harvested, a factor that may supersede optimal retention rates.

Additionally, we consider agricultural residues that have existing uses in other industries to be unavailable for biofuel production. Existing uses include mushroom cultivation, horticulture, and livestock feed and bedding. Feedstock quantities consumed in these applications are expected to remain constant through 2030. Agriculture residues are also used in heat and power generation with quantities expected to increase in coming years. Future quantity estimates are extrapolated from planned "agricultural residues and byproducts" consumption reported in each member state's National Renewable Energy Action Plans. Accounting for in situ retention rates and existing uses, an estimated 76.5 Mt of feedstocks from agricultural residues will be available for biofuel production in 2030.

Forestry residues

Forestry residues are the treetops and branches left over from logging. They contain little commercial value but can be collected and used for heat and power or potentially for biofuel production (Searle & Malins, 2016). Like agricultural residues, forestry residues have ecological value, providing nutrients for soils, fostering biota, and reducing erosion (Searle & Malins, 2016).

Searle and Malins (2016) calculate forestry residue availability similarly to agricultural residues, by estimating total forestry residue production and subtracting the amounts expected to be used in other applications and necessary for soil health. Searle and Malins take total roundwood production from FAOSTAT, corrected for bark volume. The authors then use U.S. data on residue production by tree species to calculate total residue production for conifers and nonconifers, the two tree categories in the FAOSTAT data.

There is much less research on the soil health impacts of forest residue removal than on agricultural residues. In the absence of other evidence, Searle and Malins assume that a minimum of 50% of available residues should remain in situ in all cases. Existing uses of forestry residues in heat and power generation are also excluded from 2030 availability estimates. Usage in these sectors is similarly extrapolated using planned consumption data from National Renewable Energy Action Plans. Based on these assumptions, a total of 5.1 Mt of forestry residues are considered available for biofuel production in 2030.

Biogenic fraction of municipal and industrial waste

Waste collected from household, commercial, and industrial sources has high biogenic content from the paper, cardboard, food, and garden products in waste streams. When discarded in landfills, municipal and industrial waste can generate methane from anaerobic decomposition. Diverting waste from landfills to produce biofuels can thus generate significant emissions savings (Searle et al., 2017).

Municipal and industrial waste availability is again taken from Searle and Malins (2016). In that study, waste generation rates are sourced from Eurostat (n.d.). For these wastes, the authors assume a 63% biogenic content (IPCC, 2006). Biogenic waste has existing uses in recycling, reuse, and energy recovery. Accordingly, "waste that is landfilled, released into water bodies, or incinerated without energy recovery" is considered to be sustainably available for biofuel production (Searle & Malins, 2016). The authors assume that reduced waste and increased composting and recycling capabilities will reduce the quantity of available waste in 2030 by 50% due to policies such as the EU Waste Framework Directive (2008/98/EC) and the Packaging and Packaging Waste Directive (94/62/EC). An additional 50% reduction in incineration without energy recovery is assumed, leaving a total of 21.2 Mt of available municipal and industrial waste feedstock in 2030 for all uses.

Cover crops

Cover crops, also called intermittent crops, are grown during the winter and harvested in the spring before sowing of principal crops. These crops could provide additional feedstock for SAF production, though their future potential contribution is uncertain. Cover crops can be grown as livestock fodder. Their cultivation can contribute to improved soil fertility and soil carbon and reduced erosion. Common cover crops include low-starch legumes and grasses including crimson clover and ryegrass, as well as food crops like oats and rapeseed (Magdoff & van Es, 2010). Cover cropping is relatively uncommon in Europe, so theoretically there is considerable potential to expand it without substantial negative environmental or market impacts. There is some potential to use oilseeds such as rapeseed and carinata grown as cover crops, with ability to convert fuel through the existing, commercialized HEFA pathway (Del Gatto et al., 2015). Alternatively, the diversion of cover crops from livestock fodder would necessitate additional production of livestock feed ingredients such as wheat, with associated GHG emissions, but it is unknown what fraction of cover crops currently grown in Europe are used as fodder.

Data on cover cropping is very limited, and it is not possible to accurately assess quantities of cover crops that could be used for biofuel in future years. Baldino, Berg, Pavlenko & Searle (2018) provide an illustrative estimate of the amount of cover crops that could be used for biogas production in 2050 based on the small amount of information available. We use that calculation to estimate the amount that could potentially supply SAF in 2030. The most recent data on EU cover crops is reported in the 2010 Farm Structure Survey, which finds that just over 3% of arable land is planted with cover crops (Alliance Environnement, 2017, as cited in Baldino et al., 2018). Extrapolating from historical trends, Baldino et al. estimate that 10% of land used for annual crops in 2050 may be cover cropped and assume that half of this could be available for biofuel production without displacing fodder. This amounts to about 4.5 million hectares. To estimate potential yields, Baldino et al. use oats as a model cover crop because more data is available than for other types of cover crops. Because Alliance Environnement (2017) reports that cover crops are typically harvested or ploughed under before they reach maturity, Baldino et al. assume that only oat residue is produced. Baldino et al. further assume a 40% biomass yield reduction in winter oats compared with oats grown as a main crop in each EU member state due to slower growth during the winter and further that 20% of the crop falls below the harvester height and cannot be collected. These assumptions are made in the absence of widespread evidence of cover crop yields in different EU member states. With these assumptions, Baldino et al. estimate that cover crops could provide an additional 7.15 Mt of lignocellulosic feedstocks for SAF production in 2030.

Electrofuels

There are also nonbiological pathways for producing SAF. Electrofuels, also called power-to-liquids (PtL), are a potentially low-carbon yet resource-intensive pathway to produce SAF. To generate drop-in jet fuel, water molecules are split into hydrogen and oxygen via electrolysis. The hydrogen is then synthesized in a reactor with carbon dioxide to produce liquid or gaseous hydrocarbons or alcohols (Baldino, 2019). To ensure that these fuels are both sustainable and low-carbon, renewable electricity used in SAF production should not be diverted from other uses.

The amount of PtL that could theoretically be available for SAF is very large because the physical resources needed are mainly the raw materials for constructing solar panels and wind turbines and land for siting the installations. It is unlikely, however, that this theoretical potential would be met given the high cost and time required to commercialize an emerging industry. For the amount of PtL that could be available in the European Union in 2030, we rely on an EU member state-level assessment by Searle and Christensen (2018).

That study projects the volumes of PtL from wind and solar electricity that could be economically produced at varying levels of policy support. Searle and Christensen project EU wind and solar electricity prices, and using that build a cash-flow model including inputs for the costs of capital, operations and maintenance, equipment replacements, and country-specific taxes. The study models a number of different systems, including various types of electrolyzers, grid versus direct connection to the renewable electricity installation, and CO_2 sourced from industrial plants versus direct air capture. Searle and Christensen assume significant cost reductions in renewable electricity installations and electrolyzers in future years. The study uses a deployment model to project how quickly PtL could be ramped up for pathway combinations that become economical over time in each EU member state.

We use that study's results for the most economical scenario, grid-connected wind electricity and industrial CO_2, at €2 per liter policy support, or about five times the current wholesale price of jet fuel. Compared with current alternative fuel subsidies and other forms of policy support in Europe, €2 per liter is very high, but it could conceivably be provided in the 2030 time frame if SAF is a high political priority. At that incentive level, the study estimates that the availability of electrofuels for transport fuels would range from 0.006 Mt in 2025 to 0.15 Mt by 2030 and 0.23 Mt by 2035. Achieving higher production quantities would be possible with greater policy support and especially with more time for the industry to commercialize and for renewable electricity prices to decline as renewable electricity prices are the largest cost component. We note that higher volumes of e-fuels may be possible with dedicated policy support, such as a dedicated, sub-target blending target for e-fuels, despite their higher production costs. Therefore, the exact contribution of PtL is more cost-constrained than resource-constrained in this analysis.

Industrial flue gases

Industrial flue gases, primarily energy carriers such as CO and H_2, can be captured, fermented and upgraded into SAF. The emerging process for upgrading flue gas is the Lanzatech process developed for steel mills, although similar processes could be applied at other heavy industry facilities. In the Lanzatech process, carbon-rich flue gases captured from industrial sources such as steel mills undergo fermentation to produce an ethanol intermediate (Bazzanella & Ausfelder, 2017). Ethanol is then converted to ethylene via dehydration and oligomerized to form a synthetic hydrocarbon (Pavlenko, 2019a).

In the absence of fermentation, flue gas is often either flared or used for onsite energy recovery. Diverting flue gas from onsite energy recovery would necessitate the use of another fuel, such as natural gas, to replace the lost energy; however, this effect may be modest because the energy recovery from flue gas combustion is typically inefficient (Searle et al., 2017). As the electricity grid decarbonizes, the impacts of diverting flue gas from on-site energy production could decline over time.

To estimate total availability of flue gases, we first draw upon Bazzanella and Ausfelder (2017) to estimate the conversion yield of synthesized ethanol in the European Union from crude steel production. Bazzanella and Ausfelder first estimate the CO and H_2 composition of off-gases for blast and basic oxygen furnace conversion pathways in cubic meters per tonne of steel produced. The blast furnace process is commonly used at steel mills to generate electricity by extracting pig iron from iron ore using coke. The iron byproduct is later refined and converted to steel in a blast oxygen furnace. Off-gases are generated in the coke plant, blast furnace, and blast oxygen furnace converters. Electric arc furnaces, another steel production process (World Steel Association, 2016), generate substantially fewer flue gases and contribute only minor quantities to the estimate of total availability.

To determine total CO and H_2 production, emission factors for off-gas production per tonne of steel is multiplied by total steel mill production in the European Union (World Steel Association, 2016). We assume that 70% of steel mill flue gases are already recovered and combusted for energy recovery onsite (Wortler et al., 2013). Assuming that steel production remains near 2018 levels and conversion efficiencies of 3.65 tonnes of CO per tonne of ethanol, we estimate that the approximately 12 million tonnes of industrial flue gases produced would yield 3.3 million tonnes of ethanol for further upgrading to transport fuels.

Total feedstock availability

Figure 1 presents a summary of the sustainable availability for biofuel feedstocks in 2030 for the European Union. The largest share of total available feedstock comes from agricultural residues, followed by municipal and industrial wastes. There is less feedstock available from waste oils, forestry residues, cover crops, and industrial flue gas. Note that our subsequent calculations assume that all of the feedstocks are converted into a mix of transport fuels. Depending on the exact conversion process, biorefineries produce a mix of different hydrocarbons of varying chain lengths, ranging from light ends such as propane to middle distillates such as diesel. In this analysis, we assume that where possible, biorefineries maximize the jet fuel output of their product slate. However, in some cases it may be more efficient and economical to maximize the output of the diesel share of liquid fuels (Pavlenko et al., 2019).

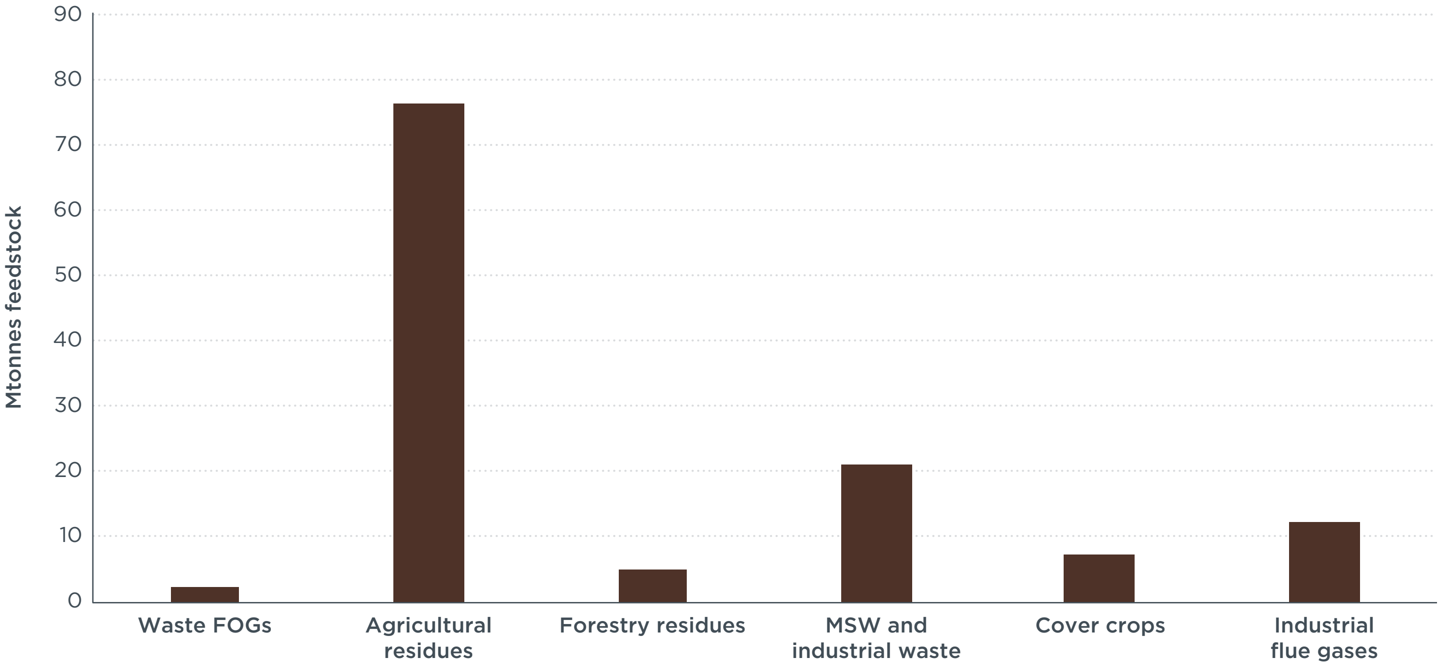

Figure 1: Estimated tonnes of available advanced alternative fuel feedstocks

Note: Electrofuel potential is not included here as this pathway uses renewable electricity as a feedstock.

Conversion assumptions

The quantity of SAF produced from each source varies by feedstock type and conversion pathway. We assume that all feedstocks are converted into a mix of transport fuels, and we present the estimated SAF share of total output. We use yield factors to convert between feedstock quantities and SAF volumes for various conversion pathways. We take HEFA fuel assumptions from Pearlson et al. (2013), which estimates the quantities of input waste oil feedstock to produce a mixed slate of fuels including light ends such as naphtha and propane, renewable diesel, and jet fuel. HEFA estimates are supported by conversion factors in the GREET model (2018) reported in tonnes of fuel produced per tonne of feedstock input. Gasification-FT conversion factors, which vary by input feedstock, are sourced from the GREET model. A techno-economic analysis by Tao et al. is referenced for ethanol-to-jet conversion pathways.

Table 1: Feedstock conversion pathways (adapted from Pavlenko et al., 2019)

Feedstock	Conversion pathway	Yield (tonnes liquid fuel/tonne feedstock)	Source
Waste oils	HEFA	0.9	GREET, 2018; Pearlson et al., 2013
Ag residues	Gasification-FT	0.2	GREET, 2018
Forestry residues	Gasification-FT	0.22	GREET, 2018
Municipal and industrial waste	Gasification-FT	0.07	GREET, 2018
Cover crops	Gasification-FT	0.2	GREET, 2018
Flue gas	ATJ (ethanol-to-jet)	0.46	Tao et al., 2017
Electrofuels	PtL	-	

Although most biorefineries are optimized to maximize their liquid product slate with a focus on diesel fuel, their slate can be adjusted to produce higher volumes of shorter chain-length jet fuel through hydrocracking. While it can increase costs, hydrocracking can be used to maximize the jet share of the liquid fuel product slate (ICAO, 2019). For this analysis, we assume that biorefineries will maximize their jet fuel fraction. Therefore, we introduce a factor of 0.59 to estimate the share of SAF output from the HEFA and a factor of 0.5 for the jet-optimized gasification-FT SAF yield. We use a 0.75 factor for ATJ pathways, as the ATJ process yields a much higher share of SAF in its product slate than either HEFA or gasification-FT conversion.

Deployment constraints

While this study focuses primarily on the resource base for advanced SAF production, we also incorporate deployment constraints on the contribution of fuels made from novel or emerging pathways. In contrast to first-generation biofuels and HEFA fuels, there is less certainty about the quantity of SAF that could be supplied from these emerging technologies that are at lower technology readiness levels—particularly lignocellulosic conversion pathways. While there are sufficient quantities of lignocellulosic feedstocks to produce nearly 10 Mt of SAF in the European Union, that would require the wide-scale deployment of those technologies at commercial scales within the next decade. Efforts to develop such technologies at commercial scale, for example the cellulosic ethanol industry in the United States, have thus far resulted in substantial delays and low production volumes.

Table 2 below summarizes the state of project development for biomass thermal gasification to fuel and for the fermentation of industrial flue gases, which are both included as technology options in this analysis. The project list is drawn from the International Civil Aviation Organization's 2019 SAF Stocktaking Seminar and includes facility technology, scale, and expected project timeline (Hupe, 2019). It is evident that despite nearly a decade of support, particularly in the United States, the advanced biofuel industry has been slow to scale up. While the table reflects the duration of construction for several projects, it does not show delays that occurred during project planning and permitting. Furthermore, some pioneer cellulosic biofuel projects have documented difficulties ramping up to their designed capacities in their initial year of operation. Therefore, any projections on the ramp-up of these projects should include a note of caution about the exact timeline for their design, construction, and operation.

Table 2: Operating and planned lignocellulosic biorefineries and industrial flue gas-to-ethanol

Operator/project	Location	Pathway	Capacity	Output	Completion date
Enerkem	Canada	Gasification-FT	38 million liters	Methanol, ethanol	2013
Lanzatech	China	Industrial flue gas fermentation	58 million liters	Ethanol	2018
Total – BioFuel	France	Gasification-FT	256 million liters	Middle distillates	In progress (Begun 2016)
Red Rock Biofuels	U.S.	Gasification-FT	57 million liters	Middle distillates	Under construction (Begun 2018; planned for 2020)
Aemetis	U.S.	Gasification-to-ethanol	45 million liters	Ethanol	Under construction (Begun 2018; planned for 2020)
Fulcrum Bioenergy	U.S.	Gasification-FT	40 million liters	Middle distillates	Under construction (Feedstock processing facility construction in 2016; biorefinery construction begun 2018; planned for 2020)
Lanzatech – Port Talbot	U.K.	Industrial flue gas fermentation	100 million liters	Ethanol	Under construction (Planning and permitting; planned for 2021)
Lanzatech – Freedom Pines	U.S.	Gasification to ethanol	38 million liters	Ethanol	Under construction (Planned for 2022)
LTU Greenfuels	Sweden	Gasification-FT	0.4 to 0.8 million liters (64 million liters with planned expansion)		Under construction (Begun 2017, 2023 target)
Velocys – Altalto	U.K.	Gasification-FT	40 million liters	Ethanol	Under construction (Planned for 2024)
Velocys – Bayou Fuels	U.S.	Gasification-FT	95 million liters	Middle distillates	Under construction (Planning and permitting)

We introduce a set of deployment rate assumptions to estimate the maximum number of lignocellulosic biofuel facilities and the maximum amount of fuel that could be produced from these pathways, based on reasonable construction expectations for the 2025–2035 time frame. We assume a maximum of one facility per member state with sufficient feedstock prior to 2030 and an additional facility coming online between 2030 and 2035. Each project is assumed to take five years to design, attract investment, and be built, and during the first year to operate at half capacity. For context, there are currently only a small number of commercial-sized facilities producing cellulosic ethanol, the most technology-ready lignocellulosic conversion pathway available (Padella et al., 2019). There are currently no operating commercial-scale biomass gasification-to-fuel facilities globally. Thus, our assumption that one such facility could be built in each European Union member state within the next five years is optimistic. Nations with low availability of lignocellulosic feedstocks are assumed to have no facilities, while countries with moderate availability may deploy only a small-scale facility. We do not consider trade between member states due to the difficulty and expense of transporting lignocellulosic residues.

Facility design capacities for small- and large-scale projects are sourced from Shahabuddin et al. (2020) and Pavlenko et al. (2019), respectively. We take the size of small-scale facilities according to specification data from microchannel FT systems developed by Velocys with a rated capacity of 1,400 barrels per day, or 0.06 million tonnes of oil equivalent per year. Theoretical large-scale facility capacities are based on the upper end of literature projections for cellulosic ethanol facilities. In their estimates, Pavlenko et al. (2019) assume gasification-FT systems for large, N^{th}-of-a-kind gasifiers with an output capacity of 0.19 million tonnes of oil equivalent per year, and we follow that assumption. To determine the maximum quantities of feedstocks that would be consumed per facility, capacities are divided by the respective yield conversion factor for each lignocellulosic feedstock (Table 2). In 2030, between 10% and 39% of available feedstocks would be used for a total volume of 1.34 Mt of SAF. With these assumptions, we estimate total SAF production from lignocellulosic feedstocks to be 0.36 Mt in 2025 and 1.96 Mt in 2035, accounting for a ramp-up in facility deployment capacity.

For industrial flue gases, the deployment rate is also uncertain. However, as this pathway relies on centralized feedstocks without the need for developing new supply chains or pretreatment, we see this pathway as having fewer technical barriers. Therefore, we assume linear growth in the deployment of this pathway from 2020 to its full feedstock potential by 2035.

Table 2: Maximum FT-gasification and industrial flue gas facility deployment

	2025		2030		2035	
Feedstock(s)	**SAF production (Mt)**	**% Feedstock utilized**	**SAF production (Mt)**	**% Feedstock utilized**	**SAF production (Mt)**	**% Feedstock utilized**
Agricultural residues, cover crops	0.19	2%	0.87	10%	1.35	16%
Forestry residues	0.06	11%	0.22	39%	0.31	56%
Municipal and industrial waste	0.10	14%	0.26	35%	0.31	41%
Industrial flue gases	0.38	33%	0.76	67%	1.14	100%
Total	**0.74**		**2.10**		**3.11**	

Baseline jet fuel demand

We project future EU-27 jet fuel demand by applying a 4.5% growth rate based on the 2014-2018 five-year average (Eurostat, 2020) in conjunction with a 2.0% annual efficiency improvement (EASA, EEA, EUROCONTROL, & ICAO, 2019). For our central estimate, we expect jet fuel demand to be 55.5 Mt in 2025, 62.8 Mt in 2030, and 71.1 Mt in 2035. The sharp and likely temporary emission reductions across the aviation sector as a result of the COVID-19 pandemic were not accounted for this analysis.

Findings

We estimate that there is a sufficient resource base to theoretically support peak production of 12.2 Mt a year of SAF. However, technical and economic constraints would make realistic production volumes far smaller in 2030. Incorporating even an optimistic deployment rate for novel conversion technologies reduces the deployment rate substantially. With a deployment constraint in place, our estimate of maximum potential SAF production drops to 3.4 Mt, or 5.5% of 2030 jet fuel demand. However, without any targeted support for more challenging pathways, the actual SAF potential could be closer to 1.9%, primarily drawn from easier-to-convert HEFA fuels.

Figure 2 illustrates the potential growth in SAF volumes from 2025 to 2035, breaking down the contribution by broad feedstock category in each year. The markers on the chart illustrate the estimated contribution of SAFs to projected fuel demand for each year (right axis). Assuming greater incentives for SAF than for road fuels, volumes produced via HEFA would reach their maximum potential by 2025, primarily via diversion from the road sector. ATJ ethanol from industrial flue gases may be more expensive and technically challenging to produce, so we assume that its potential increases linearly. In the optimistic deployment scenario, we assume that electrofuels and SAF produced via FT-gasification are constrained by the rate of facility deployment through 2035. In the pessimistic deployment scenario, we assume incentives are insufficient to mobilize deployment of these new pathways.

Because we expect total jet fuel demand to increase over time, the potential for SAF to displace conventional jet fuel on a percentage basis (as shown by the markers in the graph) declines in the pessimistic scenario from 2025 to 2035 compared with the increase in potential SAF volumes in Mt.

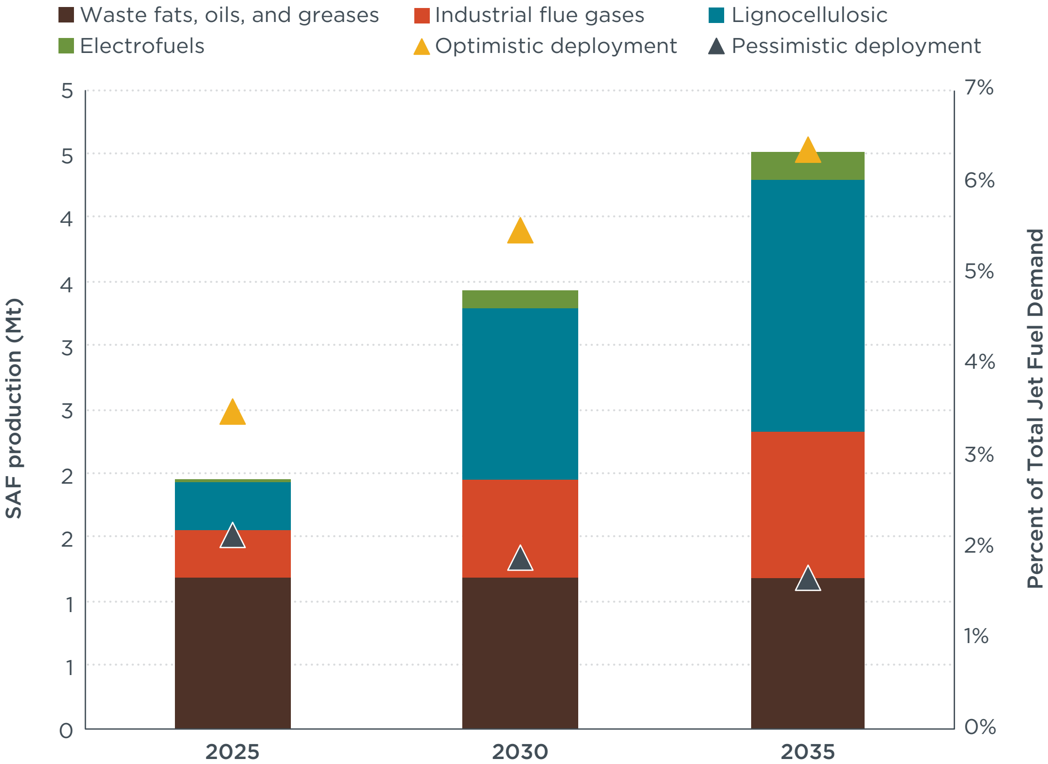

Figure 2: Estimated annual advanced SAF production (Mt) (left axis) and percent of total jet fuel demand that could be displaced, depending on facility deployment success (right axis)

The contribution of waste FOGs to 2030 aviation fuel demand can be estimated with the highest degree of certainty as it utilizes the most mature conversion pathway for producing SAF. Hydrotreated vegetable oils are already produced at commercial scales for the road sector, and large quantities may be diverted to the aviation sector through biorefinery optimization.

We estimate that waste FOGs-derived HEFA fuels could produce as much as 1.2 Mt of SAF in 2030 but note that this value will vary depending on the biorefinery product slate and the extent to which existing production for the road sector can be diverted to aviation. In addition, Pavlenko et al. (2019) find that maximizing the HEFA pathway would generate lower quantities of liquid alternative fuels overall as biorefineries would operate less efficiently to maximize the jet fuel fraction. An increase in HEFA production using FOGs may not be a desirable outcome from the perspective of displacing petroleum use in the transport sector overall, especially in the near term. Thus, in our analysis SAF production from waste FOG feedstocks remains steady through 2035 (Figure 2).

Although agricultural residues account for the largest share of available feedstocks by a substantial margin, their overall contribution to SAF production is expected to be limited as a result of deployment constraints. Due to the time lag associated with project design, construction and ramp-up of new types of biorefineries, it is unlikely that many large, commercial-scale operations will begin to produce fuels from these feedstocks by 2025. Even with substantial policy support, the expansion of the industry will take time. Taking these deployment constraints into account, we estimate that the bulk of deployment from lignocellulosic feedstocks would most likely occur after 2030. With significant incentives and targeted policy support for pioneer projects, these feedstocks could contribute about 2.1% of projected 2030 jet fuel demand.

We estimate that flue gas ethanol could contribute an additional 0.76 Mt of SAF in 2030. This analysis assumes that flue gas ethanol production can be scaled up quickly because the centralized nature of steel mills means there's no need for new supply chains or substantial pretreatment, in contrast to lignocellulosic feedstocks. Thus, we assume that the entire share of flue gases that is either flared or emitted into the atmosphere, or 30% of total flue gases generated, can be converted to SAF by 2025. Commercial-scale electrofuel projects have not yet been introduced in the European Union, largely reflecting unfavorable project economics. Drawing from Searle and Christensen (2018), we assume that only 0.15 Mt of electrofuels could be produced with €2/L of policy support. At lower subsidy rates, that study finds that projects would be largely infeasible. We assume that the entire potential production amount would be used as SAF rather than road fuel.

We estimate that with deployment rate and feedstock availability constraints in place, the EU could produce a maximum of 3.4 Mt of SAF by 2030, displacing 5.5% of projected 2030 jet fuel demand in 2030. Cover crops and agricultural residue estimates are summed on the assumption that those feedstocks would be combined at the same processing facility. Table 3 summarizes the maximum quantities of feedstocks and SAF we find to be available and their contribution to the total estimate. Tables for additional years are provided in the Appendix.

Table 3: 2030 SAF production and contribution to overall EU jet fuel demand by feedstock

Feedstock	Available feedstock quantity (Mt)	Max SAF production (Mt)	% 2030 Jet fuel demand
Waste FOGs	2.4	1.2	1.9%
Agricultural residues, cover crops	83.7	0.9	1.4%
Forestry residues	5.1	0.2	0.3%
Municipal and industrial waste	21.2	0.3	0.4%
Industrial flue gases	12.1	0.8	1.2%
Electrofuels	-	0.1	0.2%
Total	**124.4**	**3.4**	**5.5%**

Conclusion

Taking into account sustainable availability and an optimistic assumption for the deployment rate of novel conversion technologies, we estimate that there is a resource base to meet approximately 5.5% of the European Union's projected 2030 jet fuel demand using advanced SAFs. However, if the European Union adopts weaker incentives that primarily encourage the use of waste oils and diversion from the road sector, we estimate a maximum advanced SAF deployment of only 1.9% of projected 2030 EU jet fuel demand. In the pessimistic scenario, the bulk of SAF production would come from the optimization of existing or near-term hydrotreated vegetable oils produced from waste oils to maximize SAF output. In either case, achieving these small volumes would require strong policy support and significant near-term investment. The limited resource base for producing advanced SAFs suggests that biogenic SAFs alone cannot decarbonize aviation in the EU and will have only a limited impact through 2030. Other measures, such as accelerated progress in design and operational efficiency of aircraft and carbon pricing and demand reduction may be necessary to achieve deeper decarbonization by 2050.

We find that waste FOGs are expected to constitute the largest source of feedstocks, contributing about 1.9% to 2030 EU jet fuel demand. This pathway is resource-constrained, and the availability of waste FOGs for aviation may be further limited by competition from the road sector. However, waste FOGs have the highest and most certain near-term potential for SAF use as they are converted through the technologically mature HEFA pathway and can be readily produced by optimizing existing road-sector biorefineries for higher jet fuel output.

In total, we estimate that lignocellulosic feedstocks, including municipal and industrial wastes and forestry residues, could be used to supply about 2.1 % of 2030 jet fuel demand assuming an optimistic rate of facility deployment. However, due to limited commercial success to date and uncertain deployment timelines for lignocellulosic fuel pathways, the contribution of these feedstocks to SAF production remains uncertain and could indeed be much lower in 2030, particularly if the incentives for new facilities remain weak. We estimate that agricultural residues will contribute the largest quantities of available feedstock, although we expect that with the time required to ramp up the FT-gasification industry, only 10% of sustainably available agricultural residues could be converted to jet fuel in 2030.

We estimate that there are sufficient industrial flue gases to generate approximately 0.76 Mt of ATJ before 2030, which could meet approximately 1.2% of EU jet fuel demand. Based on our previous modeling work, we estimate that electrofuels will largely remain cost-prohibitive without very high policy support through 2030 due to the combination of high electricity consumption of this pathway in conjunction with the high price of renewable electricity. Even with a break-even cost of five times the price of petroleum jet fuel, we estimate a 2030 contribution of only 0.2% of jet fuel demand. It is unlikely that any electrofuels could be produced for SAF without dedicated policy support, such as a sub-target within the overall blending mandate, due to economic barriers. However, this pathway could provide a much larger share of SAF in 2050 as the price of renewable electricity continues to decline. Early investment and a strong long-term signal for SAF could help to motivate long-term success for electrofuels.

This analysis finds that there is a resource base to expand SAF usage substantially relative to current levels through the use of advanced SAFs with high carbon savings. However, expanding SAF beyond today's production levels will require substantial financial incentives to overcome the economic and technical barriers that have thus far kept production low. Absent strong policy support and long-term commitments to advanced fuels, it will be difficult to do more than divert waste oils from other sectors. High blending targets in the absence of complementary policies may instead open the door to higher use of food-based biofuels in aviation. Even with strong policies in place, the limited availability of the best-performing feedstocks suggests that SAF production alone cannot achieve the EU aviation sector's long-term GHG reduction obligations.

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Appendix: SAF production estimates by year

2025 SAF production estimates

Feedstock	Available feedstock (Mt)	Max SAF production (Mt)	% 2025 Jet fuel demand
Waste FOGs	2.4	1.2	2.1%
Ag residues, cover crops	83.7	0.2	0.4%
Forestry residues	5.1	0.1	0.1%
Municipal and industrial waste	21.2	0.1	0.2%
Industrial flue gases	12.1	0.4	0.7%
Electrofuels	-	0.0	0.0%
Total	**124.3**	**1.9**	**3.5%**

2030 SAF production estimates

Feedstock	Available feedstock (Mt)	Max SAF production (Mt)	% 2030 Jet fuel demand
Waste FOGs	2.4	1.2	1.9%
Ag residues, cover crops	83.7	0.9	1.4%
Forestry residues	5.1	0.2	0.3%
Municipal and industrial waste	21.2	0.3	0.4%
Industrial flue gases	12.1	0.8	1.2%
Electrofuels	-	0.1	0.2%
Total	**124.3**	**3.4**	**5.5%**

2035 SAF production estimates

Feedstock	Available feedstock (Mt)	Max SAF production (Mt)	% 2035 Jet fuel demand
Waste FOGs	2.4	1.2	1.7%
Ag residues, cover crops	83.7	1.3	1.9%
Forestry residues	5.1	0.3	0.4%
Municipal and industrial waste	21.2	0.3	0.4%
Industrial flue gases	12.1	1.1	1.6%
Electrofuels	-	0.2	0.3%
Total	**124.3**	**4.5**	**6.4%**