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Fueling flight: Assessing the sustainability implications of alternative aviation fuels

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Aviation faces large technical barriers to making a transition to hydrogen or electricity-powered airframes, so the industry will probably have to rely on liquid fuels through 2050. That is particularly true for the medium- and long-haul flights that generate two-thirds of aviation emissions. If the industry is to meet its long-term climate goal of cutting greenhouse gas (GHG) emissions 50% by 2050 without curbing traffic growth or using out-of-sector carbon offsets, sustainable aviation fuels (SAFs) will need to play a key role. SAFs can be used to generate in-sector GHG reductions when they supplant conventional petroleum jet fuel. In 2018, less than 0.01% of aviation fuel came from alternative sources (Hupe, 2019; Graver, Zhang, & Rutherford, 2019). While reducing petroleum consumption in aviation is an important objective for decarbonization, the specific types of alternative fuels used to displace petroleum will determine the net climate impact of any alternative fuels policy. A fuel's feedstock and its conversion process—together called the fuel pathway—determine the fuel's life-cycle GHG emissions.

The European Union's recently announced Green New Deal framework calls for a clear regulatory roadmap for the decarbonization of aviation, to be achieved using a combination of new technology, SAFs, modal shift, and improved efficiency (European Parliament, 2020). As part of this effort, the European Commission announced the ReFuelEU initiative to deploy SAFs to decarbonize EU aviation (European Commission, n.d.). However, the actual climate impact of the policy will depend strongly on the design and incentive structure for different fuel pathways. This working paper provides background and analysis to help identify how an effective policy for alternative aviation fuels could distinguish among fuels that can deliver deep GHG reductions and those that cannot. It summarizes the GHG performance of various SAF pathways and highlights important sustainability considerations for their use, with the goal of informing EU decisions on which SAF pathways to support in developing policy. The emission estimates for SAFs presented here are intended to illustrate broadly the climate impacts across various pathways rather than to recommend specific values for EU policy development.

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Overview of current and near-term SAF pathways

SAFs make up a minuscule share of current global jet fuel consumption despite a variety of conversion technologies and fuels that could be used in commercial aircraft. The standards organization ASTM International has certified seven fuels for use in aviation under its ASTM D7566 standard. This standard establishes through multiple levels of testing that fuels meet the chemical and performance characteristics of conventional petroleum jet fuel up to a specific blend level for each fuel (ASTM International, n.d.). ASTM certification does not relate to the technology-readiness level or sustainability of certified fuels.

The approved and in-progress ASTM pathway certifications are summarized in Table 1. The table details the approval status of each pathway and what types of feedstocks may be used to produce each fuel. The table also indicates the maximum level at which each fuel can be blended with petroleum jet fuel and still constitute a "drop-in" fuel, or direct substitute, within the ASTM certification. In excess of the blending limits, these fuels would not necessarily meet physical and chemical specifications for conventional "Jet A" fuel and would thus not be suitable for commercial flight.

Table 1: Summary of approved and pending SAF production pathways.

Fuel	Blend level	Typical feedstocks	Status
Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	50%	Vegetable oils, waste fats, oils & greases	Approved in 2011
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	10%	Sugar crops	Approved in 2014
Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)	50%	Lignocellulosic crops, residues & wastes	Approved in 2015
Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	50%	Starchy & sugary crops, lignocellulosic crops, residues & wastes, industrial flue gases	Approved in 2016
Co-Processing Bio-Oils in Petroleum Refinery	N/A[a]	Vegetable oils, waste fats, oils & greases	Approved in 2018
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	50%	Lignocellulosic crops, residues & wastes	Approved 2019
Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)	50%	Vegetable oils, waste fats, oils & greases	Approved in 2020
Integrated Hydropyrolysis and Hydroconversion (HC-HEFA-SPK)	10%	Lignocellulosic crops, residues & wastes	Approved in 2020
Co-Processing Synthetic Crude Oil in Petroleum Refinery	N/A	Lignocellulosic crops, residues & wastes	Approved in 2020
High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK or HEFA+)	10%	Vegetable oils, waste fats, oils & greases	In Progress
Hydro-Deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)	N/A	Starchy & sugary crops, lignocellulosic crops, residues & wastes	In Progress
Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	N/A	Starchy & sugary crops, lignocellulosic crops, residues & wastes	In Progress

Note: Pathways marked with a blend level "N/A" are either not applicable (in the case of co-processed bio-oils) or are not available as testing is ongoing.

[a] Separately, the co-processing of small quantities of vegetable oils, waste fats, and bio-crudes has been approved by ASTM via a separate certification for standard D1655; if fats are processed in a refinery at less than 5% of its processing volume, the resulting jet product can meet the specifications for conventional jet fuel.

Climate and sustainability impacts from SAF production

Based on the list of fuel pathways and potential feedstocks in Table 1, we next present a summary of climate and sustainability impacts of SAF production. First, we present the direct GHG emissions attributable to SAF production, broken out by pathway. Next, we present the indirect emissions for relevant SAF pathways, including indirect emissions attributable to market-mediated effects, such as the emissions from land-use change. We also discuss the impact of displacement emissions for waste and by-product materials diverted from existing uses and their impact on fuels' sustainability. Based on the total impact of these emissions, we assess the relative sustainability of each feedstock and pathway combination for achieving long-term aviation decarbonization.

Direct emissions from fuel production

While certification validates the operational qualities and safety of a given fuel, it does not assess that fuel pathway's sustainability or climate performance. Evaluating the climate performance of jet fuel necessitates a full life-cycle analysis (LCA) of that fuel's emissions from feedstock extraction and processing through to final combustion, or "well-to-wake" (WtWa) emissions. This value can then be compared with the well-to-wake emissions of conventional petroleum jet fuel to determine whether alternative fuels deliver GHG savings over conventional fuel, and if so, how much.

The carbon intensity of jet fuel can vary according to region, crude oil well, and refinery and can change over time. Different studies have estimated the carbon intensity of conventional petroleum-based jet fuel to range from 85 to 95 grams of carbon dioxide equivalent per megajoule (g CO_2e/MJ) of fuel, with about 73 g CO_2e/MJ attributable to fuel combustion and the remainder to fuel extraction, processing at refineries, and transportation. Across different policies, California's Low-Carbon Fuels Standard (LCFS) uses a baseline value of 87 g CO_2e/MJ for petroleum jet fuel, while the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) policy of the International Civil Aviation Organization (ICAO) and the U.S. Renewable Fuels Standard (RFS) use a baseline of 89 g CO_2e/MJ (CARB, n.d.; EPA, 2010; ICAO, 2019a). The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, a harmonized LCA model used to estimate a variety of fuels' life-cycle emissions that is applied in academia and by the California Air Resources Board to estimate LCA values for the LCFS, estimates a value of 86 g CO_2e/MJ for conventional, ultralow-sulfur jet fuel (GREET, 2019).

Generally within life-cycle accounting, the combustion emissions from biofuels are treated as zero because the biogenic emissions from combustion offset carbon from the atmosphere that was sequestered recently and stored in the feedstock during its growth. This is in contrast to petroleum, the combustion of which emits carbon that was sequestered in the earth in the distant past and now comprises a net addition to the atmosphere.

This section presents an overview of the SAF pathways likely to be used over the next decade and summarizes the literature on their direct LCA emissions. For most pathways, we will illustrate the default pathway emissions set by ICAO for the CORSIA policy and include example assessments for other pathways. Where possible, we compare ICAO estimates with carbon intensities of similar pathways found in the literature. It is important to note that actual GHG emissions for an alternative fuel pathway depend on the specific case facility, feedstock source, and supply route. ICAO's GHG intensity values and other estimates reported in the literature are not necessarily a substitute for a more tailored assessment of individual biorefineries. In some cases, important regional considerations for feedstock acquisition, transportation, and energy source may have a large impact on site-specific emissions relative to modeled values. While a European Union-specific assessment of direct LCA emissions for SAFs is likely to vary slightly from

ICAO global estimates due to these factors, the values estimated by the ICAO are largely indicative of the direct emissions impact of the various SAF pathways.

Hydroprocessed esters and fatty acids (HEFA)

Hydroprocessing converts virgin vegetable oils or waste fats, oils, and greases (FOGs) into hydrocarbons through deoxygenation followed by hydrotreating, hydroisomerization, or hydro-cracking (Baldino, Berg, Pavlenko, & Searle, 2019). This process produces hydrotreated vegetable oil (HVO), a drop-in diesel substitute for the road sector, as well as HEFA fuel, which can be used as a kerosene substitute. This process can be optimized to increase the share of HEFA (Pavlenko, Searle, & Christensen, 2019). HEFA+ is another fraction that can be produced through hydroprocessing oils and fats. This fuel is also known as high freeze point HEFA or HFP-HEFA-SK and is nearing final ASTM approval as a fuel. HEFA+ bears more similarity to HVO for the road sector as it requires less isomerization and has higher yields, thus reducing costs in exchange for having worse cold-flow properties.

Emissions from HEFA and HEFA+ vary considerably depending on the feedstock. Jet fuel produced from waste FOGs is usually assessed as having generally low life-cycle GHG emissions, as it is typical to count emissions only from the point of feedstock collection or separation onward, whereas life-cycle analysts typically attribute GHG emissions from crop production and induced land-use change (ILUC) to virgin vegetable oils when used as a biofuel feedstock. The GHG emissions for the HEFA conversion process mainly come from the production of hydrogen—a key chemical component of the process—and energy used at the biorefinery. Due to similarities in production, the emissions from HEFA+ production are expected to be similar to those from HEFA and HVO fuels made using similar feedstocks.

The range of emissions for HEFA pathways estimated by ICAO for fuel emissions accounting within CORSIA provides a representative range of possible emission factors for this process, as shown in Figure 1. For any particular feedstock the exact value for a given facility can vary according to hydrogen source and regional electricity grid emissions intensity at the biorefinery in question. In particular, the use of green hydrogen could reduce direct GHG emissions from fuel conversion by 20%, according to the GREET model (GREET, 2019). However, the use of green hydrogen remains uncommon because of cost (ICAO, 2019a).

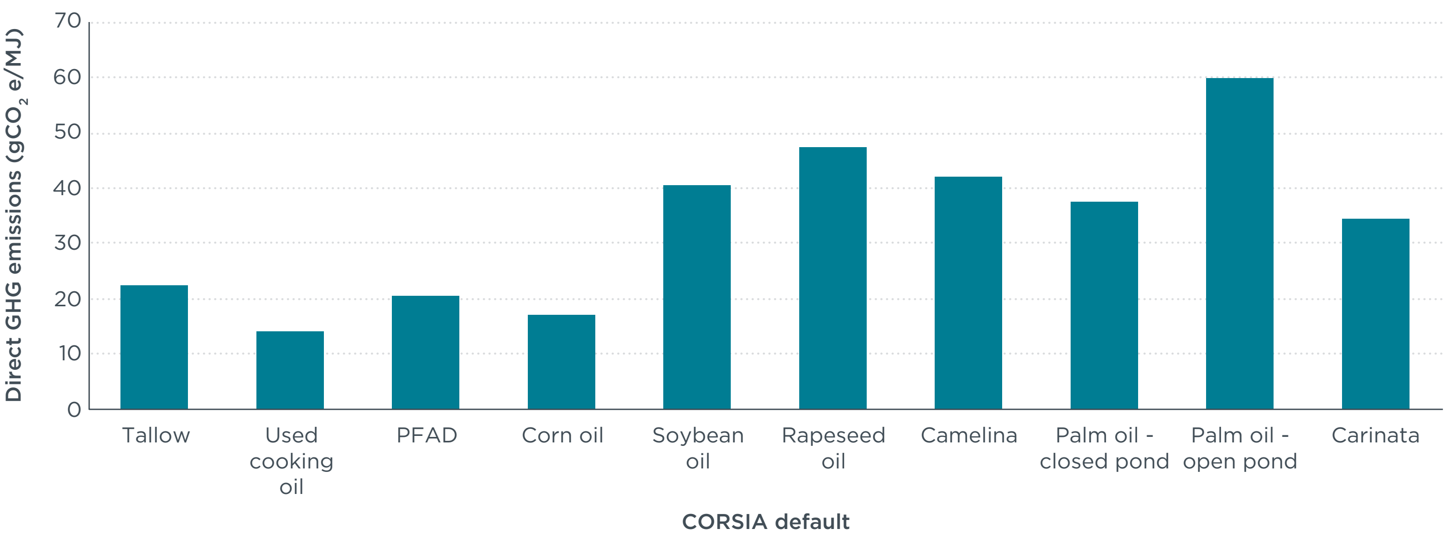

Figure 1: Summary of direct LCA emissions for HEFA SAF production pathways. HEFA emissions may differ based on additional processing and allocation methodology. Camelina and carinata have had their direct LCA emissions assessed, but their ILUC emissions have not been estimated by the ICAO.

The values used for CORSIA in Figure 1 are consistent with direct LCA estimates from the literature as well as the GREET model (GREET, 2019). For example, O'Connell, Kousoulidou, Lonza, and Weindorf (2019) estimate a range of 39–53 g CO_2e/MJ for direct emissions from HEFA pathways, and the recast Renewable Energy Directive (RED II) presents typical values ranging from 15–62 g CO_2e/MJ (EU, 2018). The pathway with the highest emissions is palm oil-derived HEFA produced with an open pond for the treatment of palm oil mill effluent at 60 g CO_2e/MJ, due to the emissions attributable to methane released from the pond. This remains the predominant configuration for palm biodiesel production (ICAO, 2019a).

Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK)

The gasification-Fischer Tropsch (gasification-FT) pathway, with and without added aromatics (FT-SPK and FT-SPK/A), allows for a wide variety of waste and residue-based feedstocks to be processed into drop-in hydrocarbons. The feedstocks are first pre-treated to ensure uniform consistency, then put through a partial oxidation process called gasification to produce syngas — primarily a mix of CO and H_2 with a smaller quantity of other gases such as CO_2 and CH_4 — which is then cleaned and conditioned to remove impurities. Intermediate steps during cleaning and conditioning can include water-gas shift reactions and steam reforming to produce the desired syngas composition. The syngas is then treated using Fischer-Tropsch synthesis with a chemical catalyst to produce a range of hydrocarbons including synthetic kerosene and diesel (Baldino et al., 2019). While this pathway is not common at commercial scales, there are still many life-cycle assessments of it. The process tends to produce excess heat and electricity; if used, these co-products reduce the life-cycle GHG intensity of FT-SPK fuel from gasification.

Electrofuels are produced via FT synthesis using hydrogen generated from electrolysis and CO_2. A life-cycle assessment of this pathway has not yet been conducted for CORSIA. So long as the CO_2 captured for the process is either taken from the atmosphere or captured from an existing point source without indirectly increasing emissions of CO_2, emissions from combustion for this pathway are considered to offset carbon capture during upstream fuel production. Due to conversion losses associated with hydrolysis and fuel production, which can range from 38% to 63% depending on configuration, it is necessary for renewable electricity to be used for this pathway to achieve GHG reductions (Schmidt, Weindorf, Roth, Batteiger, & Riegel, 2016). Using grid-average electricity in Europe, the WtWa emissions from electrofuels would exceed the petroleum baseline (Schmidt et al., 2016). To illustrate this, we include an estimate of the well-to-wheel emissions for synthetic diesel produced from European grid-average electricity based on the most recent average of 296 g CO_2e/kWh and an assumed conversion efficiency of 64% to SAF on an energy basis (European Environment Agency, 2020). Because a large amount of renewable electricity is needed to produce electrofuels because of the overall low conversion efficiency of this pathway, the GHG emissions from construction of renewable electricity installations are sometimes included in the LCA. For example, the U.S. National Renewable Energy Laboratory estimates the full life-cycle emissions for wind power as approximately 11 g CO_2e/kWh supplied to the grid, of which the upstream materials and construction emissions necessary to build turbines account for 86% (NREL, 2013).

Figure 2 presents the direct LCA emissions from the gasification-FT pathways, as estimated by ICAO for CORSIA (ICAO, 2019a). We supplement these estimates with a value for electrofuels produced using renewable electricity, taken from Schmidt et al. (2016). These pathways provide 85%–95% GHG savings relative to conventional petroleum jet fuel, with the exception of municipal solid waste (MSW)-derived fuel, which has a broad range of emissions depending on its nonbiogenic content. Plastic in MSW effectively sequesters carbon over a long time period if it remains in a landfill, whereas this is less likely for biogenic material, much of whose carbon content would be released as methane or oxidized if left in a landfill, or combusted into biogenic CO_2. MSW with higher plastic content thus has a higher GHG intensity (Suresh, 2016). The results of CORSIA's gasification-FT LCA analysis generally align with those from the GREET model, which estimates direct emissions of 5–12 g CO_2e/MJ for FT diesel produced from biomass. Similarly, default direct LCA GHG emission estimates for FT diesel for the RED II range from 3 to 12 g CO_2e/MJ (EU, 2018). While this pathway does not utilize food crops, some feedstocks such as energy crops may bear indirect emissions attributable to their use.

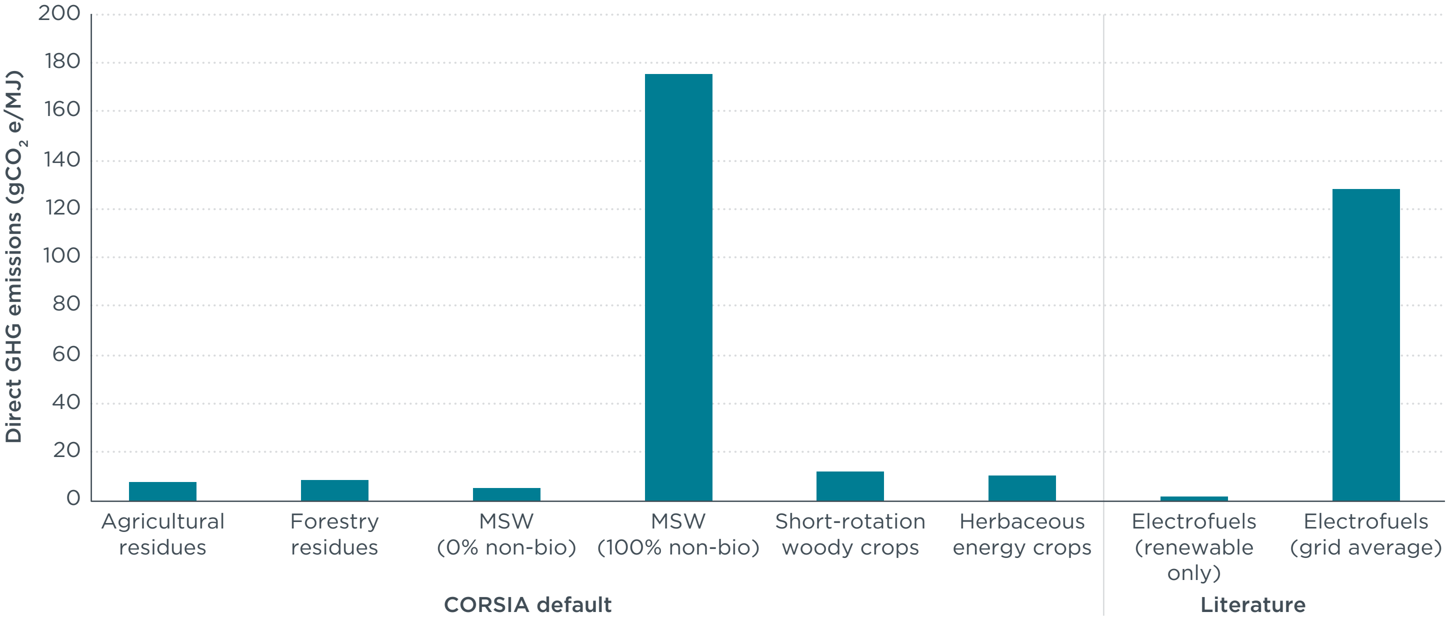

Figure 2: Summary of direct LCA emissions for FT-SPK SAF production pathways. FT-SPK emissions may differ based on additional processing and allocation methodology.

Alcohol to jet (ATJ)

Producing jet fuel from alcohols can be done by first producing alcohol through biochemical or thermochemical conversion and then upgrading that alcohol through a combination of dehydration, oligomerization, and finally hydrotreating to assemble drop-in hydrocarbons. This pathway can use conventional sugar and starch crops such as sugar cane and maize in addition to more challenging lignocellulosic feedstocks, such as energy crops or agricultural residues. This pathway has variation depending on feedstock choice and the choice of intermediate alcohol, which can be either ethanol or isobutanol.

Direct LCA GHG emissions for this pathway have been estimated by ICAO for a variety of feedstocks. There are also several direct LCA's for ATJ in the literature. The body of literature suggests that ATJ fuels generally have higher emissions than either HEFA or gasification-FT fuels; in most cases, the biochemical process for alcohol production is already GHG- and energy-intensive, particularly for starches such as maize and cereals; sugary crops such as sugar beet and sugar cane tend to be more efficient to grow and process (ICAO, 2019a). It is also possible to ferment flue gases such as those from steel mills, which contain energy-rich gases such as CO and H_2 into ethanol as a precursor to ATJ production. ATJ generally has higher direct emissions than first-generation ethanol or cellulosic ethanol pathways for the road sector, due to the added energy and emissions required for alcohol upgrading (Tao, Markham, Haq, & Biddy, 2017).

Figure 3 summarizes the direct LCA emissions from a selection of ATJ pathways. ICAO's LCA analysis for CORSIA estimates that the various ATJ pathways have direct LCA emissions ranging from 23.8 to 65.7 g CO_2e/MJ. Sugar cane-derived ATJ generally has low emissions reflecting high efficiency and yields from sugar cane production, whereas maize-derived ATJ fuel has higher emissions because of the additional energy required for maize cultivation, milling, and fermentation (ICAO, 2019a).

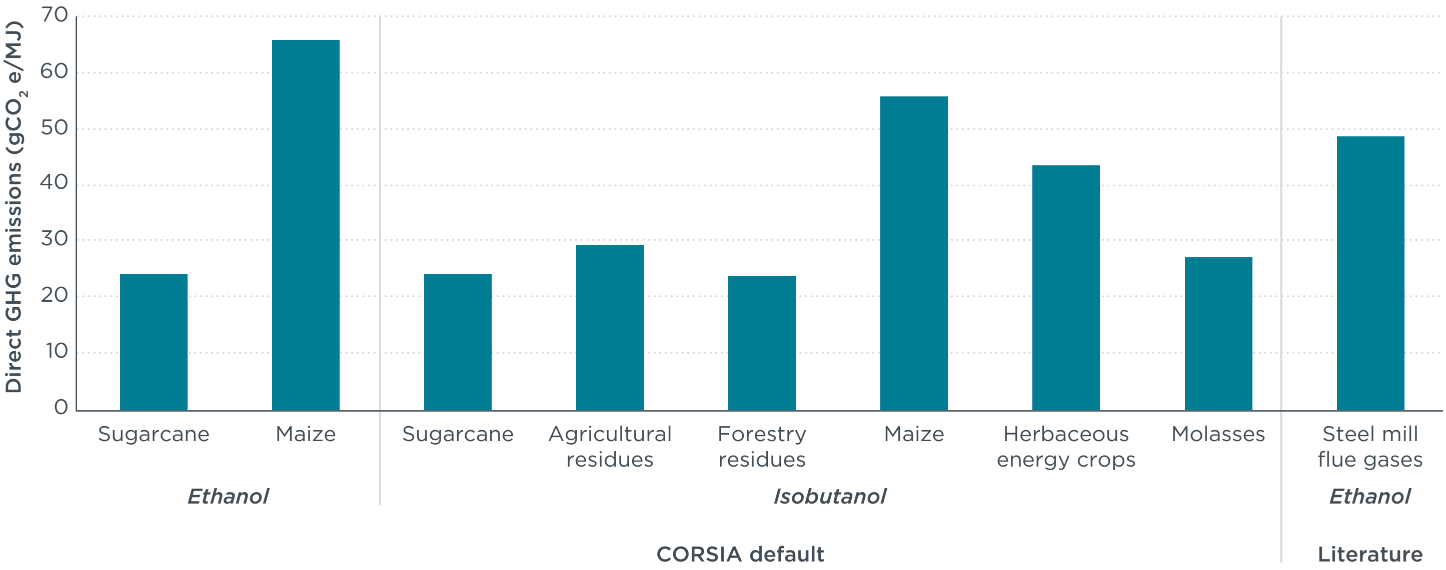

Figure 3: Summary of direct LCA GHG emissions for ATJ SAF production pathways.

ATJ pathways using either lignocellulosic residues or energy crops could have emissions on the lower end of the spectrum. This is because of much lower feedstock production emissions than most purpose-grown food crops and because combusting the lignin in these crops, which cannot be hydrolyzed into sugars, produces renewable electricity as a by-product.

Another potential source of feedstocks for ATJ are flue gases from steel mills. While default emissions for ATJ produced from flue gases has not yet been characterized by the ICAO, a recent LCA for the Lanzatech process estimates that ethanol production emissions from blast furnace gas are 31.4 g CO_2e/MJ (Handler, Shonnard, Griffing, Lai, & Palou-Rivera, 2016). This LCA represents a case where the flue gas would otherwise have been flared, releasing CO_2 into the atmosphere. Direct emissions in that analysis are primarily driven by utility-derived steam and electricity for the fuel production process, which are directly proportional to the carbon intensity of the local grid; in that case, the authors assume a U.S.-average electricity grid carbon intensity. Assuming the average yield of drop-in fuel per kg of ethanol in the CORSIA LCA methodology, or 0.50 kg of drop-in jet fuel per kg ethanol, and the ethanol upgrading emissions estimated in GREET, we estimate that this pathway has life-cycle GHG emissions of approximately 48.5 g CO_2e/MJ.

Synthetic iso-paraffins (HFS-SIP)

Instead of more-common alcohols, sugars can also be fermented into farnesene ($C_{15}H_{24}$), which has a longer carbon chain length and higher energy density than ethanol or isobutanol. Farnesene is then hydrotreated into farnesane ($C_{14}H_{32}$), a hydrocarbon that can be used at 10% blend levels in jet fuel. This pathway primarily uses sugary feedstocks such as sugar cane or sugar beet, though it is possible to use cellulosic feedstocks if the cellulose is first hydrolyzed into sugar (Mitrovich & Wichmann, 2017).

The direct LCA emissions from this pathway have been estimated by ICAO for CORSIA, as summarized in Figure 4. While more than half of the GHG emissions for this pathway are attributable to feedstock cultivation, there may be opportunities to reduce the GHG intensity at the bio-refinery through the increased use of renewable electricity and green hydrogen for hydroprocessing (GREET, 2019). Compared with other pathways, the SIP process is in an earlier stage of technological readiness and therefore there are fewer comparable studies in the literature. In part due to uncertainty over the farnesene yield from this process, estimates of the LCA GHG emissions can vary considerably (Klein-Marcuschamer et al., 2013). De Jong et al. (2017) estimate WtWa emissions of 45 g CO_2e/MJ for sugar cane SIP, noting that the results are highly sensitive to the assumption on the SIP yield. Moreira, Gurgel, and Seabra (2014) estimate a value of 21 g CO_2e/MJ for sugar cane SIP.

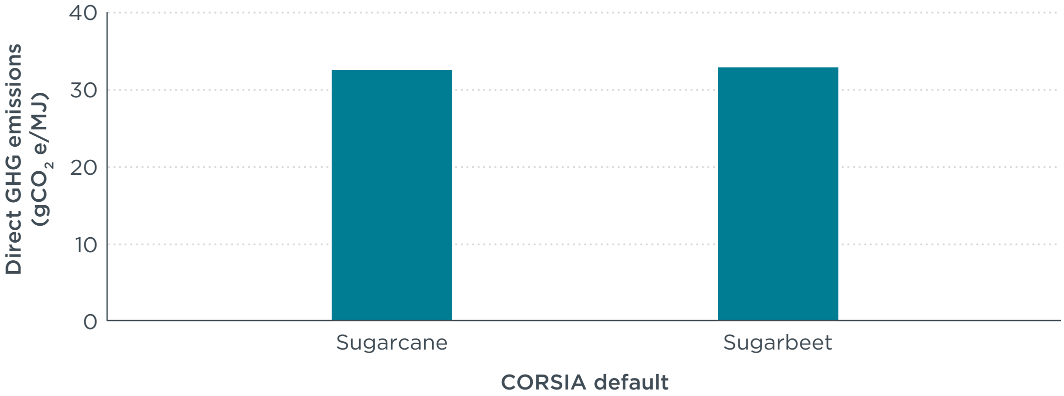

Figure 4: Summary of direct LCA emissions for SIP SAF production pathways

Other near-term SAF pathways

While we have focused so far on pathways that have been certified or are in the later stages of certification, there remain several other pathways have not yet been well documented. This is true particularly for pathways that produce only a portion of SAF in their overall product slate. While we can draw broad conclusions on the sustainability impacts of these pathways based on their chosen feedstocks, there is still insufficient information to present LCA factors for the direct production of these fuels for SAF or road-sector HVO.

The catalytic hydrothermolysis jet (CHJ) process, certified in 2020, utilizes FOGs but has several important differences from the HEFA process despite a similar name. After cleaning and filtering of the recovered waste oils, FOGs undergo hydrothermolysis, where they are combined with water and brought up to high heat and pressure. The resulting mixture is cracked and isomerized to produce a mix of hydrocarbons in the middle distillate range (Sapp, 2020). After that stage, the output requires less hydrotreatment than HEFA fuels; furthermore, the range of compounds contains levels of aromatics similar to those of conventional petroleum crude and may allow higher blend levels than HEFA fuels (Zschocke, Scheuermann, & Ortner, 2012). This pathway has not been characterized in the LCA literature, but we can draw some conclusions on its GHG performance based on feedstocks. Like the HEFA pathway, it is very likely that CHJ fuels will deliver higher GHG savings if produced from waste FOGs rather than from virgin vegetable oil.

It is also possible to co-process FOGs in a conventional petroleum refinery in limited quantities. This pathway may be cheaper than building a dedicated biorefinery, as it would use existing petroleum refining infrastructure. Given the small quantities of FOGs blended, the refinery outputs are difficult to distinguish from pure fossil fuel refinery outputs without chemical testing to track the biogenic share of the product, which could make verification more challenging (CARB, 2017). Total LCA emissions from this pathway could be estimated through a mass balance approach, based on the share of bio-oils input into the refinery relative to crude oil. The resulting fuel's life-cycle GHG emissions would vary according to the upstream emissions intensity of the bio-oil while also including the proportionate energy and emissions attributable to refining.

Indirect emissions from SAF production

Indirect land-use change emissions

Increased demand for biofuels made from crops grown on dedicated cropland, such as wheat or palm, may displace commodity use for food and feed and increase the total agricultural area needed to meet demand. The conversion of high carbon-stock forests, natural lands, and pastures to agriculture to meet increased demand would release carbon from disturbed biomass and soil and thereby would generate indirect emissions attributable to those biofuels. ILUC emissions, while not directly measured in an LCA like inputs and outputs at a biorefinery, are nonetheless an important consideration when evaluating the climate implications of alternative fuels. ILUC emissions are generally estimated through the use of an economic model that estimates the changes in global land use in response to an increase in biofuel demand (Malins, Searle, & Baral, 2014).

Multiple jurisdictions have conducted ILUC assessments for road-sector biofuel policies, including the ICAO, the European Union, the United States, and California (Woltjer et al., 2017). Additional ILUC assessments have been developed by researchers at universities and institutions such as Argonne National Laboratory (ANL) (Qin, Dunn, Kwon, Mueller, & Wander, 2017). The magnitude of estimated ILUC emissions varies significantly based on the feedstock in question, the economic model used for the assessment, and the modelers' assumptions (Malins et al., 2014). As a result, there is high uncertainty on the magnitude of ILUC emissions.

The ILUC assessment conducted by ICAO for CORSIA to estimate default life-cycle values for SAFs includes results generated via two economic models with different analytical frameworks, the Global Trade Analysis Project (GTAP-BIO) model and the Global Biosphere Management Model (GLOBIOM). The GTAP-BIO model is a computable general equilibrium model that simulates the global economy, whereas the GLOBIOM model is a partial equilibrium model focused on the agricultural, livestock and forestry sectors. While the task group at ICAO developing the ILUC assessment sought to harmonize the assumptions across the two models as closely as possible, the divergence in estimates for some pathways illustrates the impact of the analytical framework on the results.

A closer analysis of the modeling documentation suggests that differences are attributable to several factors. Overall, GTAP-BIO is more optimistic in assuming that the increased demand for crops can be offset by higher crop yields and reduced commodity consumption in food and other sectors than would occur in the absence of biofuel policies. The models have different global trade frameworks, and international shifts in land from the demand shock manifest differently across the two models. Underlying differences in land categories and their assumed carbon stock also influence differences between the two results. For example, GTAP-BIO includes a category called "cropland-pasture," which is pastureland that was recently cropped and can easily transition back to cropping without significant carbon loss (Malins, 2019). GLOBIOM does not include this category, but it does include abandoned and "other natural land" categories that in some cases are used for biofuel production. The GLOBIOM modelers assume that both of these land categories have higher carbon stocks than the assumption by the GTAP-BIO modelers for cropland-pasture (Malins, 2019).

Figure 5 illustrates ICAO's estimated ILUC factors for a selection of pathways relevant to the EU context, separated by conversion technology, feedstock, and the ILUC model.[1] The default factor used for CORSIA for each feedstock is the average of the two model results for that feedstock if the difference between those results is less than 8.9 g CO_2/

1 We do not include camelina or carinata as these pathways do not yet have ILUC assessments for the CORSIA process. U.S.-specific energy crop pathways are excluded as these pathways are unlikely to be used in the EU.

MJ, or 10% of the baseline GHG intensity. When the model results diverge by a greater amount, 4.45 g CO_2e/MJ, or half the allowed divergence, is added to the lower estimate. The two models present similar results for starchy and sugar crops, but there is wide divergence for oilseeds, resulting in default ILUC values much closer to the GTAP-BIO results. This approach may understate the risk of high ILUC emissions, particularly for pathways where using one model's ILUC estimate would cause the fuel's total WtWa emissions to exceed the petroleum baseline, such as the case of either Brazil soy HEFA or palm oil HEFA when using the GLOBIOM factors.

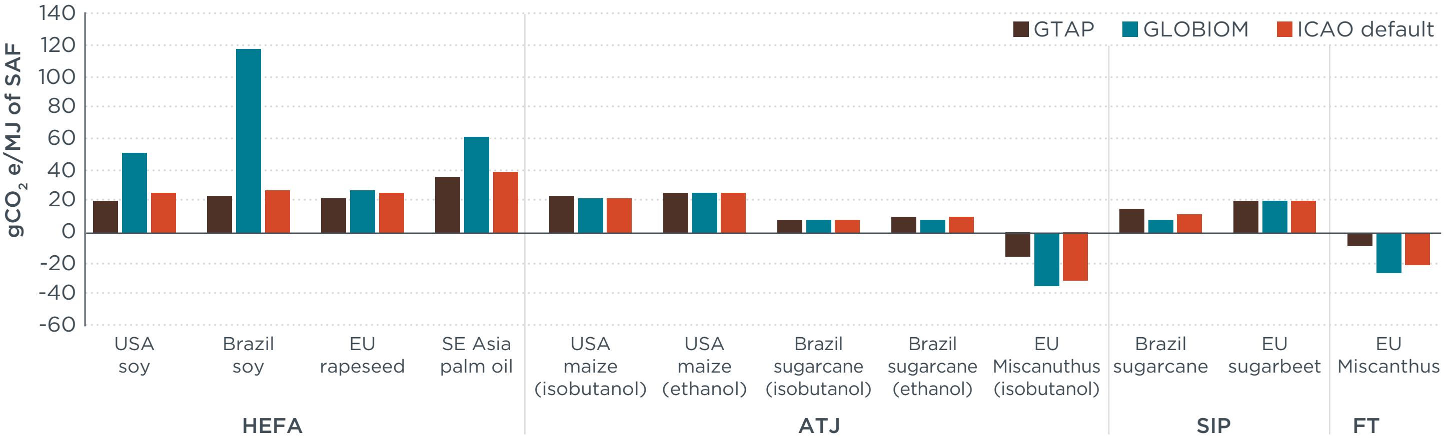

Figure 5: Summary of ILUC emissions for food crop-derived SAF production pathways.

Within these categories, we observe several trends in ILUC across feedstocks.[2] Generally, oilseeds have the highest ILUC emissions. For palm oil, this is attributable to expansion onto high carbon stock peatlands in Southeast Asia. Peatland conversion also influences estimated ILUC emissions from other oilseeds, reflecting substitution effects between vegetable oils. The ICAO estimates for palm oil HEFA in particular are much smaller than values previously estimated in California using GTAP-BIO and in a previous GLOBIOM modeling study conducted for the European Union (CARB, 2015; Valin et al., 2015). On the other hand, ILUC emissions estimated for starch and sugar crops by the ICAO are generally in agreement not only between the two models but also with previous ILUC analyses conducted using GTAP-BIO and GLOBIOM for California's LCFS and the RED II, respectively. When factoring in ILUC, it is evident that oilseeds may have ILUC emissions that increase their emissions above the petroleum baseline, whereas starch and sugar crops have lower ILUC emissions.

Despite variation between the two models, energy crop ILUC estimated for SAF production is generally low or negative. As with the food crops, there are some pathways with large differences between the two models. In some cases these differences are attributable to differing assumptions of soil carbon stock and land cover in the models, as GTAP-BIO projects that energy cropping occurs predominantly on cropland-pasture, which the modelers assume has lower initial carbon stocks compared with the assumption for abandoned agricultural land in the GLOBIOM model. This results in higher soil carbon sequestration with energy cropping in the GTAP-BIO model compared with the GLOBIOM model (Malins, 2019).

2 We note that while camelina and carinata's direct LCA emissions have been assessed, these feedstocks have still not had ILUC emissions estimated by ICAO.

Indirect displacement emissions

While there have been several ILUC assessments for crop-derived biofuels over the past decade, less attention has been paid to indirect effects of using by-products, wastes, and residues for alternative fuels production. While LCA methodology for fuels generally treats by-products, wastes, and residues as bearing no upstream emissions prior to their collection or diversion, many of these materials are not true wastes—in fact, many of them have valuable existing uses. Their diversion from existing uses can in some cases generate indirect emissions from the materials that would be used in their place. In some cases, these diversion emissions can be as high as ILUC emissions and greatly change the perceived GHG savings from some feedstocks.

Indirect displacement emissions for wastes, residues, and by-products have attracted some recent interest in the literature and among policymakers. Preliminary analysis suggests that some of these materials have well-documented existing uses with established markets and carry a high likelihood of substitution by crops or fossil fuels, with associated GHG emissions (Malins, 2017). For example, palm fatty acid distillates (PFADs) are by-products of the palm oil production process that in the absence of biofuel demand are almost entirely consumed. Their diversion from existing uses in the oleochemical industry and in livestock feed would be likely to result in substitution by palm oil, which is comparably priced, has flexible supply, and has similar physical properties (Malins, 2017). Research has also noted displacement effects for materials that have existing uses in heat and power. For example, materials combusted for energy recovery where they are produced, such as tall oil and black liquor from the wood pulping process, would most likely be replaced by the next-cheapest substitute, often fossil fuel (Malins, 2017).

Renewable fuels of nonbiological origin, such as electrofuels or fuels made from captured flue gases, may also cause displacement. While electrofuels made using renewable electricity have near-zero direct emissions, it is important to ensure that renewable electricity used for electrofuel production is both new and additional. In jurisdictions without that protection in place, such renewable electricity could be diverted from existing demand and be replaced by a marginal source of electricity (Searle & Christensen, 2018). Industrial flue gases from steel mills, a potential feedstock for jet fuel production, are already captured and combusted for onsite energy recovery at many European steel mills. Therefore, diverting only those flue gases that are either emitted into the atmosphere or flared would avoid necessitating substitution by a new source of energy (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

Table 2 summarizes the existing literature on displacement emissions for a selection of feedstocks that could be used for SAF production, showing the existing markets for each feedstock and the materials that could be used in their place. The final column illustrates the risk of displacement effects for each feedstock, based on assessments of existing uses and potential substitutes. Materials like agricultural residues and some forestry residues, if collected in quantities that would not affect soil quality, can generally be diverted with low indirect emissions. Likewise, MSW diverted from landfills can have negative displacement emissions due to avoided methane leakage from anaerobic digestion at some landfills; even in cases where landfill gas collection is in place, some quantity of methane escapes during the landfilling process. The sourcing of some feedstocks can have a large impact on displacement emissions. For example, while used cooking oil sourced from the European Union is considered a waste, in the United States it might be diverted from animal feed and could thus entail some displacement emissions (Pavlenko & Searle, 2020).

Generally, lignocellulosic materials with fewer or less well-developed existing markets have a lower risk of displacement emissions than higher-value FOGs that may be replaced with fossil fuels or virgin vegetable oils.

Table 2: Existing markets, substitute materials, and displacement emission risks for potential by-products, wastes, and residues for SAF production.

Feedstock	Existing market or use	Likely substitutes	Displacement emissions risk
Animal fats	Oleochemical applications, heat and power	Heavy fuel oil, vegetable oil, natural gas	High
Corn oil	Animal feed	Vegetable oil, corn, wheat, barley	High
Palm fatty acid distillates	Oleochemicals, animal feed, heat and power	Vegetable oil, heavy fuel oil	High
Molasses	Animal feed, yeast	Cereals, sugar beet	Medium
Industrial flue gases	Heat and power	Natural gas, grid electricity	Medium
Renewable electricity	Electricity sector	Marginal electricity source	Medium
Used cooking oil	None	None	Low
Agricultural residues	Livestock bedding and feed, mushroom cultivation, horticulture, heat and power, soil health	Cereals, lignocellulosic energy crops, renewable electricity, rubber, sand, gypsum, and dried manure	Low[a]
Forestry residues	Heat and power, soil health	Natural gas, grid electricity	Low[a]
Municipal solid waste	Heat and power, landfill gas recovery	Natural gas, grid electricity	Low

[a] Assuming that residue removal is consistent with sustainable removal rates.

Note: Information sourced from Malins (2017); Searle et al. (2017); and Searle and Christensen (2018).

Results and discussion

The true climate performance of SAFs varies enormously by feedstock and can be fully understood only by considering both direct and indirect effects together. In this section, we present the total WtWa emissions for each pathway, taking into account both direct and indirect emissions, and identify those feedstocks and pathways that would deliver the greatest emission savings relative to baseline petroleum jet fuel.

Figure 6 illustrates the WtWa emissions from food and energy crop-based SAFs with LCA values estimated by ICAO, relative to the petroleum baseline. The direct emission values presented here don't reflect the real-world variability between facilities and supply chains, but rather, a broad average; individual facilities may have higher or lower values depending on their specific operating parameters. The primary value on the chart utilizes the ICAO ILUC default factor, and the error bars illustrate the range when taking into account the separate ILUC estimates for both the GTAP-BIO and GLOBIOM economic models. After taking into account ILUC emissions, the emission savings from oilseed-derived SAFs diminish considerably when using the default value—providing a range of 12.5%–27.0% GHG savings versus petroleum jet fuel. Using the default ILUC factor, GHG emissions from open-pond palm oil HEFA exceeds the petroleum baseline by 11.4%. Soy and palm HEFA emissions could both exceed the petroleum baseline using the GLOBIOM ILUC factors; this possibility is understated when using the default ILUC factors.

These results also indicate that maize ATJ fuels are generally energy and emissions-intensive. Their high direct emissions, in conjunction with moderate ILUC, nearly eliminate any GHG savings from these fuels. In contrast, sugar cane and sugar beet-derived fuels have higher GHG savings, largely due to the high yields and efficiencies of these feedstocks, which translate into lower direct production and ILUC emissions. The SIP pathway has higher emissions, most likely reflecting lower feedstock conversion efficiencies than ATJ, resulting in greater direct and ILUC emissions per MJ fuel produced.

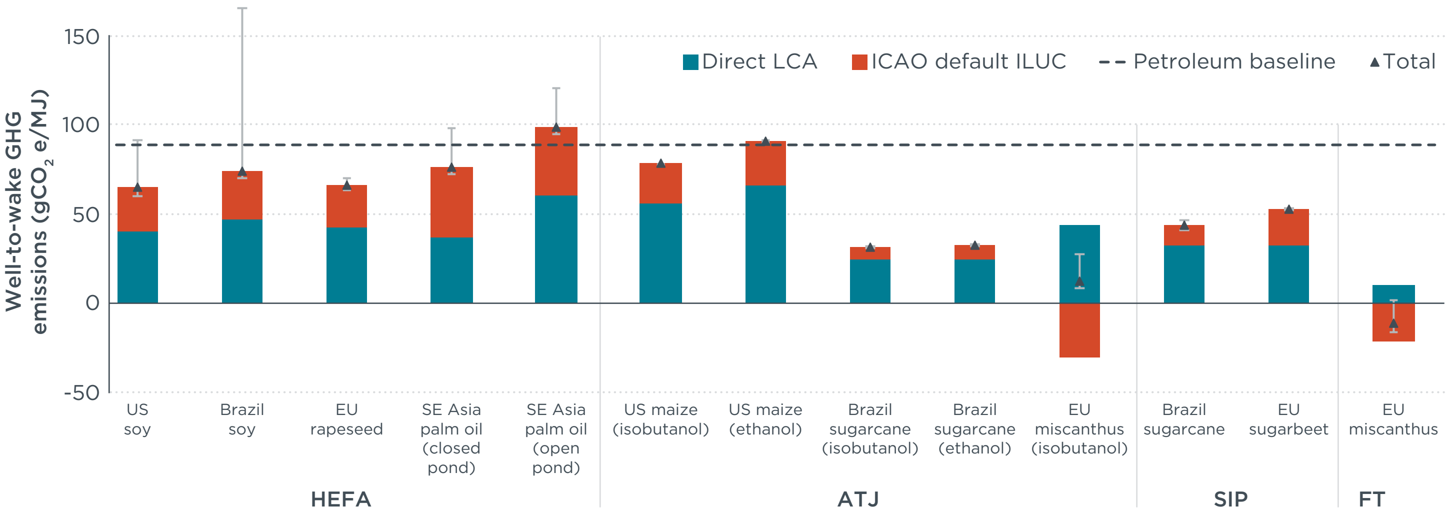

Figure 6: Well-to-wake GHG emissions for crop-based SAFs relative to petroleum jet fuel baseline. Note: Range of WtWa GHG emissions using ICAO ILUC estimates.

For energy crops in Figure 6, there is a trend toward low overall WtWa values compared with food crops, even from ATJ pathways with high direct LCA emissions. The variation in the ILUC results across models underscores that there is substantial uncertainty in ILUC emissions for the EU-grown grass Miscanthus. Overall, ICAO estimates a range of total WtWa GHG emission reductions of 70%–118% compared with the fossil baseline for energy crops. While these results generally align with previous research on energy crop-derived fuels, energy cropping is not yet in wide scale practice. If anticipated yields, carbon stock sequestration and the types of land used for energy cropping vary from the model assumptions, the net impact of these fuels could change considerably.

Figure 7 illustrates the WtWa emissions from SAFs produced from a variety of noncrop feedstocks, including electrofuels as well as different by-products, wastes, and residues. We also include indirect emissions attributable to displacement as well as construction GHG emissions for renewable electricity for electrofuels specifically. This chart includes several emission factors estimated by ICAO, as well as emission estimates inferred from the production of road sector fuels. With the exception of MSW produced from nonbiogenic wastes, these pathways generally deliver more than 50% GHG reductions relative to the baseline—if only direct emissions are considered. However, the indirect displacement emissions, while uncertain, could affect the GHG savings of some feedstocks substantially. In particular, the potential substitution of palm oil for PFADs and corn oil results in substantial indirect emissions which counteract those fuels' GHG savings. Taking displacement into effect, the GHG emissions from PFAD SAF are 10% higher than the fossil baseline, whereas corn oil would deliver GHG emissions reduction of only 18%. Similarly, the displacement of animal fats from existing uses for heat and power and oleochemicals causes substitution by virgin vegetable oils with high ILUC as well as fossil fuels, decreasing their emissions savings to 45%.

The best-performing fuels in this category are generally those produced via the gasification-FT pathway with low energy inputs and low risk of displacement. Feedstocks with high carbon savings in this category include agricultural residues, forestry residues, and the biogenic fraction of MSW. Fuels made from these feedstocks reduce emissions by 58%–140% relative to the petroleum baseline. MSW-derived may have high indirect emissions savings due to avoided methane emissions at landfills. Used cooking oil SAF also delivers some of the highest GHG reductions — 84% — of any feedstock assessed and has no indirect emissions, as it does not have any existing uses outside of biofuel in the European Union. This relationship may be different for used cooking oil and other waste fats imported into the European Union, for example from the United States, where these materials are used in livestock feed. Additionally, electrofuels can offer high GHG savings relative to petroleum provided that they can be produced using electricity that is both additional and renewable. Otherwise, electrofuels produced from grid-average electricity exceed the emissions from petroleum jet fuel. Several of the ATJ pathways have relatively higher emissions, as both molasses and steel mill flue gas-to-jet fuel have both high direct production emissions as well as existing uses with displacement effects.

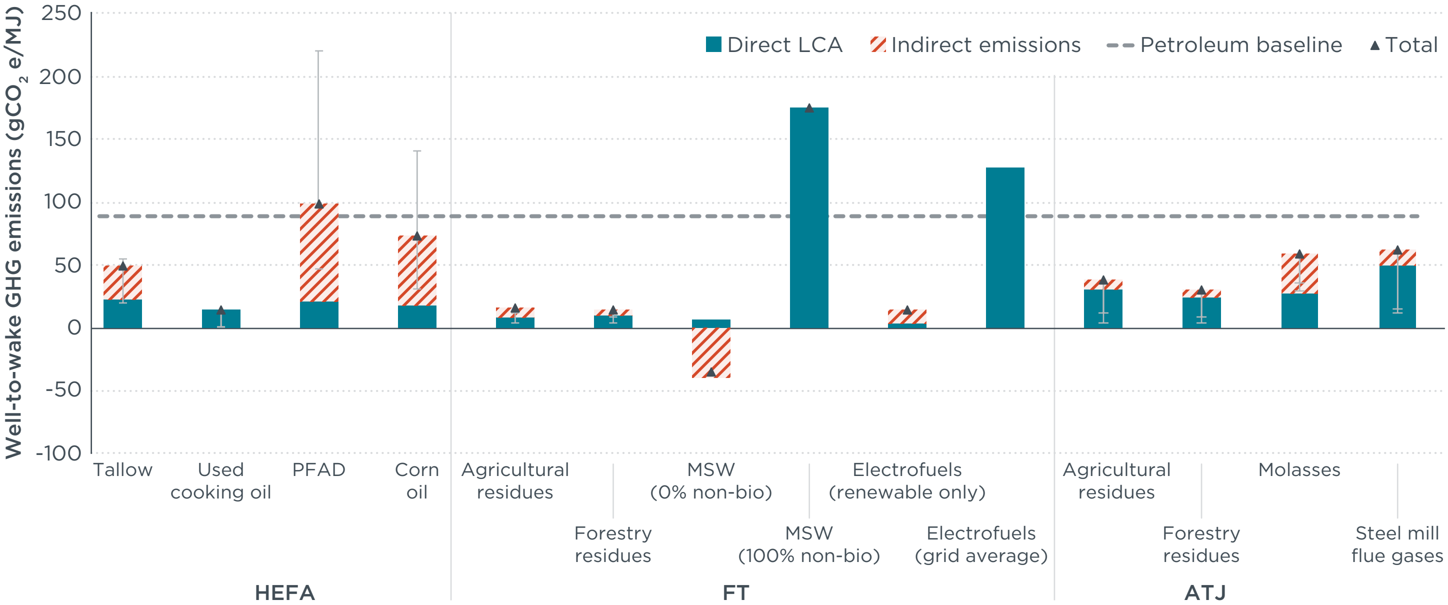

Figure 7: Well-to-wake GHG emissions for SAFs made from noncrop feedstocks relative to petroleum jet fuel baseline. The error bars on this figure reflect the range of possible displacement emissions taking into account the low and high ends of the ranges estimated by Malins (2017) and Searle et al. (2017) for relevant feedstocks.

Beyond the direct and indirect GHG emissions attributable to SAFs, there are other important sustainability considerations critical for SAF policy. As of 2020, ICAO's CORSIA scheme had only two sustainability criteria for eligibility, including a 10% GHG reduction threshold and a requirement that biofuels not be grown on high carbon stock land (ICAO, 2019b). In contrast, the RED II has a 70% GHG reduction threshold for fuel producers beginning production starting in 2021. However, the European Union's GHG threshold applies only to direct emissions, thus failing to safeguard against fuels with high ILUC emissions. EU policymakers could consider implementing more-stringent criteria to ensure that EU SAFs are held to a higher standard, including some that the ICAO previously considered. For example, a GHG reduction threshold higher than ICAO's 10%, when applied to both direct and indirect emissions, would limit the policy to waste-oil HEFA fuels, second-generation biofuels, and electrofuels. Additional criteria that may be relevant include environmental considerations such as minimizing impacts on local soil and air quality as well as societal considerations, such as ensuring that feedstock supply chains have no adverse effects on food availability, human rights, and labor rights. Some of these issues, such as soil erosion, would apply to some noncrop feedstocks like agricultural residues. Implementing these criteria would most likely require sustainability certification schemes that could apply local assessments and knowledge on a case-by-case basis.

Conclusion

The wide variation in climate impacts across different SAF feedstocks and conversion technologies illustrates that simply displacing petroleum jet fuel with any alternative jet fuel will be insufficient to drive deep decarbonization in aviation. While the implementation of CORSIA provides both the framework for crediting the use of SAFs in aviation as well as an extensive set of default emission factors to understand their climate impacts, eligible SAFs do not necessarily need to provide greater than a 10% emission savings. For example, limiting eligibility to those pathways that offer at least 70% GHG savings relative to the baseline, a similar threshold to the RED II, could help ensure that the only fuels with a high certainty of achieving real GHG reductions would receive support. Therefore, it is incumbent on the European Union to improve upon the foundation provided by the CORSIA methodology and focus its policy support on only those pathways that have a high certainty of achieving strong GHG savings. Based on an analysis of the sustainability of various near-term SAF pathways that may be used over the next decade, we can draw the following conclusions:

1. **High ILUC emissions from virgin vegetable oil HEFA pathways undermine any GHG savings from these fuels.** While the HEFA pathway has the highest technological readiness of any SAF pathway and could provide high volumes of fuels in the near-term, their overall WtWa emissions are high even using CORSIA's optimistic ILUC factors. Based on life-cycle GHG estimates for virgin vegetable oil HEFA, most of these pathways are either only slightly better than or worse than the petroleum baseline. Given the limited potential for reducing direct emissions from the HEFA pathway, there is substantial risk and little long-term benefit to supporting vegetable oil HEFA fuels.
2. **Lignocellulosic by-products, wastes, and residues generally have low WtWa emissions and a low risk of indirect effects.** This analysis suggests that processing these feedstocks with gasification-FT can produce fuels with high GHG savings, ranging from 58% to 140%. With protections in place to ensure that only the sustainable fraction of residues is taken for use in biofuel production, these feedstocks can be applied with a low risk of indirect effects and soil carbon losses. Agricultural residues, forestry residues, and the biogenic fraction of MSW are either not fully used in existing markets in the European Union or can be diverted with low displacement emissions.
3. **Diverting by-products, wastes, and residues with high-value existing uses to SAF production carries sustainability risks.** Displacement effects from the increased use of by-products, wastes, and residues for SAF production may warrant further analysis before SAF production from these feedstocks is scaled up. While used cooking oil has attracted substantial interest as a low-GHG feedstock for SAF use, other waste or by-product fats, oils, and greases tend to have displacement effects. Furthermore, importing greater quantities of used cooking oil for the European SAF market may cause indirect effects in those markets where it is already in use. We find that diverting animal fats, corn oil, PFADs, and tall oil from existing uses to SAF production would be likely to increase the emissions from these pathways when factoring in substitution by virgin vegetable oils or fossil fuels.
4. **Electrofuels require strong sustainability protections to avoided unintended indirect emissions and ensure GHG savings.** The environmental performance of electrofuels varies significantly based on what type of electricity is used to produce them. While they approach carbon neutrality when produced with additional, renewable electricity, electrofuels produced from grid-average electricity may have higher GHG emissions than petroleum jet fuel. Therefore, strong sustainability protections to ensure that electrofuels are produced from additional, renewable electricity and that the electricity is not double-counted toward other policies are necessary to ensure the climate benefits of these fuels.

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