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Peer-reviewed author version

Staples, Mark D.; MALINA, Robert; Suresh, Pooja; Hileman, James I. & Barret, Steven R.H. (2018) Aviation CO2 emissions reductions from the use of alternative jet fuels. In: Energy policy, 114, p. 342-354.

DOI: 10.1016/j.enpol.2017.12.007
Handle: http://hdl.handle.net/1942/25646

Aviation CO_2 emissions reductions from the use of alternative jet fuels

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Pre-print

Abstract

Although a relatively small contributor to annual anthropogenic CO_2 emissions (~2.6%), commercial aviation activity is growing at ~5% per annum. As a result, alternative jet fuel (AJF) technologies have garnered interest as a means to achieve large, near-term emissions reductions for the industry. This analysis quantifies the potential for AJF to reduce aviation's CO_2 emissions by assessing: the availability of AJF feedstock; AJF volumes that could be produced from that feedstock; the lifecycle emissions of AJF compared to petroleum-derived jet fuel; and the number of bio-refineries and capital investment required to achieve the calculated emission reductions. We find that, if the use of AJF is to reduce aviation's lifecycle GHG emissions by 50% or more by 2050, prices or policies will have to significantly incentivize the production of bioenergy and waste feedstocks, and AJF production will need to be prioritized over other potential uses of these resources. Reductions of 15% by 2050 would require construction of ~60 new bio-refineries annually (similar to growth in global biofuel production capacity in the early 2000s), and capital investment of ~12 billion USD_{2015} per year (~1/5 of annual capital investment in petroleum refining).

Keywords: aviation; climate change; alternative jet fuel; LCA; ICAO; CORSIA

1 Introduction

Commercial aviation currently accounts for approximately 2.6% of annual global carbon dioxide (CO_2) emissions from fossil fuel combustion (ICAO, 2016a; IEA, 2016), and ~3.5% of total anthropogenic radiative forcing (Lee et al. 2009). Aviation activity is expected to grow by an annual average of approximately 4.5-4.8% in the coming decades (Airbus, 2016; Boeing, 2016), and as a result aviation's contribution to global fossil fuel CO_2 emissions could grow to 4.6-20.2% by mid-century.

Policies in a number of jurisdictions aim to address aviation's climate impact. For example, in the United States (US) the goal of the Continuous Lower Energy, Emissions and Noise program is to accelerate reductions in aircraft fuel burn and emissions, and aviation has been included in the European Union Emissions Trading Scheme since 2012 (EC, 2017; US FAA, 2016). At the intergovernmental level, the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations (UN), has adopted a goal of carbon neutral growth of international aviation from 2020 (ICAO, 2013). The International Air Transport Association (IATA), an airline industry group, has a further goal of a 50% reduction in CO_2 emissions by 2050 (IATA, 2017). To facilitate these international goals, member states to ICAO's Committee for Aviation Environmental Protection recently agreed to a global market-based mechanism to address international aviation emissions, called the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO, 2016b). Under CORSIA, the aviation sector will be required to offset international aviation CO_2 emissions in excess of average emissions during 2019 and 2020. This requirement may be satisfied by the purchase of offset credits from crediting mechanisms, or allowances from emissions trading schemes, such as the UN Clean Development Mechanism (CDM) or the Reducing Emissions from Deforestation and forest Degradation (REDD+) programme (ICAO 2017). The implementation of this policy means there is financial incentive for the airlines to reduce their international CO_2 emissions.

In order to mitigate the cost of offsetting CO_2 emissions to comply with sectoral climate policies such as CORSIA, the aviation industry may reduce its CO_2 emissions directly through improvements in airframe and engine technologies (Graham et al. 2014; Cansino & Román, 2017; Schäfer et al. 2016), more efficient aircraft and ground operations (Linke et al. 2017; Niklaß et al. 2017), and the use of sustainable alternative jet fuels (AJF). Hileman et al. (2013) found that, in order to achieve a 50% reduction in CO_2 emissions by 2050 without purchasing offset credits or emissions allowances, an 84% reduction in the lifecycle greenhouse gas (GHG) emissions intensity of aviation is required in the US context. Dray et al. (2010) and Sgouridis et al. (2011) used partial-equilibrium and system dynamics modeling approaches to assess the potential for reductions in aviation CO_2 emissions. All three of these studies indicate that keeping annual aviation CO_2 emissions at or below 2020 levels is only possible with a combination of technological, operational, and policy measures, together with the large-scale use of AJF. The International Energy Agency (IEA) (2015) found that, without the purchase of offsets or emission allowances from other sectors, post-2020 carbon neutral growth is out of reach for the aviation industry. Notably, the IEA (2015) analysis did not consider the use of AJF. Finally, Wise et al. (2017) showed that, in the absence of AJF, aviation CO_2 emissions mitigation potential is limited and would likely be at the expense of growth in demand for aviation services.

While these previous analyses have found that achieving the aviation industry's CO_2 emissions goals will require the use of AJF, no peer-reviewed work to date has addressed the implications of industrial-scale AJF use for commercial aviation. In this paper, we quantify the global potential for AJF production on the basis of feedstock availability, and the associated lifecycle CO_2-equivalent (CO_2e) emissions benefit of AJF compared to petroleum-derived fuels, under a number of scenarios out to 2050. We estimate the number of fuel production facilities and associated capital expenditures required for the calculated AJF production volumes, and derive practical and policy implications from our findings. The remainder of the paper proceeds as follows: in section 2 the overarching modeling approach is outlined; the detailed methods as well as data are presented in section 3; results are presented and discussed in section 4.; and section 5 concludes and summarizes the policy implications.

Note that this analysis is limited to CO_2 combustion emissions from aviation, as well as CO_2, CH_4 and N_2O emissions from upstream processes in the fuel production supply chain. Non-CO_2 aviation combustion emissions, aviation-induced contrails and cloudiness, and the climate impacts of surface albedo due to land use change (LUC) are outside of the scope of this analysis (for more information on these topics see Caiazzo et al. 2014 and Lee et al. 2009).

2 Modeling Approach

The scope of this analysis is limited to "drop-in" AJF, defined as hydrocarbon fuels that have properties similar to those of petroleum-derived jet fuels, such that they are fully compatible with existing aircraft and infrastructure and do not inhibit aircraft performance or operation. Additionally, we focus on AJF pathways that could reduce lifecycle GHG emissions compared to petroleum-derived fuels, meaning that synthetic fuels derived from coal or natural gas are not included. The AJF pathways considered in this work are derived from either biomass or waste feedstocks (such as fats, oils and greases (FOG), or municipal solid waste (MSW)).

This analysis includes three components, the first of which quantifies the potential global availability of AJF by 2050. Primary bioenergy and waste resources are quantified under assumed physical constraints (such as arable land availability, crop yields), socio-economic conditions (such as global population, gross domestic product (GDP)) and future environmental policies. The share of primary energy available for use as AJF feedstock is then calculated as a function of assumed market prices that incentivize feedstock production to varying degrees. Finally, AJF volumes are calculated based on the proportion of available feedstock converted to AJF, as opposed to other potential end uses for the feedstock.

The second component of the analysis quantifies the lifecycle GHG emissions associated with AJF. CO_2e emissions from feedstock production, transportation, and fuel production for the AJF pathways of interest, and petroleum-derived jet fuel, are taken from the peer-reviewed literature. These lifecycle assessment (LCA) data are augmented to reflect the impact on lifecycle emissions of anticipated changes in agricultural yields, nutrient application rates, farming energy requirements, process efficiencies, and the emissions associated with electricity and hydrogen requirements for fuel production to 2050, where relevant. In addition, LUC emissions are accounted for based on the land requirements, feedstock crop yields, and changes in soil and biomass carbon stocks associated with bioenergy from cultivated feedstock crops, calculated in the first component of the analysis described above.

In the third component of the analysis, the scenarios previously discussed are combined to calculate the potential for reductions in aviation's lifecycle GHG emissions to 2050. The number of production facilities and associated capital investment required to meet the resulting emissions reductions are also calculated in order to assess the feasibility of our findings.

3 Methods and Data

This analysis uses a scenario-based approach to quantify the potential for reductions in aviation-attributable CO_2 emissions from the use of AJF. The following sections describe the methods and data sources used to carry out the analysis, as well as the scenario definitions employed to quantify the sensitivity of the results to key assumptions and parameters.

3.1 Primary bioenergy and waste resources

This component of the analysis concerns the quantity of primary energy from biomass and waste resources, as constrained by physical limits (such as arable land area, crop yields, and agricultural residue generation) and socio-economic factors (such as environmental policies, population, and GDP). The feedstock scope includes cultivated feedstock crops, agricultural residues from food and feedstock crop production, MSW, waste FOG, and forest and wood processing residues. Three scenarios are defined in order to explore the range of results, where S1 and S3 correspond to the combination of assumptions that lead to the largest and smallest calculated global primary energy resource, respectively. The following sections describe the methods and data used to calculate primary energy from each of the feedstock categories.

3.1.1 Cultivated feedstock crops

Data from the Land Use Harmonization (LUH) project[1] is used to estimate the arable land area for feedstock crop cultivation in 2050, where land use is described in terms of five categories: crop, pasture, urban, primary, and secondary lands. Primary land is defined as land undisturbed by human activities since 1700AD, and secondary land is defined as land disturbed by human activities since 1700AD and in the process of recovery (Hurtt et al., 2011). Land area data for these categories is given for the four Representative Concentration Pathway (RCP) scenarios from IPCC. In order to avoid competition for food, feed, and other projected future land use demands, this analysis considers crop and urban land areas from the LUH data to be unavailable for feedstock crop cultivation. Primary forested and protected land areas are also assumed to be unavailable for feedstock crop cultivation on the basis of ecosystem conservation, and are identified by overlaying data from the Global Agro-Ecological Zones (GAEZ) model [2] (IIASA/FAO, 2012).

[1] Data, documentation and project description available at hhtp://luh.umd.edu
[2] Data, documentation and model available at http://www.fao.org/nr/gaez/en/

The pasture, non-forested primary, and secondary land categories are considered for feedstock crop cultivation in this analysis, however the areas that are available depends on parameter assumptions that vary between three primary waste and bioenergy scenarios. These define whether or not secondary forested lands are available for feedstock crop cultivation, the degree to which pastureland is available, the minimum required agro-climatic suitability of lands for crop cultivation, and the maximum allowable LUC emissions from conversion of a given land area to feedstock crop cultivation. LUC emissions associated with the conversion of land areas for feedstock crop cultivation are based on agro-ecological zone-specific emission factor (AEZ-EF) data[3] developed for the Global Trade Analysis Project (GTAP) model (Gibbs et al., 2014). Additional detail on the land use data sources used, and the assumptions that determine land areas for this analysis, are in section S1 of the Supplementary Information (SI).

Four categories of cultivated feedstock crops are included in the calculation of primary bioenergy: vegetable oil, starchy, sugary, and lignocellulosic. While many feedstock crop types exist, the modelling of crop yields is limited here to feedstocks for which globally resolved data is available in order to capture regional variability. Therefore, based on data from the GAEZ model, vegetable oil crops are represented by soybean, rapeseed, jatropha and palm oil; starchy crops are represented by maize grain, sorghum grain and cassava; sugary crops are represented by sugarcane and sugar beet; and lignocellulosic feedstock crops are represented by switchgrass, miscanthus and reed canary grass. The areal yields of these feedstock crops types are calculated in two steps.

First, historical data on average yields are projected to 2050 for five world regions: Middle East and Africa (MAF); Latin America and the Caribbean (LAM); Asia (ASIA); the countries of the Organization for Economic Co-ordination and Development (OECD); and Reforming economies

[3] Data and documentation available at https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=4344

of Eastern Europe and the Former Soviet Union (REF). For eight of the twelve crops modelled (soybean oil, rapeseed oil, oil palm, maize grain, sorghum grain, sugarcane, sugar beet and cassava), we use empirical yield data from the UN Food and Agricultural Organization Statistical Programme of Work (FAOSTAT, 2017)[4]. Two cases for linear annual increases in yield are considered: 0.25% and 1.5% of average 2013 yields. These values are in line with growth rates assumed in previous studies that quantify the size of the global bioenergy resource (Slade et al., 2014), and capture the highest observed historical growth rates for the crops considered in this analysis.

For the four feedstock crops for which no FAOSTAT data exist (switchgrass, miscanthus, reed canary grass, and jatropha) yield estimates for 2050 are taken from Searle & Malins (2014), Achten et al. (2008) and Jongschaap et al. (2007). The resulting global average yields range from 10.5 to 24.0 tonnes of dry biomass per ha for lignocellulosic crops, and 1.4 to 2.0 tonnes of oil per hectare for jatropha, in 2050.

Next, average yield values for each world region in 2050 are used to scale geo-spatially disaggregated yield data from the GAEZ model at a 0.083° resolution. Scaling the globally resolved data with the 2050 yield projections takes into account location-specific differences in crop yields, and the agro-climatic limits on yield growth. The empirical data and results of the yield projections for soybean oil are shown in Figure 1, and in Figures S2-S9 of the SI for the other feedstocks. The scaling factors applied to the data from GAEZ are shown in Table S7 of the SI. The underlying GAEZ data is also a function of the assumed climate projection for 2050, and this analysis uses the data generated for the IPCC SRES scenarios using the Hadley Centre Coupled Model version 3 (HadCM3) (Collins, M., et al. 2001).

[4] Data and documentation available at http://faostat3.fao.org/home/E

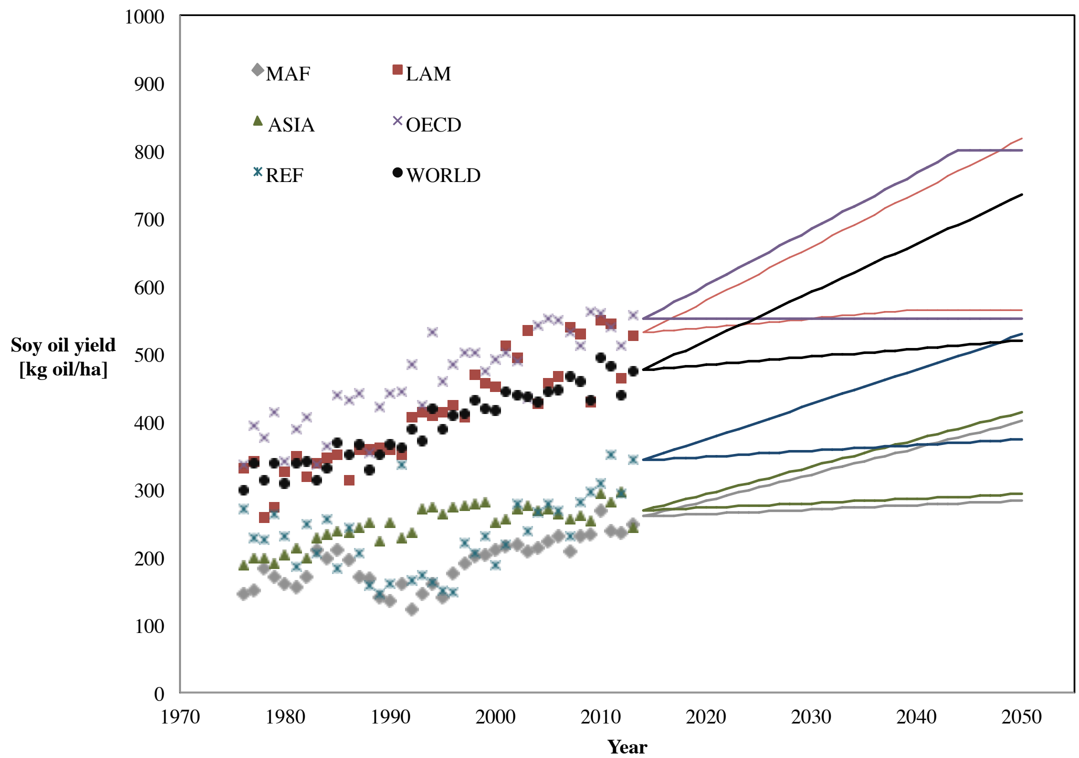

Figure 1: 2050 yield projections for soybean oil. The upper and lower lines for each world region correspond to annual linear growth in crop yields of 1.5% and 0.25% of average 2013 yields, respectively. The projected average yield in each world region is used to scale globally resolved agro-climatically attainable yields from the GAEZ model. If projected yields exceed the agro-climatically attainable yield from GAEZ, the GAEZ value is used as an upper bound on crop yields: this is can be observed in the plateau in soybean oil yields in 2045 under the 1.5% growth case in OECD.

In regions where more than one of the twelve crop types could be cultivated, the feedstock crop that results in the greatest areal energy yield is selected for each grid cell. Calculation of areal energy yield accounts for the main product (vegetable oil in the case of soybean, rapeseed, oil palm and jatropha; grain or starch in the case of maize, sorghum and cassava; sugar in the case of sugarcane and sugar beet) and any residues from the crop.

This modelling approach (drawing upon land use data from LUH, empirical and agro-climatically attainable yields from GAEZ and FAOSTAT, and LUC emissions factors from the AEZ-EF database) has been used in previous peer-reviewed work (Staples et al. 2017).

3.1.2 Crop residues

Alexandratos & Bruinsma (2012) estimates of 2050 agricultural production by major crop type are used to quantify primary energy from agricultural residues. This data is scaled to five GDP and population projections corresponding to the IPCC Shared Socio-economic Pathways (SSPs) by establishing the relationship between GDP per capita and caloric intake per capita, shown in Figure S10 of the SI (IIASA, 2014).

The quantity of primary bioenergy from agricultural residues also depends on the residues produced from agricultural commodities, and the proportion of those residues that can be removed and made available for use. The residue-to-crop ratios used here are from Lal (2005), and are shown in Table S8 of the SI.

Andrew (2006) indicates that a maximum of 33% of crop residues may be removed without causing erosion or soil carbon and nutrient loss, however more recent work indicates that the maximum removal rate may be up to 75% if certain management practices, such as cover cropping, are employed (Pratt et al., 2014). This analysis assumes a range of removal rates between 20% and 50%. Agricultural residues used for livestock fodder and bedding, cultivation of fungi, or other horticultural uses are not considered in this analysis, and Searle & Malins (2013) estimate that this accounts for 5% to 30% of residues. In combination, these assumptions mean that 14-48% of total agricultural residues are included in the calculated primary bioenergy and waste results.

3.1.3 Municipal solid waste (MSW)

Municipal solid waste (MSW) quantities are calculated by building off the Hoornweg & Bhada-Tata (2012) analysis for 2025. Data from the existing study is used to quantify the change in MSW generation per capita as a function of GDP per capita. Using this relationship, MSW generation estimates consistent with the IPCC SSP GDP, population and urbanization projections are calculated for five world regions for 2050.

The composition of generated MSW is derived from Hoornweg & Bhada-Tata (2012), where MAF and ASIA are assumed to correspond to "lower middle income" regions; LAM is a "upper middle income" region; and OECD and REF are assumed to correspond to "high income" regions in 2050, according to the definitions from that work. In addition, only the fraction of MSW that would otherwise be discarded is considered available for bioenergy generation, based on US EPA (2012) estimates. The lower heating value (LHV) of discarded MSW in each world region is calculated based on an aggregation of LHV data from US EIA (2007). These data are available in Table S10 of the SI.

3.1.4 Waste fats, oils and greases (FOG)

Waste FOG quantities are calculated based on tallow and animal fat generation from the livestock slaughtering and processing industry. 2050 livestock production is estimated using Alexandratos & Bruinsma (2012) projections scaled to the IPCC SSP scenarios, described in Section S1.2 of the SI. Tallow extraction and rendered tallow fractions are estimated from the sources shown in Table 1, assuming that between 30% and 70% of waste FOG cannot be considered available due to use in the oleo-chemical and animal feed production industries.

Table 1: Waste FOG assumptions

	By-product fraction	Source	Rendered tallow & free fatty acid fraction from byproducts	Source	Fraction not used for oleo-chemical and feed production	Net waste FOG availability from animal carcass weight
Cattle	27.5%	Jayathilakan et al. (2012)	27.8%	Lopez et al. (2010)	30-70%	2.3-5.4%
Sheep	17.0%	Jayathilakan et al. (2012)	24.0%	Niederl et al. (2006)	30-70%	1.2-2.9%
Pigs	4.0%	Jayathilakan et al. (2012)	24.0%	Niederl et al. (2006)	30-70%	0.3-0.7%
Poultry	29.1%	Lopez et al. (2010)	20.3%	Lopez et al. (2010)	30-70%	1.8-4.1%

3.1.5 Wood and forestry residues

Primary bioenergy from wood products are considered only where the projected supply exceeds projected demand in 2050, in order to avoid additional deforestation caused by competition for scarce wood resources. The "ecological potential" of wood fuel and round wood supply, defined as "the theoretical potential taking into account ecological criteria related to biodiversity…and soil erosion", is compared to 2050 demand projections from Smeets & Faaij (2007). By combining the range of 2050 supply and demand estimates from this reference, three scenarios for surplus wood fuel and round wood are derived, as shown in Table 2.

Table 2: Surplus wood fuel and round wood, adapted from Smeets & Faaij (2007)

		S1	S2	S3
Supply [EJ/yr]	Plantations	23.5	13.1	9.1
	Non-forest trees	12.6	12.6	12.6
	Ecological potential from forests	36.7	36.7	36.7
Demand [EJ/yr]	Wood fuel & round wood	41.7	54.0	66.6
	Surplus [EJ/yr]	**31.1**	**8.4**	**0.0**
Regional disaggregation [EJ/yr]	MAF	3.5	1.0	0.0
	LAM	3.6	1.0	0.0
	ASIA	10.3	2.8	0.0
	OECD	12.1	3.3	0.0
	REF	1.6	0.4	0.0

We consider a residue fraction of harvested wood between 32% and 71%, and a recoverable fraction between 25% and 50% (Smeets & Faaij, 2007; Searle & Malins, 2013; McKeever, 2004). For industrial wood processing residues, we consider a residue fraction ranging between 30% and 70%, a recoverable fraction between 33% and 75%, and a fraction unused for other purposes between 10% and 50% (Smeets & Faaij, 2007; McKeever, 2004). Combined with the wood product supply estimates shown in Table 2, these parameters are used to define three scenarios for wood and forestry product residues in 2050 as shown in Table 3.

Table 3: Wood and forestry residue assumptions

		S1	S2	S3	Note
Wood logging residues	Residue fraction of wood harvested	71%	52%	32%	Only plantations and forests considered
	Recoverable fraction	50%	38%	25%	
	Total availability [EJ/yr]	21.4	9.8	3.7	
Wood processing residues	Residue fraction of wood processed	70%	50%	30%	Only industrial roundwood considered
	Recoverable fraction	75%	54%	33%	
	Fraction unused for other products	50%	30%	10%	
	Total availability [EJ/yr]	9.4	2.4	0.3	
	Total residue potential [EJ/yr]	**30.8**	**12.2**	**3.9**	
Regional disaggregation [EJ/yr]	MAF	1.5	0.6	0.2	
	LAM	2.3	0.9	0.3	
	ASIA	5.5	2.2	0.7	
	OECD	19.1	7.6	2.5	
	REF	2.3	0.9	0.3	

3.1.6 Primary bioenergy and waste scenarios

Three scenarios (S1-S3) are constructed to represent the range of assumptions that drive the primary bioenergy and waste quantities calculated for 2050, as shown in Table 4. The set of assumption selected for S1 and S3 result in the highest and lowest calculated quantities of primary bioenergy and wastes, respectively. S2 is defined to more fully describe the sensitivity of the results to key assumptions.

Table 4: Assumptions for scenario construction for 2050 primary bioenergy and waste

<table>
<tr><th></th><th></th><th></th><th>S1</th><th>S2</th><th>S3</th></tr>
<tr><td rowspan="14">Cultivated feedstock crops</td><td></td><td>Representative concentration pathway (RCP) Land Use Harmonization (LUH) scenario</td><td>RCP 8.5</td><td>RCP 6.0</td><td>RCP 4.5</td></tr>
<tr><td></td><td>Hadley climate change scenario for GAEZ yields</td><td>B1</td><td>B2</td><td>A1F1</td></tr>
<tr><td></td><td>Inclusion of secondary forested land</td><td colspan="2">Yes</td><td>No</td></tr>
<tr><td></td><td>Protected areas</td><td>Crop cultivation in some protected areas</td><td colspan="2">No crop cultivation in protected areas</td></tr>
<tr><td></td><td>Land use change (LUC) emissions threshold*</td><td>100% of lifecycle emissions reduction</td><td>60% of lifecycle emissions reduction</td><td>20% of lifecycle emissions reduction</td></tr>
<tr><td></td><td>Agro-climatic suitability threshold</td><td>Medium</td><td>Good</td><td>High</td></tr>
<tr><td></td><td>Pastureland availability</td><td>20.0%</td><td>10.0%</td><td>0.0%</td></tr>
<tr><td></td><td>Shared socio-economic pathway (SSP) scenario</td><td>SSP5</td><td>SSP4</td><td>SSP3</td></tr>
<tr><td rowspan="5">p.a. assumed yield growth rate</td><td>MAF</td><td rowspan="5">1.50%</td><td rowspan="3">1.50%</td><td rowspan="5">0.25%</td></tr>
<tr><td>ASIA</td></tr>
<tr><td>LAM</td></tr>
<tr><td>REF</td><td rowspan="2">0.25%</td></tr>
<tr><td>OECD</td></tr>
<tr><td colspan="2">Agricultural residues</td><td>Net available fraction</td><td>47.5%</td><td>28.9%</td><td>14.0%</td></tr>
<tr><td colspan="2">MSW</td><td></td><td colspan="3">Dependent on assumed SSP</td></tr>
<tr><td colspan="2">Waste FOG</td><td>Net available fraction</td><td>70.0%</td><td>50.0%</td><td>30.0%</td></tr>
<tr><td colspan="2" rowspan="2">Wood & forestry products</td><td>Wood fuel & roundwood availability [EJ/yr]</td><td>36.0</td><td>14.0</td><td>0.0</td></tr>
<tr><td>Net available fraction of residues</td><td>Primary: 35.5%
Secondary: 26.3%</td><td>Primary: 19.8%
Secondary: 8.1%</td><td>Primary: 8.0%
Secondary: 1.0%</td></tr>
<tr><td colspan="6">*Defines the maximum percentage of lifecycle emissions reduction (of AJF pathway of interest compared to petroleum-derived jet fuel), that may be offset by LUC emissions. If LUC emissions contribute more than this percentage of the lifecycle emissions reduction, that particular land area is considered unavailable for feedstock crop cultivation in this analysis.</td></tr>
</table>

A number of the assumptions (LUH scenario, Hadley climate projection and SSP) were selected on the basis of local sensitivity analyses in order to define scenarios leading to the lowest and highest primary bioenergy and waste results. LUC emissions thresholds are defined to exclude *a priori*, to a degree varying according to the scenario, land areas where conversion to biomass cultivation would result in significant LUC emissions. The assumed yield growth rates in different world regions in scenario S2 reflects that developing world regions having a greater yield gap to close, and therefore may experience greater yield growth rates than developed regions.

3.2 Feedstock availability

In this component of the analysis, the proportion of calculated primary bioenergy and waste resources that is available for use as feedstock is calculated as a function of market prices.

3.2.1 Cultivated feedstock crops

This analysis builds off of work by Hoogwijk et al. (2009), which models feedstock crop cultivation on abandoned and rest land in 2050 at feedstock market prices of \$4/GJ, \$2/GJ and \$1/GJ. This is shown in Table 5, where the values represent the proportion of total cultivated feedstock crops that is available, under the assumed price in each region for three scenarios (A1-A3).

Table 5: Proportion of total cultivated feedstock crops available for use, adapted from Hoogwijk et al. (2009)

World region	A1	A2	A3
MAF	48.3%	41.1%	11.6%
LAM	78.4%	25.7%	0.0%
ASIA	59.8%	32.5%	0.4%
OECD	75.8%	55.2%	4.6%
REF	74.8%	70.5%	0.3%

3.2.2 Crop residues

The proportion of total crop residues that are available as feedstock under different market price assumptions is calculated based on the US Billion-Ton Update (US DOE, 2011). This data is shown in Figure S10 of the SI, and the proportions corresponding to feedstock market prices of \$4/GJ, \$2/GJ and \$1/GJ are shown in Table 6 for scenarios A1-A3, respectively.

Table 6: Proportion of total crop residue available, adapted from US Billion-Ton Update (US DOE, 2011)

A1	A2	A3
90.6%	37.9%	0.1%

3.2.3 MSW and waste FOG

MSW and waste FOG are by-products of processes that would take place regardless of exploitation of these resources. Therefore, the availability of these feedstocks is based on collection rates. These values are taken from Hoornweg & Bhata-Tata (2012) for MSW, assuming the five world regions of interest belong to the income level regions defined in Section 3.1.3. This is shown in Table 7.

Table 7: MSW and waste FOG collection rates, adapted from Hoornweg & Bhada-Tata (2012)

World region	A1	A2	A3
MAF	95.0%	72.5%	50.0%
LAM	100.0%	75.0%	50.0%
ASIA	95.0%	72.5%	50.0%
OECD	100.0%	88.0%	76.0%
REF	100.0%	88.0%	76.0%

3.2.4 Wood and forestry residues

Building on the method described in Section 3.1.5, data from Smeets & Faaij (2007) is used to quantify the availability of these feedstocks. The values for "ecological-economical potential" from Smeets & Faaij (2007) reflect bioenergy availability from wood resources when economic considerations are taken into account. In all cases, there is no ecologically and economically viable supply of wood fuel or round wood that is in excess of projected demand for wood resources in 2050.

Data from Walsh (2008) are used to estimate the availability of logging and wood processing residues as a function of feedstock market prices, shown in Figure S11 in the SI. The proportion of total forestry residues available under feedstock market prices of \$4/GJ, \$2/GJ and \$1/GJ are shown in Table 8 for scenarios A1-A3, respectively.

Table 8: Forestry residue availability, adapted from Walsh (2008)

A1	A2	A3
90.6%	38.1%	0.1%

3.2.5 Micro-algae

Micro-algae is first included at the feedstock availability step of this analysis because some economic considerations must be included to meaningfully quantify the limits of bioenergy from this feedstock. We build on the methodology described in Ames (2014) and Wigmosta et al. (2011), which calculates the areal energy yield of micro-algae cultivated in open ponds as a function of the photosynthetically active solar radiation available to micro-algae in a given location, and the temperature of the saltwater growth medium. Bioenergy cultivation from micro-algae is further limited by proximity to a source of surface saltwater, availability of land for open-pond cultivation, proximity to a concentrated CO_2 source, and a threshold of minimum required areal productivity. The governing equations and spatial and temporal data are described in Section 2.3 of the SI. The assumptions and references for three feedstock availability scenarios for micro-algae cultivation are shown in Table 9.

Table 9: Parameter assumptions for feedstock availability from open-pond micro-algae cultivation

	A1	A2	A3	Units	Reference
Photon efficacy	1.86	2.38	2.9	[μmol/J]	Al-Shooshan (1997)
Maximum distance from saltwater shorelines	175	125	75	[km]	Ames (2014), Florentinus et al. (2008)
Natural gas power plant efficiency	35.0%	45.0%	60.0%	[%]	Graus et al. (2007)
Coal power plant efficiency	25.0%	33.0%	45.0%	[%]	Graus et al. (2007)
CO_2 catchment area	2x2	1x1	0.5x0.5	[deg.]	-
CO_2 requirements of algal biomass growth	0.0588	0.0625	0.0741	[$kg_{CO2}/MJ_{biomass}$]	Carter (2012)
Algal biomass lipid content	60.0%	25.0%	15.0%	[%]	Ames (2014)
Algal biomass LHV		32.8		[$MJ/kg_{biomass}$]	Ames (2014)
Algal oil LHV		39.0		[MJ/kg_{oil}]	Ames (2014)
Minimum required monthly productivity	1000	3000	6000	[$kg_{biomass}$/ha/mo.]	Slade & Bauen (2013)

3.3 AJF scenarios

The AJF scenarios are defined by the share of available feedstock that is converted to AJF, as opposed to other potential end uses for these scarce resources (such as electricity or heat generation, road and marine transportation fuels, or bio-chemicals). We develop three scenarios for this step of the analysis: a maximum AJF production scenario (F1); a scenario in which feedstock is allocated to AJF in proportion to aviation's share of final energy demand in 2050 (F2); and a scenario in which other priorities are first satisfied before AJF is produced (F3).

3.3.1 Maximum AJF (F1)

This scenario represents the greatest quantity of AJF that could be produced from the feedstock that is available, as described in Section 3.2. This quantity is limited by the assumed feedstock-to-fuel conversion efficiency and proportion of the fuel product slate that is AJF, and these parameters are shown below in Table 12. The values are derived from the high efficiency and maximum jet fuel product slate scenarios from Staples et al. (2014) for advanced fermentation

(AF) jet fuels and Pearlson et al. (2013) for hydro-processed esters and fatty acids (HEFA) jet fuels, respectively.

3.3.2 Proportional allocation (F2)

The proportional allocation scenario quantifies AJF production if available feedstocks were allocated to competing uses in proportion to final energy demand in 2050. We assume that lignocellulosic feedstocks (cultivated feedstock crops, agricultural and forestry residues, and MSW) are allocated in proportion to final energy demand for aviation, and 2050 demand for other uses of primary bioenergy including transportation fuels, heat generation and electricity generation. In contrast sugary, starchy and oily feedstocks are only allocated between 2050 demand for aviation and other transportation fuels because these feedstocks are unlikely to be combusted directly for electricity or heat generation.

Non-aviation final energy demand in 2050 is estimated from the International Energy Agency (IEA) (2016) 4°C scenario, and aviation final energy demand of 38.5 EJ per year in 2050 from ICAO (2016a). These two data sources are combined to allocate available feedstocks to AJF production, as shown in Table 10.

Table 10: Aviation's proportional share of 2050 final energy demand

	2050 final energy demand [EJ/yr]	**Proportion for aviation**	**References**
All transportation	152.7	25.2%	ICAO (2016a), IEA (2016)
All end uses	590.7	6.5%	

3.3.3 Other priorities for bioenergy and waste resources (F3)

Previous peer-reviewed work suggests that, from a climate change mitigation perspective, using scarce bioenergy and waste feedstocks to offset demand for fossil fuel-derived electricity, heat and road transportation fuels may be more environmentally beneficial than producing AJF to offset demand for petroleum-derived jet fuel (Staples et al., 2017; Trivedi et al., 2015; Steubing et al., 2012; IEA, 2012; EEA, 2008). Therefore, in this scenario we assume that feedstocks are only used to produce AJF once other demands for final fossil energy are offset. Any remaining available feedstock resources are subsequently used for AJF production.

We assume that non-aviation demand for final energy derived from crude oil is preferentially satisfied by sugary, starchy and oily feedstocks, and non-aviation demand for final energy derived from non-oil fossil fuels is preferentially satisfied by lignocellulosic feedstocks. The final energy demand that must be satisfied under this scenario, before bioenergy or waste feedstocks are used to produce AJF, is shown in bold in Table 11 (IEA, 2016; ICAO, 2016a).

Table 11: Non-aviation oil and non-oil final fossil energy demands in 2050

	2050 final energy demand [EJ/yr]
Aviation	38.5
Crude oil	202.5
All fossil fuels	451.2
Non-aviation oil	**164.0**
Non-oil fossil fuels	**248.7**

3.3.5 Additional parameters for AJF scenarios

In addition to the proportion of available feedstock allocated to the production of AJF, defined above, the fuel yield from different feedstocks is necessary to quantify AJF production volumes.

These are shown in Table 12. The LCA allocation factors associated with the fuel yields are given in Table S5 in the SI.

Table 12: AJF yields from bioenergy and waste feedstocks

Feedstock		F1	F2	F3	References
Oily	Soybean, rapeseed, jatropha, oil palm, waste FOG and algal oil	21.8 MJ_{jet}/kg_{oil}			Based on max. jet fuel product slate from Pearlson et al. (2013)
Starchy	Maize grain (15.5% mst. content)	9.96 MJ_{jet}/kg_{grain}	5.28 MJ_{jet}/kg_{grain}		Based on high efficiency case from Staples et al. (2014). F1 corresponds to 100% jet fuel, and F2 & F3 correspond to 53% jet fuel product slates, respectively.
	Sorghum grain (12.4% mst. content)	9.96 MJ_{jet}/kg_{grain}	5.28 MJ_{jet}/kg_{grain}		
	Cassava (59.6% mst. content)	3.56 $MJ_{jet}/kg_{cassava}$	1.89 $MJ_{jet}/kg_{cassava}$		
Sugary	Sugarcane (50% mst. content)	2.88 $MJ_{jet}/kg_{sugarcane}$	1.53 $MJ_{jet}/kg_{sugarcane}$		
	Sugarbeet (75% mst. content)	4.04 $MJ_{jet}/kg_{sugarbeet}$	2.14 $MJ_{jet}/kg_{sugarcane}$		
Lignocellulosic	Switchgrass	8.21 $MJ_{jet}/kg_{dry\ biomass}$	4.35 $MJ_{jet}/kg_{dry\ biomass}$		
	Miscanthus	8.67 $MJ_{jet}/kg_{dry\ biomass}$	4.60 $MJ_{jet}/kg_{dry\ biomass}$		
	Reed canarygrass	8.61 $MJ_{jet}/kg_{dry\ biomass}$	4.56 $MJ_{jet}/kg_{dry\ biomass}$		
	Other lignocellulosic feedstocks (wood, ag. and wood residues, MSW)	0.49 $MJ_{jet}/MJ_{dry\ biomass}$	0.26 $MJ_{jet}/MJ_{dry\ biomass}$		

3.4 GHG emissions

This analysis accounts for two aspects of GHG emissions associated with the large-scale use of AJF to offset demand for petroleum-derived jet fuel: lifecycle emissions from fuel production, transportation and use, and emissions from LUC attributable to the cultivation of feedstock crops.

3.4.1 Lifecycle emissions

We draw on peer-reviewed analyses to quantify the lifecycle emissions of AJF and petroleum-derived jet fuel, including feedstock production and transportation, fuel production and transportation, and combustion. The emissions are allocated among all co-products, including energy products, animal meal, chemicals, liquid fuels and electricity, on the basis of energy content, and the results are reported in units of grams of 100-year Global Warming Potential (GWP) CO_2-equivalent per mega joule of jet fuel (gCO_2e/MJ_{jet}) for CO_2, N_2O and CH_4.

Two cases are defined for the lifecycle emissions of the pathways of interest: values taken directly from existing LCA studies in the literature (with only the allocation methodology changed to energy allocation in order to maintain consistency), and values that are augmented to capture changes in LCA emissions to 2050. The second case reflects the impact on lifecycle emissions of anticipated changes in agricultural yields, nutrient application rates, farming energy requirements, process efficiencies, and the emissions associated with electricity and hydrogen requirements for fuel production. A detailed description of the methods and data sources used to augment the LCA values to 2050 is in section S4 of the SI. Table 13 shows LCA values from existing studies and LCA values augmented to 2050 that are pathway specific, and also aggregated to the relevant feedstock groupings.

Table 13: Feedstock grouping aggregated LCA values used for this analysis, from existing LCA studies and augmented to 2050

Feedstock grouping	Pathway	LCA emissions [gCO_2e/MJ_{jet}] Pathway value	LCA emissions [gCO_2e/MJ_{jet}] Aggregate value for feedstock grouping	2050 LCA emissions [gCO_2e/MJ_{jet}] Pathway value	2050 LCA emissions [gCO_2e/MJ_{jet}] Aggregate value for feedstock grouping	References
Oily crops	Soybean HEFA	42.2	**49.5**	29.6	**35.6**	Stratton et al., 2010
	Rapeseed HEFA	58.3		39.4		
	Jatropha HEFA	58.3		47.2		
	Oil palm HEFA	39.1		26.1		
Starchy crops	Maize grain AF	52.2	**52.2**	27.8	**27.8**	Staples et al., 2014
Sugary crops	Sugarcane AF	10.7	**10.7**	3.8	**3.8**	
Lignocellulosic crops	Switchgrass AF	37.4	**28.4**	18.4	**17.4**	
	Switchgrass FT	19.4		16.3		Stratton et al., 2010
Agricultural residue	Corn stover FT	13.8	**13.8**	12.0	**12.0**	
Forestry residue	Forest residue FT	7.7	**7.7**	7.2	**7.2**	
MSW	MSW FT	27.6	**27.6**	38.2	**38.2**	Suresh, 2016
Waste FOG	Tallow HEFA	29.8	**24.6**	16.5	**12.5**	Seber et al., 2014
	Yellow grease HEFA	19.4		8.5		
Algae	Algal oil HEFA	68.1	**68.1**	27.0	**27.0**	Carter, 2012
Petroleum jet fuel		**88.9**		**92.0**		Rosen, 2017

3.4.2 LUC emissions attributable to cultivated feedstock crops

CO_2 emissions from LUC are estimated from the soil and biomass carbon stock AEZ-EF database (Gibbs et al., 2014). This data reflects the pulse of CO_2 emissions per unit area from a one-time change in land use, from forest or pasture land to feedstock crop cultivation. Together with the location specific feedstock crop yields in Section 3.1.1, the feedstock-to-jet fuel conversion efficiencies in Table 12, the LCA allocation factors in Table S5 of the SI, and an assumed emissions amortization period of 25 years, we calculate location and pathway specific LUC emissions associated with AJF derived from cultivated feedstock crops. 25 years was selected as the amortization period because current EU legislation dictates that LUC emissions be spread evenly over 20 years (EC, 2009), whereas US regulation amortizes evenly over 30 years (US EPA, 2010).

4 Results and Discussion

In this section, we present the results for each component of the analysis in terms of primary bioenergy and waste resources, feedstock availability, and AJF production volumes, and the resulting impact on lifecycle GHG emissions attributable to aviation under a number of scenarios.

4.1 Primary bioenergy and waste

Figure 2 shows the calculated quantities of primary bioenergy and waste resources for three scenarios in 2050, broken out by feedstock type. The findings range over an order of magnitude between scenarios S1-S3, from 41.0-510.0 EJ/yr. This is consistent with Slade et al. (2014), which reviewed similar studies and found 2050 global bioenergy estimates ranging between 16.0-600.0 EJ/yr when environmental and societal limits are taken into account. The arable land areas required for bioenergy cultivation (including sugary, starchy, lignocellulosic and vegetable oil crops) are 1083, 314 and 8 Mha in scenarios S1, S2 and S3, respectively. These results are also given in Figure S15 of the SI, disaggregated by previously existing land use type. For reference, current global primary energy demand is approximately 585.0 EJ/yr, and global cultivated land area is currently approximately 1417 Mha (IEA 2016, FAOSTAT 2017).

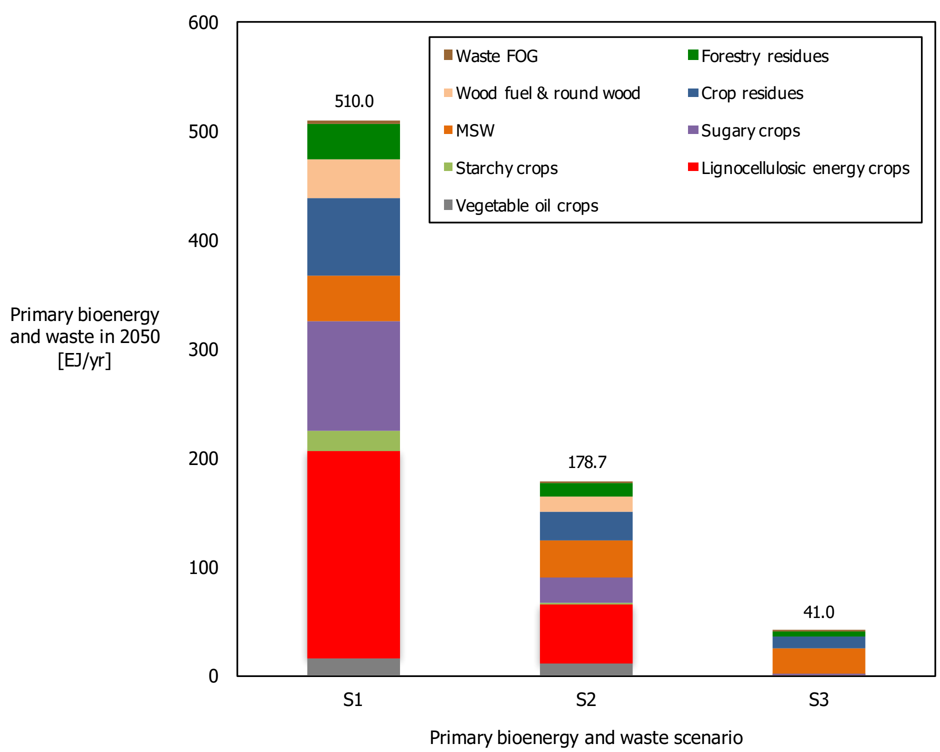

Figure 2: 2050 primary bioenergy and waste results, broken out by feedstock type. Note that microalgae is not included at this step of the analysis.

A sensitivity analysis was carried out using the S2 scenario as a baseline. The definitions for each of the parameter sensitivities are given in Table S34 of the SI, and the results are shown in Figure 3. The four parameters to which the results are most sensitive (agro-climatic suitability threshold, feedstock crop yield growth, LUC emissions threshold, and RCP LUH scenario) all define either the land area available for bioenergy cultivation, or the anticipated feedstock crop yields on those lands. This highlights the importance of cultivated feedstock crops on total quantity of bioenergy and waste resources in 2050. In addition, the waste and residue results (such as waste FOG, MSW, forest residues, and crop residues) vary less between the three scenarios than energy from cultivated feedstock crops. Therefore, wastes and residues make up a larger fraction of the total in scenarios with lower 2050 primary energy (61%, 67% and 92%, in S1, S2 and S3, respectively).

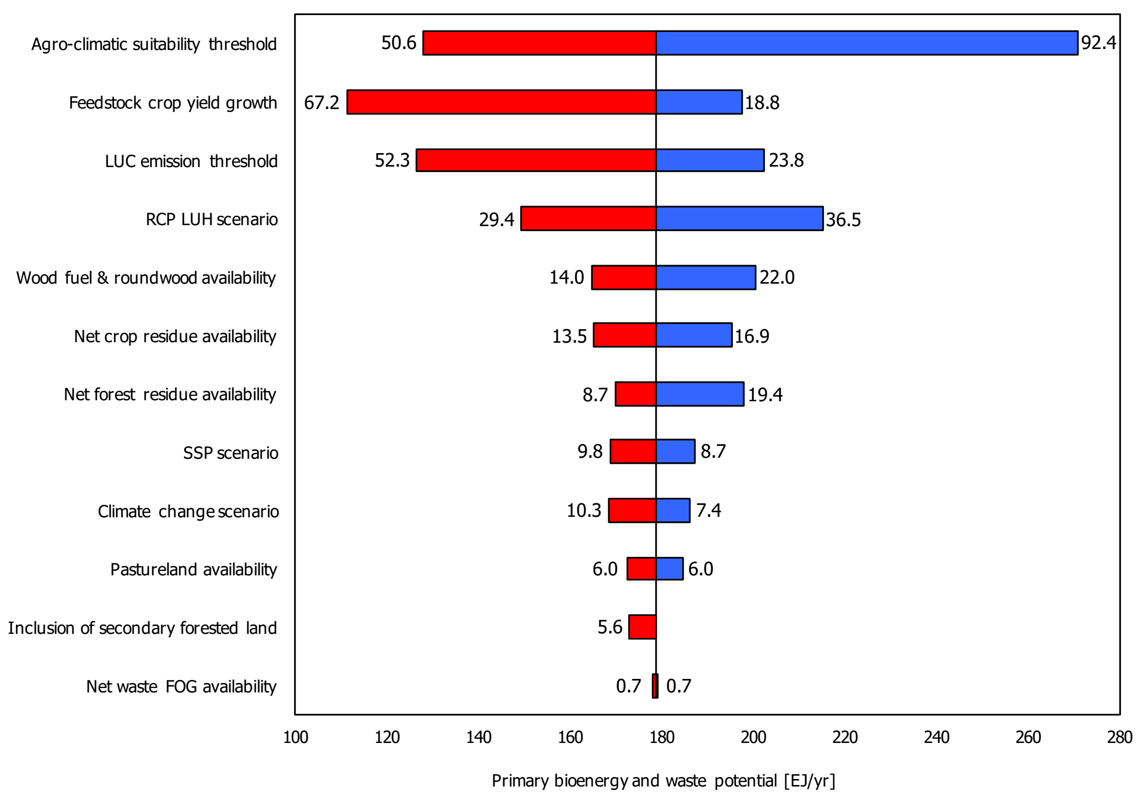

Figure 3: S2 results (178.7 EJ/yr) sensitivity to 2050 primary bioenergy and waste scenario assumptions. Scenario and sensitivity parameter definitions found in Table S34 of the SI.

4.2 Feedstock availability

The second step of the analysis quantifies the proportion of primary bioenergy and waste resources that could be available under a number of feedstock market price assumptions. Scenarios A1-A3 correspond to assumed feedstock prices of \$4/GJ, \$2/GJ and \$1/GJ, respectively, applied to the feedstocks included in the 2050 primary bioenergy and waste scenario results shown above. The primary energy from algal oil is also included in this step of the analysis, under the assumptions outlined in Section 3.2.5. The results for feedstock availability are shown in Figure 4 broken out by feedstock type, ranging from 14.1-366.1 EJ/year.

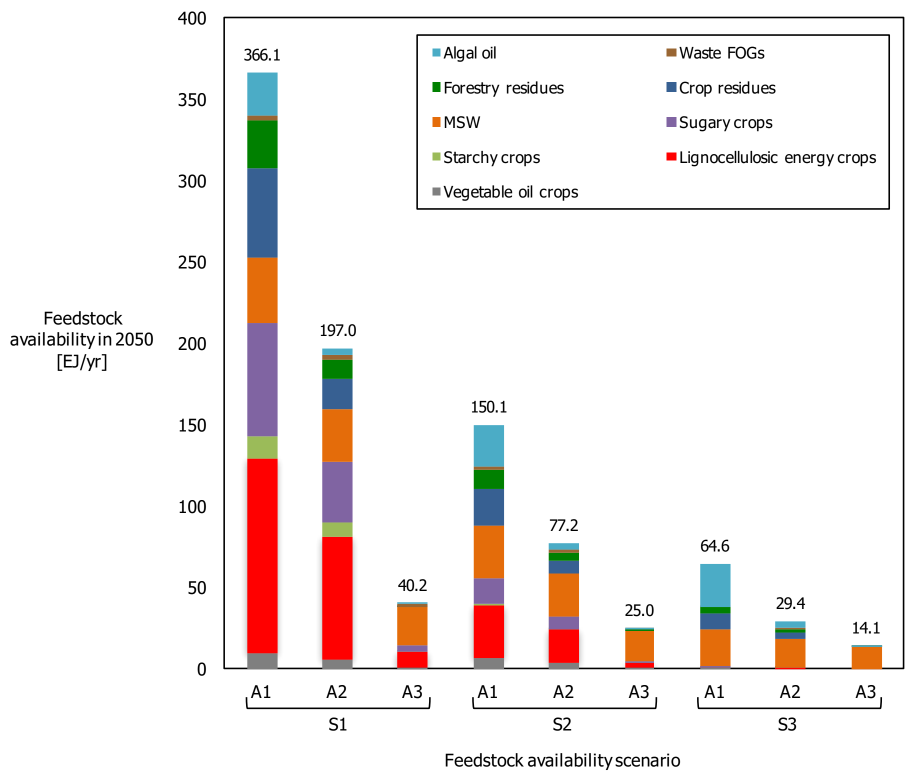

Figure 4: 2050 feedstock availability results

4.3 AJF scenarios

The third step of the analysis quantifies AJF production volumes from the feedstock availability scenario results. This is calculated for three scenarios described in Section 3.3, which define the proportion of available feedstock used to produce AJF, as opposed to other potential end uses.

Note that the scenario F3 assumption results in no feedstock availability for AJF production, therefore the results are not shown here.

The results for scenarios F1 and F2 are shown in Figure 5, compared to global projected demand for jet fuel in 2050 (ICAO 2016a). There is sufficient AJF production to offset 100% of projected 2050 demand in only four of the F1 scenarios. Recall that the F1 scenarios assume the maximum quantity of AJF is produced from available feedstocks.

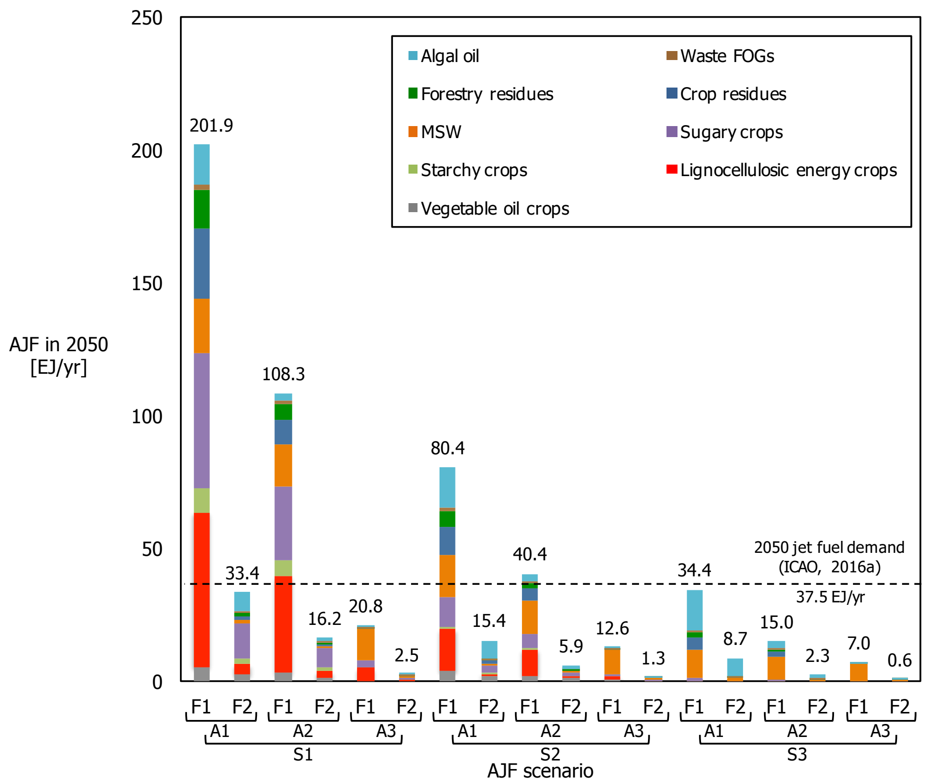

Figure 5: AJF scenario results, compared to projected 2050 jet fuel demand (ICAO, 2016a)

4.4 Scenario results for lifecycle GHG emissions from aviation

Next, the AJF scenario results from section 4.2 are combined with the pathway specific lifecycle GHG emissions given in section 3.4.1, and LUC emissions based on the arable land areas required for feedstock crop cultivation. The LUC emissions calculated for cultivated feedstock crops, by AJF scenario, are given in Figure 6.

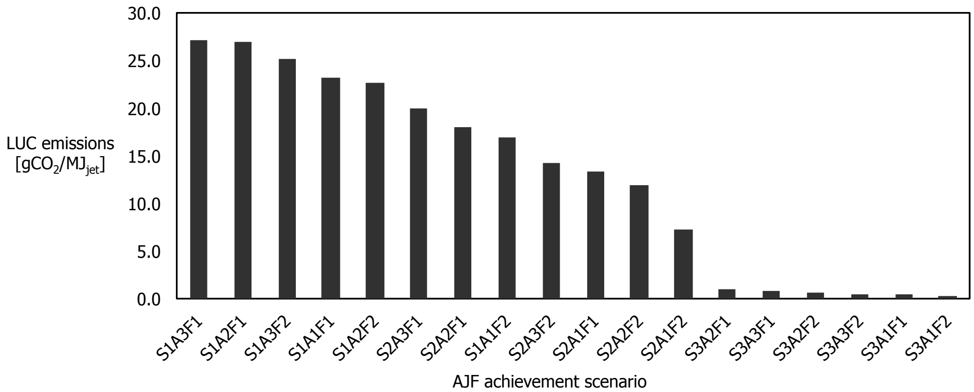

Figure 6: LUC emissions [gCO_2/MJ_{jet}] averaged over AJF from all cultivated energy crops, by AJF scenario.

The total lifecycle GHG emissions of the AJF scenarios are compared against the assumption of 100% petroleum-derived jet fuel, and a global jet fuel demand of 37.5 EJ/yr in 2050 (ICAO 2016a). The percentage reduction in lifecycle GHG emissions in each AJF scenario is given in Figure 7. These results are presented in a matrix, where the calculated reduction in aviation lifecycle GHG emissions varies along three dimensions: the size of the primary bioenergy and waste resource (scenarios S1-S3); the price or policy emphasis placed on using primary bioenergy and waste as feedstock (scenarios A1-A3); and the price or policy emphasis placed on AJF versus other potential feedstock uses (scenarios F1-F3).

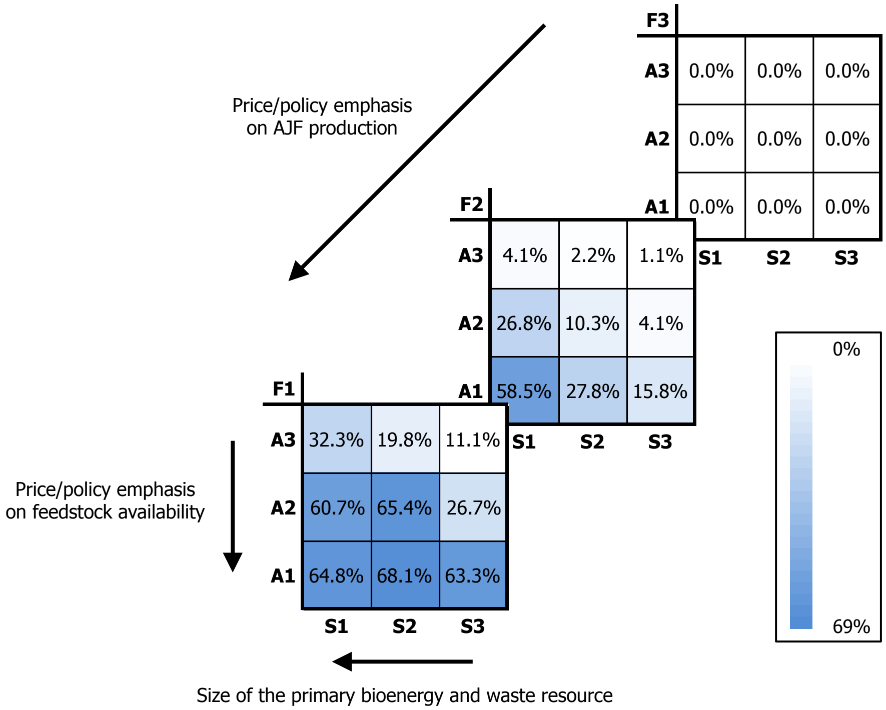

Figure 7: Percentage reduction in aviation CO_2e emissions by AJF scenario, compared to projected 2050 jet fuel demand satisfied by petroleum-derived jet fuel (ICAO, 2016a)

In order to put these results in perspective, the number of bio-refineries required to achieve the 2050 AJF production volumes of four scenarios are calculated, assuming a nameplate capacity of 0.22 Mt total fuel production per year per facility (~5000 bpd) and that 50% of total fuel production at each facility is AJF (Pearlson et al., 2013). Facility capital costs are calculated based on a range of 775-3100 USD_{2015} per tonne of fuel production capacity per year, corresponding to literature estimates of petroleum refining capacity capital costs and lignocellulosic-derived FT fuel production capacity, respectively (Gary et al., 2007; Larson et al., 2009; NREL, 2010). The number of bio-refineries that would need to come on line each year, and the associated rate of capital investment, are calculated assuming near-term (defined here as 2020) global AJF production capacity of approximately 3.0 Mt per year (Radich, 2015) and linear growth in capacity between 2020 and 2050. The results are shown in Table 14.

Table 14: Selected AJF scenarios and the required corresponding number bio-refineries (assuming AJF is 50% of the total fuel product slate), and range of required annual capital investment

AJF achievement scenario	Aviation CO_2e emissions reduction in 2050	AJF production volume in 2050 [Mt/yr]	Number of biorefineries in 2050	New biorefineries per year (2020-2050)	Capital investment per year (2020-2050) [bil. USD_{2015}/yr]
S2A3F2	2.2%	30.2	286	9	0.7-2.8 bil. USD_{2015}
S2A2F2	10.3%	133.1	1262	41	3.4-13.4 bil. USD_{2015}
S2A1F2	27.8%	349.9	3317	110	9.0-35.9 bil. USD_{2015}
S2A1F1	68.1%	850.3	8061	268	21.9-87.6 bil. USD_{2015}

For reference, average annual growth in global conventional biofuel production (ethanol and biodiesel) was equivalent to approximately 60 new facilities of a similar size per year from 2002 to 2011 (Brown, 2012), and current capital expenditure in the global petroleum refining industry is 68 billion USD_{2015} (IEA, 2014). We note that the bio-refinery capital costs could be lower than those assumed here, to the extent that existing refining or bio-refining capacity could be retrofit for production of AJF (Staples et al., 2014).

5 Conclusions and Policy Implications

The results of this analysis indicate that the use of AJF could reduce lifecycle GHG emissions from aviation by a maximum of 68.1% in 2050. However, the six scenarios corresponding to the greatest emission reductions imply offsetting >85% of projected demand for petroleum-derived jet fuel with AJF (scenarios S1A1F1, S1A2F1, S2A1F1, S2A2F1, S3A1F1 and S1A1F2). These scenarios require that: environmental and societal constraints allow for large quantities of primary bioenergy and waste in 2050; prices or policies emphasize the production and use of that bioenergy and waste as feedstock; and prices or policies emphasize AJF production relative to other potential uses for primary bioenergy resources. For example, a reduction in lifecycle GHG emissions of one third or more is only possible with either feedstock prices ≥\$2/GJ (A1 and A2) and significant emphasis on AJF relative to other potential uses for bioenergy (F1), or several hundred EJ of primary bioenergy and waste in 2050 (S1) and feedstock prices of $4/GJ (A1).

The above findings quantify the potential for aviation lifecycle GHG emissions reductions in 2050 limited by feedstock availability, however the existence of sufficient bio-refining infrastructure for AJF production could also be a binding constraint on emissions reductions. In order to further assess the feasibility of our results, we estimate the number of bio-refineries and rate of capital investment implied by four scenarios representing a range of aviation lifecycle GHG reductions, as shown in Table 14. These findings indicate that continuous expansion of AJF production capacity, comparable to that observed in the ethanol and biodiesel industries in the early 2000s, would result in aviation emissions reductions of approximately 15% by 2050, requiring annual investment in AJF production capacity equivalent to approximately one fifth of current global investment in petroleum refining.

Our study demonstrates that AJF could contribute to reductions in lifecycle GHG emissions from aviation by 2050. However, realizing the larger reductions quantified here would require societal and policy choices that: limit environmental and other constraints on the quantity of primary bioenergy and wastes; encourage the production and use of those bioenergy and waste resources as feedstock, and; dedicate feedstocks to AJF production over other potential end uses. In practical terms, this would require significant and continuous investment in AJF production capacity over the coming decades in order to develop a global AJF production infrastructure, similar in magnitude to the existing conventional biofuels industry.

This analysis also shows that even 100% replacement of petroleum-derived jet fuel with AJF in 2050 may result in an absolute increase in aviation lifecycle GHG emissions compared to a 2005 baseline. For example, total 2050 aviation CO_2e emissions are 1101 Mt/yr in scenario S2A1F1 (the AJF scenario with the largest reduction in emissions), and lifecycle GHG emissions from global aviation were approximately 711 Mt in 2005 (based on fuel burn from ICAO 2016a in 2005, and lifecycle emissions of 88.9 gCO_2e/MJ from petroleum-derived jet fuel). This is especially relevant in the policy context of CORSIA, and for IATA and ICAO's emissions reduction goals, which are unlikely to be possible without significant use of CO_2 offsets from other sectors.

6 Acknowledgements

This work was funded by the US Federal Aviation Administration, Office of Environment and Energy, under FAA Award Number 13-C-AJFE-MIT, Amendment Nos. 003, 012, 016, and 028. The project was managed by James Hileman, Daniel Williams and Nathan Brown, FAA. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA.

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