From Pulpwood to Jet Fuel: Forest Residues and Sustainable Aviation Fuel in the Southeastern United States

Decarbonizing the aviation sector with sustainable aviation fuel

The aviation sector is responsible for 2.5% of global annual greenhouse gas (GHG) emissions and ~4% of observed climate warming[1]. To limit warming to below 2°C, the International Civil Aviation Organization (ICAO) is aiming to reduce aviation emissions by 5% in 2030 and to achieve net zero GHG emissions from aviation by 2050[2]. The aviation industry is considered a hard-to-abate sector, because electrification of airplanes is not currently possible due to long-distance travel and plane weight restrictions. Currently, the only near-term option for decarbonizing medium- to long-haul commercial aviation is the production of sustainable aviation fuel (SAF) to replace conventional fossil fuels.

Sustainable aviation fuel refers to a suite of fuels produced in various pathways; the most developed of which are biofuels derived from organic biomass. In order to qualify as SAF, a fuel must meet 14 sustainability criteria defined by the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), including at least a 10% emissions reduction compared to conventional jet fuel[3]. Additionally, SAF must replace crude oil with another raw material, known as a feedstock (see next section), and it must have the same properties as conventional jet fuel to be compatible with commercial airplanes[4].

Even though SAF combustion emissions are similar to conventional jet fuel, SAF has the potential to reduce more than 60% of aviation emissions by 2050 when we consider the fuel's total life cycle emissions[5]. The total life cycle emissions of a fuel are calculated by adding up the emissions from each step of the fuel's recovery, production, and transportation processes in a life cycle analysis (LCA). Different feedstocks and conversion pathways result in different total life cycle emissions for SAF; only those combinations of feedstocks and conversion pathways that result in lower life cycle emissions than conventional jet fuel are considered sustainable.

Currently, SAF comprises less than 1% of global jet fuel use, but that is projected to increase by 900% in the next five years under mandates across Europe, Asia, and South America and market incentives in the United States (US)[6,7]. For example, ReFuelEU aviation requires 2% of jet fuel from airports in the European Union (EU)to be SAF by 2030[8], and the United Kingdom's (UK) Sustainable Aviation Fuel Mandate requires 2% of jet fuel to be SAF in 2025, increasing by 2% annually until 2040[9]. With increased demand for SAF, new feedstocks and sustainable land management practices may be necessary for SAF production to keep pace.

Feedstocks for SAF: first-generation and advanced

Feedstocks for SAF can be split broadly into two categories: first-generation and advanced or second-generation. First-generation feedstocks include food and feed crops, like corn, palm oil, and sugar cane. These feedstocks are processed into biofuel with well-developed technologies and often have established production pipelines. Advanced feedstocks include non-food, dedicated energy crops – such as the perennial *Miscanthus* grass – agricultural or forestry residues, and other waste materials, such as

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municipal solid waste. Production pathways for biofuels made from advanced feedstocks typically require more nascent technologies that may not yet be fully deployed at scale[10].

First-generation feedstocks, while more readily available as biofuels, are associated with major environmental and social sustainability concerns. For example, corn ethanol biofuel production in the US resulted in a 20-30% increase in crop prices and 24% more GHG emissions than conventional fossil fuel due to forest land conversion to corn cropland, increased fertilizer use, intensified production, and water degradation[11]. Land conversion, water and fertilizer use, biodiversity and food system impacts are not limited to corn ethanol production in the US but are common issues surrounding biofuels produced from first-generation feedstocks[10]. In fact, the EU excludes fuels produced from "food and feed crops" entirely from its SAF mandate for these reasons[8].

Advanced feedstocks, especially wastes and residues, have fewer sustainability concerns, because they don't interfere with food production systems and are generally associated with reduced land conversion[10]. Overall, this results in greater emissions reductions compared to first-generation feedstocks; in some cases, advanced feedstocks can provide net negative emissions due to energy co-production during the biofuel production process[10,12]. Advanced feedstocks have the greatest potential to increase SAF production over the coming decades and are critical to reaching a net-zero scenario[13].

CORSIA has approved 49 feedstocks for SAF production, and 32 of these are classified as advanced feedstocks[14]. However, currently ~90% of liquid biofuels and 100% of SAF are made from first-generation feedstocks[13,15]. Increasing biofuel production from advanced feedstocks is a key next step for achieving near- and long-term SAF goals[8,13,16], but progress is hindered by high capital costs, complex supply chain logistics, scaling of new technologies, and uncertain end product pricing[17]. While SAF mandates provide guaranteed demand, long-term offtake agreements, incentives for financiers of SAF production, and penalties for fossil fuel providers (a "carbon tax") could help encourage advanced SAF production and secure project returns[18].

Forest residues as a SAF feedstock

Wood has been used for energy production since the dawn of humanity. Forest products, including charcoal, fuelwood, pellets, and wood chips, still comprise more than 85% of global bioenergy production[19]. Wood-based bioenergy in the Global North focuses primarily on generating heat and electricity, but woody biomass can also be turned into liquid biofuel for SAF via gasification and synthesis (Fischer-Tropsch pathway) or fermentation to an alcohol intermediate (alcohol-to-jet pathway)[19,20]. The use of woody biomass as an SAF feedstock has considerable potential for GHG emissions reductions compared to conventional jet fuel, especially over the next 100 years[21–23].

Woody biomass for modern bioenergy is an advanced feedstock typically sourced from residues or wastes generated from commercial harvest of timberlands and processing of timber to produce wood products. However, the exact definition of what constitutes as an approved forest residue feedstock for SAF production depends on specific energy regulations relevant to bioenergy production, which can complicate market entry for SAF producers.

In general, most international and national bioenergy regulations define forest residues as substances that are produced by forestry activities but are not the target end product. For example, the target product for a commercial timber harvest is often sawtimber—tree stems at least 30cm in diameter—to be cut into lumber, but the branches, leaves, tops, and bark of those trees are also harvested as part of the process. In forestry, these residues are also called slash and can describe low-quality stems, branches, leaves, or bark left in the forest after a harvest[24]. CORSIA follows this general definition but adds that forest residues must have an "inelastic supply and little economic value"[14]. CORSIA has approved a variety of forest residues as feedstocks for SAF, including bark, branches, cutter shavings, leaves, needles, pre-commercial thinnings, slash, and treetops. However, individual nations may further restrict what qualifies as a forest residue feedstock under their own criteria. For example, to qualify as a forest residue under the US Renewable Fuel Standard, residues must originate from "planted trees from tree plantations for use in lumber, paper, furniture, or other applications"[25]. Both the UK and EU have their own additional requirements for forest biomass for bioenergy that consider land-use change, harvest sustainability, conservation, and more[26,27]. Because the aviation industry operates internationally, SAF producers wishing to use forest resides as a feedstock must ensure that their residues meet the applicable criteria not only for CORSIA, but also any relevant national regulations. Thus, forest residues that meet the requirements of an approved SAF feedstock under CORSIA and the US Renewable Fuel Standard, might not meet the criteria for SAF under ReFuelEU.

Market opportunity for pulpwood as a SAF feedstock in southeastern US

Pulpwood – small-diameter or low-quality wood used to produce paper and other wood fiber products – is not specifically listed as an approved forest residue feedstock by CORSIA, likely because globally, pulpwood has economic value in pulp and paper markets. Regionally, however, pulpwood's economic value is highly divergent. Pulp and paper markets are growing in South America, especially in Brazil, and steady in Europe[28]. However, the US pulp and paper market has been in decline for the last two decades due to reduced demand for paper and increased international competition[29,30]. While the US remains the largest producer of pulpwood globally, severe declines have caused dozens of pulp mill closures, particularly across the southeastern US, where the majority of pulpwood is sourced[29–31].

Mill closures, in combination with historically low pulpwood prices, mean the harvest and removal of pulpwood from the land is no longer an economically viable management option for many southern US forests. Instead, forest managers may choose to forego pre- or early-commercial thinning harvests that remove smaller trees for pulpwood and allow the remaining trees to grow larger and faster. Unthinned forests tend to be less-productive, more overgrown, and prone to pest and pathogen outbreak. Managers may also conduct thinning and allow harvested pulpwood to decay naturally or burn it onsite[32]. Thus, under some circumstances in forests in the southeastern US, pulpwood may fit CORSIA's definition of forest residues, specifically the definition of residues in the form of slash and pre-commercial thinnings. If southeastern US pulpwood could qualify as an SAF forest residue feedstock, it could open an entire new market for forest managers and SAF producers, revitalizing the market for small-diameter and low-quality wood, encouraging improved forest management with thinnings, diversifying the forest products industry, and increasing the available supply of SAF feedstock.

Cautions and recommendations

Supply and demand

The International Air Transport Association (IATA) estimates we need to produce 500 million tonnes (Mt) of SAF in 2050 to achieve net zero emissions[33]. In alignment with this goal, the US' SAF Grand Challenge is set to produce 100Mt of SAF in 2050[16], and reports suggest the US currently has approximately 20 million dry tonnes of woody biomass available for bioenergy production[33,34]. It is unclear, however, whether the available feedstock supply can keep up with future SAF demand. Li et al.[32] suggest that, depending on preprocessing and conversion technologies, forest residues in the southeastern US could supply 750,000–2 milllion tonnes of SAF annually, but this would only meet up to 20% of the 2030 SAF Grand Challenge goal (10Mt) and merely 2% of the 2050 goal[16]. Thus, forest residues are unlikely to meet current policy goals and future demand for SAF on their own.

However, forest residues represent less than a quarter of all biomass available for bioenergy in the US. The majority of American biomass for bioenergy comes from agricultural residues and purpose-grown energy crops[33,35]. As stated earlier, these feedstocks are typically associated with more sustainability concerns than forest residues and other advanced feedstocks, including land conversion and increased pesticide use, especially given the detrimental impacts of corn ethanol on US food production and GHG emissions[10,11]. Therefore, encouraging the use of forest residues as an SAF feedstock, even at relatively small scales, may alleviate pressure from more abundant, but potentially less sustainable feedstocks.

Sustainability and leakage

Forest residues for bioenergy are not without sustainability concerns of their own, though, and studies vary in their conclusions about the impacts of wood-based bioenergy[21,36,37]. Some claim that increased demand for woody biomass could encourage the overharvesting of forests, ultimately leading to deforestation, resulting in net carbon losses and increased GHG emissions. Others argue that, under certain circumstances, increased demand for woody biomass could result in net carbon sequestration by spurring more efficient forest management strategies and overall increases in forested land. Modeling the consequences of a wood-based bioeconomy is complicated and requires integrated knowledge of the underlying ecology, forestry and energy sectors, wood products economy, and policy landscape. Outcomes vary widely depending on model assumptions, underlying data, and regional contexts, making broad generalizations difficult[38]. Nevertheless, despite ongoing debate and uncertainty, high-level recommendations for ensuring the sustainability of wood bioenergy emerge from the literature.

Strict and explicit definitions of allowable woody biomass feedstocks for bioenergy would help clarify what is sustainable throughout the supply chain and would also allow for more transparent GHG accounting. Varying definitions of forest residues between regulatory bodies, researchers, foresters, and energy producers create uncertainty in what are acceptable feedstocks for bioenergy, including whether pulpwood in the absence of a market could be an appropriate feedstock. Harmonization of these definitions, along with clear, published guidance, would solve much of this uncertainty and allow for stricter regulations on what forest residue feedstocks should be used for bioenergy production to maintain sustainability. For example, belowground stump removal, collection of standing deadwood, and wood harvested from primary, old-growth forests likely create more environmental harm than climate benefit as bioenergy[37]. Limiting wood feedstocks to those which can provide carbon payback—the time it takes for the carbon emitted by burning wood bioenergy to be sequestered by growing trees—within a couple decades may severely limit the available supply for bioenergy but could help ensure more immediate climate benefits[39]

Policies to protect existing natural forests from overharvest and conversion to plantation forests will further ensure net climate benefits from wood-based bioenergy. Without restrictions on plantation expansion, natural forest lands are expected to decline globally to meet the increased demand for wood[40]. Instead of increasing plantation cover, it may be more beneficial to intensify production from existing plantations by incentivizing improved forest management practices like early- and pre-commercial thinning. Furthermore, restricting the conversion of natural forests to plantation forests could lead to afforestation or reforestation efforts on former or degraded agricultural lands to meet increased demands, ultimately increasing global forest cover and carbon stocks[37,40]. Additional restrictions on the percentage and types of harvest residues to be used for bioenergy can mitigate negative impacts of removal on soil carbon, biodiversity, and nutrient availability[22,37,41–43]. However, these restrictions must be region-specific, because some forests will benefit from more residue removal than others. For example, increased residue removal in fire-prone forests may help prevent forest fires, thus ensuring longer carbon storage.

Biofuels created from forest residues have lower total life cycle GHG emissions than conventional fossil fuels, even when considering land use and ecosystem impacts[21–23]. But combustion of biofuels still results in net emissions, unless biofuel production is coupled with carbon capture and storage technology (BECCS). SAF produced from forest residues in a BECCS system provides net carbon storage, reducing lifecycle emissions by nearly 800% compared to SAF produced without carbon capture and storage. While capital and end product prices are a concern for SAF production, integrating a BECCS system, only increases total capital costs by 2% and end product prices by 8%[44]. Policy and financial incentives that encourage the combination of SAF production with carbon capture and storage would ensure greater climate benefits, help increase sustainability, and help push us from net-zero to net-negative emissions.

Market leakage is a risk under the increased demand for woody biomass for SAF production. Leakage occurs when increased demand for a material displaces it from existing uses and substitutes it with other materials. This risk is particularly pronounced in the global pulp and paper sector, where wood that would otherwise supply pulp mills may be diverted to bioenergy production, driving up prices for pulpwood and paper products and incentivizing additional harvests elsewhere[38,40,45]. In regions with active or growing pulp markets, demand could shift toward higher-quality roundwood or imported wood fiber, potentially increasing land-use impacts and GHG emissions rather than delivering net climate benefits. However, in the southeastern US, where prolonged declines in pulp demand and mill closures have left large volumes of low-value wood without viable markets, bioenergy demand may offset economic losses and reduce the likelihood of residue burning or on-site decay, mitigating leakage risks. Still, clear restrictions on eligible feedstocks and explicit definitions of forest residues are needed to prevent bioenergy demand from displacing woody biomass from existing markets and to ensure that SAF production leads to genuine emissions reductions.

Logistics and infrastructure

Despite the available supply and potential climate and economic benefits, the logistics of collecting, processing, and transporting forest residues present a bottleneck in the SAF supply chain. In the US, forest residues are relatively underutilized, because they are spread over a wide area, expensive to collect, and often require additional pre-processing before they can be converted into bioenergy[32,46]. These challenges make feedstock logistics a dominant cost driver[22] and underscore the importance of strategically locating processing and production facilities near residue sources. In the southeastern US, for example, Pokharel et al.[46] report that forest residue hauling distances beyond 60 miles are not economical, which limits the effective supply radius of SAF facilities.

Feedstock and end product transportation also present logistical challenges for SAF production. Forest residues are typically hauled by large trucks, and even modest-scale bioenergy facilities can generate substantial traffic, with potential for heavy congestion that impacts rural quality of life. As SAF production scales, dedicated truck routes or alternative transport modes, such as rail or barge transport, may be necessary to mitigate local impacts and reduce emissions associated with feedstock transport[17]. Following production, SAF must be blended with conventional jet fuel before transport via pipeline, which requires production facilities to be located near jet fuel terminals or to rely on long-haul rail or barge delivery to blending points. Without this infrastructure access, facilities face higher transportation costs and emissions, which can impact profits and the overall life cycle climate benefits of SAF[17]. These constraints highlight the need for coordinated infrastructure planning to ensure that logistical barriers do not limit the sustainable expansion of forest-residue-based SAF.

Repurposing closed pulp and paper mills in the southeastern US offers a promising pathway to address several logistical and economic constraints associated with forest-residue-based SAF production[47]. Closed pulp mills are often already strategically located within high-density forest regions and with established transportation access. Many of these facilities also retain equipment necessary for pre-processing activities, enabling more efficient integration of SAF conversion technologies. As stated previously, high capital costs remain a major challenge for SAF production, contributing to end product prices 2-8x higher than those of conventional jet fuel[22,23,32,44]. However, retrofitting existing pulp mill infrastructure for SAF production can lower capital costs by 10–37% and reduce end product prices by 6–23% compared to new-build facilities[47]. Reopening closed mills could also generate broader regional benefits by revitalizing rural economies and shortening hauling distances for nearby forest owners. Local, state, and federal incentives that support repurposing mills offer an opportunity to scale SAF production while avoiding many of the infrastructure, logistical, and sustainability concerns associated with forest-residue-based SAF.

Conclusions

Decarbonizing the aviation sector will require technological innovation and attention to how climate solutions interact with ecosystems, existing market economies, and governance structures. Sustainable aviation fuel is vital to reducing aviation emissions in the near-term, but its ultimate climate value will depend on feedstock choice, total life cycle performance, and regulatory oversight. Forest residues—particularly those associated with declining pulpwood markets in the southeastern US—represent a relatively sustainable and underutilized feedstock that could contribute to SAF supply while supporting improved forest management and rural economies. However, forest residues alone likely cannot meet projected SAF demand, and uncertainties remain related to carbon accounting, ecosystem impacts, and market leakage that caution against treating woody biomass as a simple or universal bioenergy solution.

Resolving these uncertainties will require more detailed life cycle analyses that explicitly account for short- and long-term ecosystem impacts, feedstock supply and demand, and indirect effects across regional and global markets. A more complete understanding of the complex interplay between the land, economy, and climate, can support strict sustainability safeguards within policy frameworks that present clear, harmonized definitions of forest residue feedstocks, restrict overharvesting and conversion of existing natural forests, and limit leakage into other wood products markets. Strategic financial incentives could play a critical role in aligning market actors by enabling forest owners to supply residues with sustainable forest management, supporting SAF producers that repurpose closed pulp mills, encouraging the integration of BECCS with SAF production, and spurring airlines to enter long-term offtake agreements. The need for regulatory guardrails that seek to remove barriers to SAF production, while simultaneously protecting against negative ecosystem impacts illustrate the complexity of nature-based climate solutions; yet this balance is imperative to guarantee net climate benefits from forest-residue-based SAF. Forest residues are best understood as one component of a diversified SAF feedstock portfolio that balances climate action with ecological integrity and economic realism. Integrating forest residues into SAF production at appropriate scales, with strict sustainability standards, will help advance aviation toward net-zero emissions.

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