SHORT-TERM AND LONG-TERM ALTERNATIVE JET FUEL PRODUCTION AND ASSOCIATED GHG EMISSIONS REDUCTION

February 2016

1. INTRODUCTION

1.1 One of the tasks of the Alternative Fuels Task Force (AFTF) on the tenth cycle of the ICAO Committee on Aviation Environmental Protection (2013-2016) was to evaluate the range of potential GHG emissions reductions from the use of alternative jet fuels (AJF) to 2050. The results have been used as input for inclusion in CAEP's environmental trends assessment to 2050, which were presented to the ICAO 39th Assembly (2016) in A39-WP/55.

1.2 In order to fulfill this mandate, the AFTF developed scenarios for potential AJF availability in the short- and long-term (defined as year 2020 and 2050, respectively) and developed estimates for lifecycle GHG emissions intensity for different groups of AJF. This information was used to estimate a range of possible GHG emissions reduction from AJF usage in the short- and long-term.

2. APPROACH

2.1 The short-term scenarios for AJF availability were established from fuel producers' announcements regarding their production plans and from the targets set by States in different world regions if associated with State-sponsored production plans. Six scenarios were developed for the short-term assessment. The scenarios vary according to the credibility requirements for inclusion of companies' production plans, and the consideration of existing production or production plans for green diesel as a potential future low-percentage blending opportunity with conventional jet fuel.

2.2 For the long-term scenarios, AFTF assessed future jet fuel first by estimating the primary bioenergy potential constrained by selected environmental and socio-economic factors; second by estimating the proportion of bioenergy potential that could actually be achieved or produced; and finally by exploring the quantity of AJF that could be produced from the available bioenergy. AJF availability was calculated including 9 different groups of feasible feedstocks (starchy crops; sugary crops; lignocellulosic crops; oily crops; agricultural residues; forestry residues; waste fats, oils and greases; microalgae; municipal solid waste (MSW)). Different sets of assumptions for each step of the analysis were chosen. Five different sets for primary bioenergy potential, three sets for bioenergy achievement, and four sets of aviation biofuel assumptions were developed, yielding a total of 60 different production scenarios.

2.3 AFTF calculations account for emissions from direct land-use change (LUC) due to biomass growth required for AJF production. For the purpose of the contribution of AFTF to the trends assessment, emissions from indirect LUC are not considered as bioenergy is constrained by the model not to compete against food and feed production within the scenarios, which implies that existing agricultural markets are not significantly distorted through bioenergy production. AFTF emphasizes that this approach is limited to the specific context of AJF lifecycle calculations for the trends assessments to 2050 and does not apply to the MBM work for which induced LUC will be included. Indirect LUC can take place in the real world.

2.4 AFTF created a database containing results from a literature survey on existing studies that estimate lifecycle GHG emissions of AJF for different feedstock and technology combinations. For the 2020 GHG intensities, existing study results were adapted to reflect allocation of emissions to co-products based on their energy-content, and the average emissions value of each bioenergy feedstock was calculated for all studies. No existing study projects emissions to the 2050 timeframe. AFTF therefore considered two emission cases for each feedstock group included in the assessment: in the 2050 low emission case, GHG emissions were estimated using available projections or scenarios for increases of feedstock conversion efficiency, agricultural yield increases and for changes in GHG intensities of utilities required for feedstock production and conversion. In the 2050 high emission case, conversion efficiency, and utility GHG intensity were assumed to remain constant over time.

3. **RESULTS**

3.1 AFTF calculated AJF lifecycle GHG intensities by feedstock group so that these could be coupled with the feedstock-specific fuel production results. GHG intensities of the core lifecycle – without emissions from LUC - were found to range between 7 and 64 gCO_2e/MJ of AJF, compared to lifecycle emissions of 89 gCO_2e/MJ for petroleum-derived jet fuel. Table 1 in the Appendix contains the results for all feedstock groups considered without LUC emissions. As outlined under 2.4, for calculating GHG emission intensities in 2050, AFTF has augmented peer reviewed studies. Current and future technological advances pertaining to both lifecycle GHG emission reduction potential and feedstock or conversion processes could improve the potential lifecycle GHG reduction in the future beyond what has been modeled. However, development could also fall behind what was assumed in the calculation.

3.2 For 2020, results for AJF production range from 56 kt/y to 6.5 Mt/y, corresponding to 0-2% of global aviation fuel demand in 2020 in CAEP/10 Scenario 7. This corresponds to a reduction of lifecycle GHG emissions by 0-1.3% compared to only using petroleum-derived jet fuel (see Figure 7 in the Appendix). Among the different scenarios considered for 2020, emission reduction values increase with: an assumption of green diesel being certified for use in jet engines (in low blends up to 5%) and less mature AJF production plans being included.

3.3 Emissions from LUC were calculated for each scenario in 2050 separately and found to vary among scenarios from 1g to 20gCO_2e/MJ on average, for the alternative fuel mix produced (see Figure 1 in the Appendix). Average emissions from LUC for the alternative fuel mix decrease, inter alia, as the share of feedstocks not requiring dedicated land conversion such as wastes, residues, and MSW increases in the scenarios. Overall, scenarios with higher alternative fuel production volumes tend to show higher emissions from LUC per unit of fuel produced, as AJF production becomes increasingly dependent on the conversion of additional land area for feedstock cultivation.

3.4 AFTF calculated that, depending on the assumptions made in the different scenarios, AJF production in 2050 could range from zero to 4.600 Mt per year. This production range could offset between 0-100% of the projected petroleum-derived jet fuel demand in 2050 (see Figure 2 in the Appendix). The production range translates into a reduction of total lifecycle GHG emissions reduction between 0-63% compared to lifecycle GHG emissions in the CAEP/10 Scenarios 7 and 9 fuel burn projections (see Figure 3 to 6 in the Appendix). The range of potential GHG reductions is smaller than the fuel replacement range, as the AJF mix in the different scenarios is associated with lifecycle GHG emissions of 31-64% of those of petroleum-derived jet fuel, on average.

3.5 The results indicate that the potential to reduce GHG emissions from aviation via the use of AJF increases with assumptions that imply: larger agricultural yield increases; greater land availability; higher accepted rates of residue removal; increases in feedstock and fuel production efficiencies; reductions in GHG emissions from utilities; increased policy emphasis on bioenergy production relative to other land usages in general, and on AJF production in particular; and other factors. Only some of these factors can be influenced by the aviation sector directly or indirectly.

3.6 Inferring from experience from the production ramp-up in other industries, AFTF expects the long-term development of AJF deployment to resemble an s-curve. However, there was no sufficient time for AFTF to discuss the calibration of the s-curve.

3.7 AFTF shared the full range of potential emissions reduction in 2020 and 2050 (0-63%) with MDG. AFTF also provided an "illustrative example" based on one specific scenario of 17% GHG emissions reduction with 220 Mt/yr of alternative fuel production in 2050 compared to the CAEP/10 Scenario 7 fuel burn projections (19% compared to Scenario 9 fuel burn projections used by MDG). This scenario assumes a mid-level of overall bioenergy potential, high actual achievement rates for this potential, with equal policy-emphasis on all potential end-usages of bioenergy and a relatively low GHG intensity of alternative jet fuel produced in 2050.

3.8 AFTF further investigated the conditions that would need to be in place in order for alternative aviation fuel to potentially be able to yield particular levels of GHG reductions. Below, three emission reduction levels are briefly explained. Additional details for these and additional GHG reduction values are provided in Table 1 in the Appendix.[1]

3.8.1 A 2% reduction of lifecycle aviation GHG emissions would require a global production volume of AJF of about 30 Mt/yr in 2050.

3.8.2 A 17% reduction in GHG emissions compared to Scenario 7 (19% compared to Scenario 9), which corresponds to the illustrative scenario chosen by AFTF – would entail AJF production of approximately 220 Mt/yr in 2050 for the case of relatively low GHG intensity of AJF. Under a linear growth assumption between 2020 and 2050, this would require approximately 70 biorefineries to be constructed every year (required capital investment of approximately $6B-$25B/yr) and exponential growth implies that 200-300 facilities will have to be built per year closer to 2050 (required jet-fuel specific capital investment of approximately less than $1B/yr to $2B/yr in 2025 and $30B-$110B/yr in 2050). These investments would cover the capital expenditure for the refineries and not the operational expenditures of the entire alternative fuel supply chain (e.g. feedstock and utility costs). The linear growth rates are comparable to those observed in recent years for global ethanol and biodiesel production capacity.

3.8.3 For the highest modelled GHG emissions reduction under all scenarios assessed, of 63%, approximately 870 Mt/yr of AJF would need to be produced in 2050. Besides the required capital investment in biorefineries that is necessary in this scenario with high numbers of refineries and associated costs (see Figure 2), this emissions reduction would require the realization of the highest assumed increases in agricultural productivity, the highest considered availability of land for feedstock cultivation, residue removal rates, conversion efficiency improvements, and significant reductions in the GHG emissions of utilities, as well as a strong market or policy emphasis on bioenergy in general, and AJF in particular. The latter would entail that large shares of the available bioenergy pool be devoted to producing AFJ as opposed to other end uses such as transportation fuels or electricity and heat.

3.9 Overall, in order to achieve significant reduction in aviation GHG emissions by 2050, high capital investments are required and these might be feasible only if the investments begin in time and consistently grow over time, or if existing infrastructure can be leveraged to reduce the initially required capital investments. Comparison to the development in global ethanol and biodiesel production shows that

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[1] The GHG emission reduction levels are determined based on Scenario 7 of the ICAO fuel burn projections for 2050. The number of biorefineries required is estimated using 5000 bpd facility with a 50% jet fuel share in total product slate. Capital cost estimates are derived from the existing literature.

the growth in alternative aviation fuel production would need to be on the order of recently observed growth of 5-15 Mt/yr in global biofuel production capacity to achieve a 10% and 17% emissions reduction by 2050, and would have to significantly exceed historical global biofuel production growth rates for total GHG emission reductions above 20%. For additional context, Table 1 in the Appendix compares required investment values to forecasted investment in petroleum refineries.

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APPENDIX

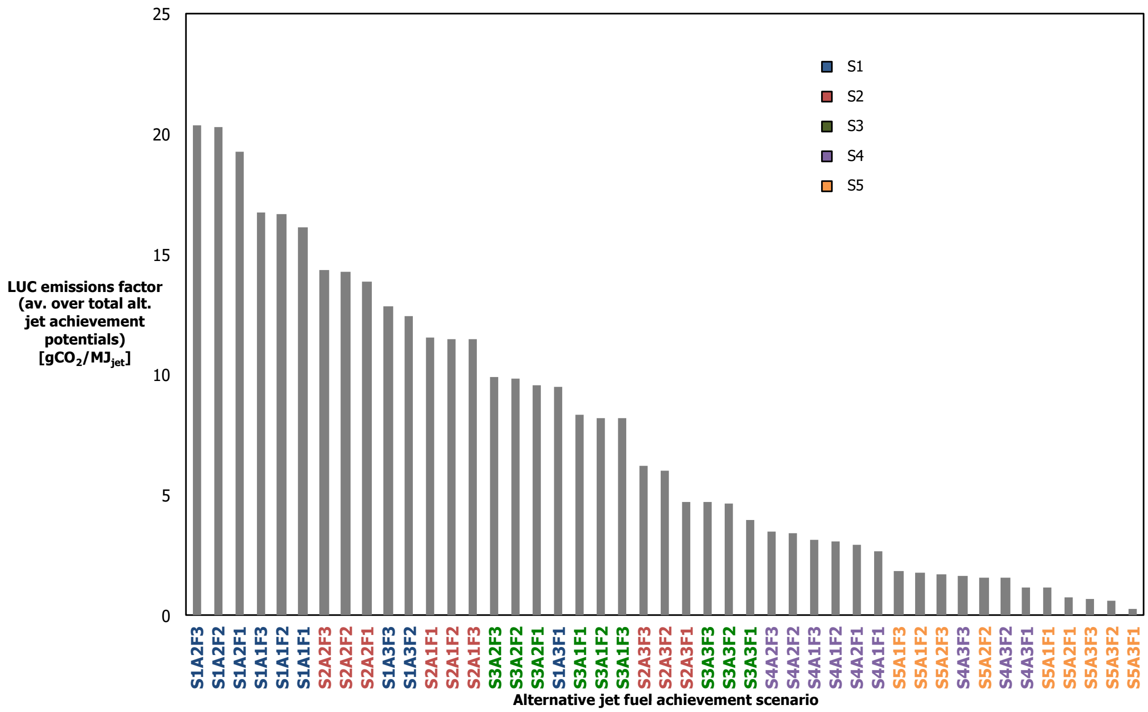

Figure 1. Allocated LUC emissions factors, averaged over total AJF achievement potential, for each AJF achievement scenario [gCO_2/MJ_{jet}] and amortized over 25 years. The "S-dimension" refers to different sets of assumptions for the primary bioenergy potential, the "A-dimension" refers to different sets of assumptions for the bioenergy achievement, and the "F-dimension" refers to different sets of assumptions for the jet fuel achievement.

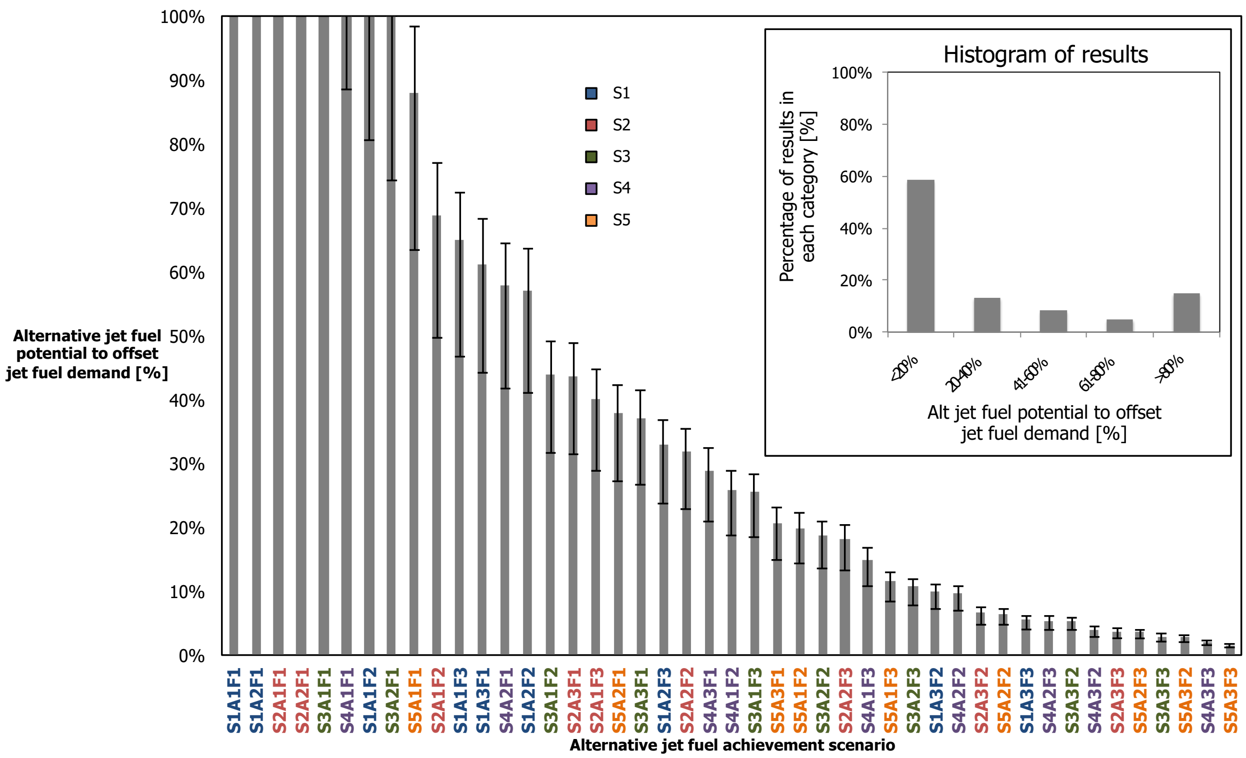

Figure 2. Percentage of 2050 jet fuel demand potentially satisfied by AJF, in decreasing size of offset potential. The whiskers indicate the change in percentage of potential offset due to the range of CAEP/10 2050 fuel burn projections. The "S-dimension" refers to different sets of assumptions for the primary bioenergy potential, the "A-dimension" refers to different sets of assumptions for the bioenergy achievement, and the "F-dimension" refers to different sets of assumptions for the jet fuel achievement. The insert in the top left shows a histogram of results.

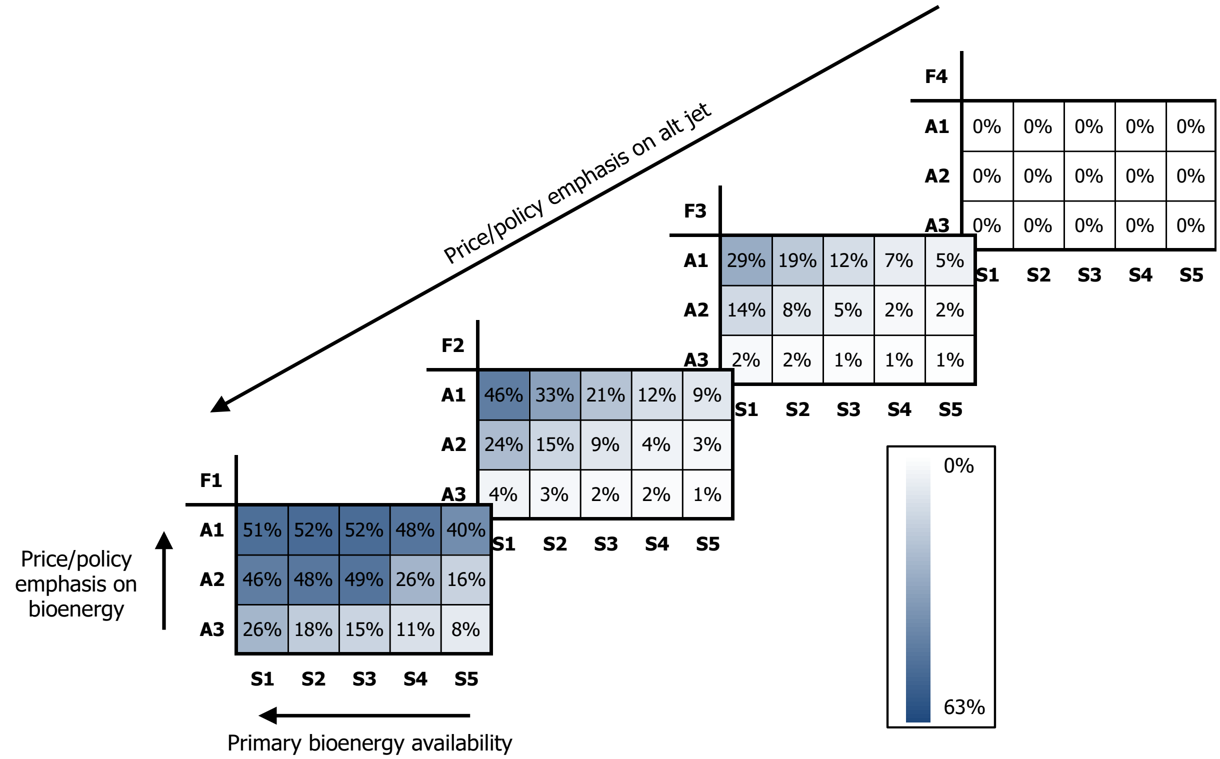

Figure 3. High emissions case reduction in aviation CO_2e emissions from 100% petroleum-derived CAEP/10 Scenario 7 fuel burn projections, by AJF achievement scenario. The "S-dimension" refers to different sets of assumptions for the primary bioenergy potential, the "A-dimension" refers to different sets of assumptions for the bioenergy achievement, and the "F-dimension" refers to different sets of assumptions for the jet fuel achievement.

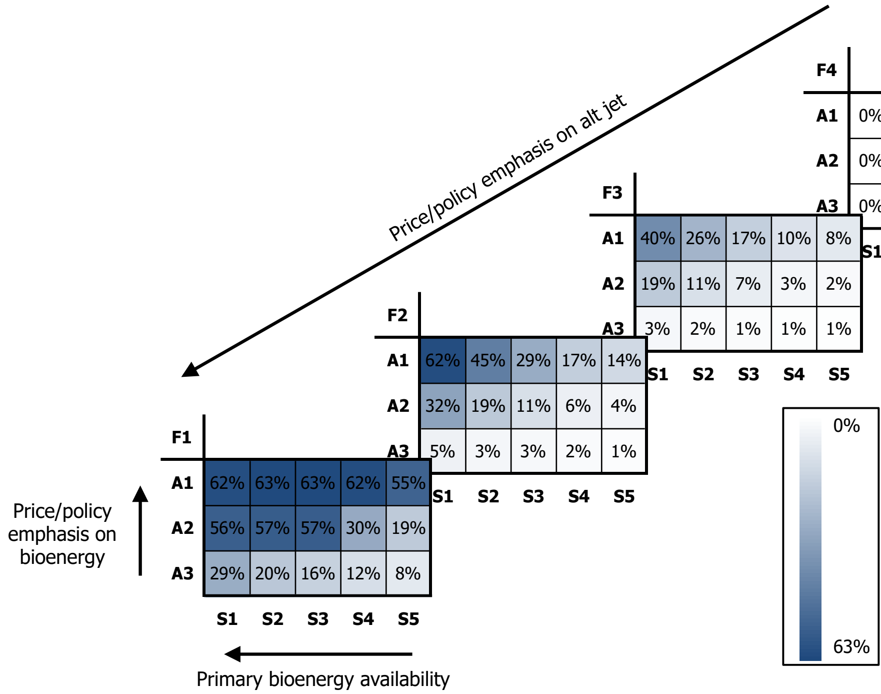

Figure 4. Low emissions case reduction in aviation CO_2e emissions from 100% petroleum-derived CAEP/10 Scenario 7 fuel burn projections, by AJF achievement scenario. The "S-dimension" refers to different sets of assumptions for the primary bioenergy potential, the "A-dimension" refers to different sets of assumptions for the bioenergy achievement, and the "F-dimension" refers to different sets of assumptions for the jet fuel achievement.

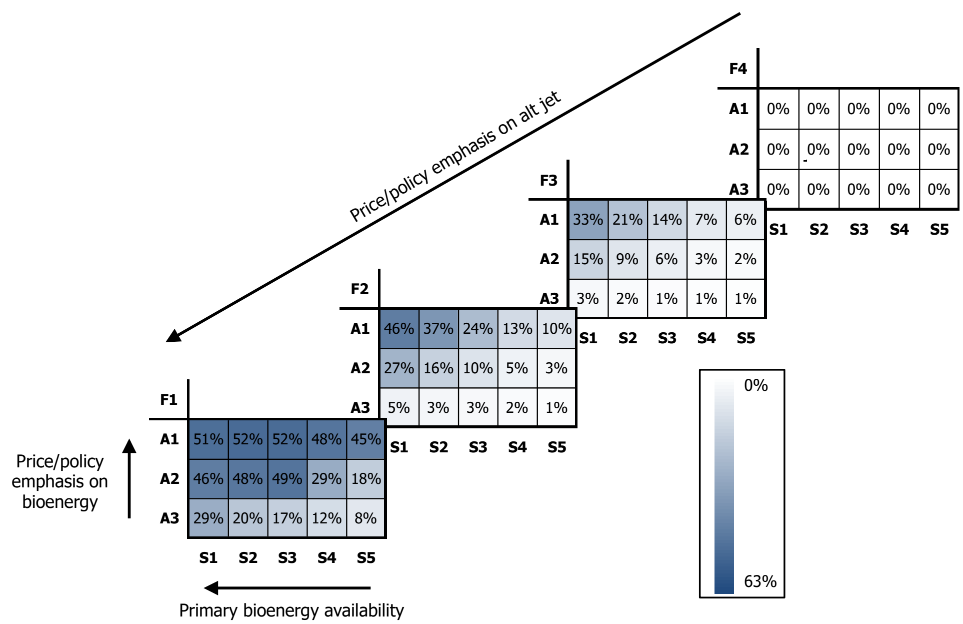

Figure 5. High emissions case reduction in aviation CO_2e emissions from 100% petroleum-derived CAEP/10 Scenario 9 fuel burn projections, by AJF achievement scenario. The "S-dimension" refers to different sets of assumptions for the primary bioenergy potential, the "A-dimension" refers to different sets of assumptions for the bioenergy achievement, and the "F-dimension" refers to different sets of assumptions for the jet fuel achievement.

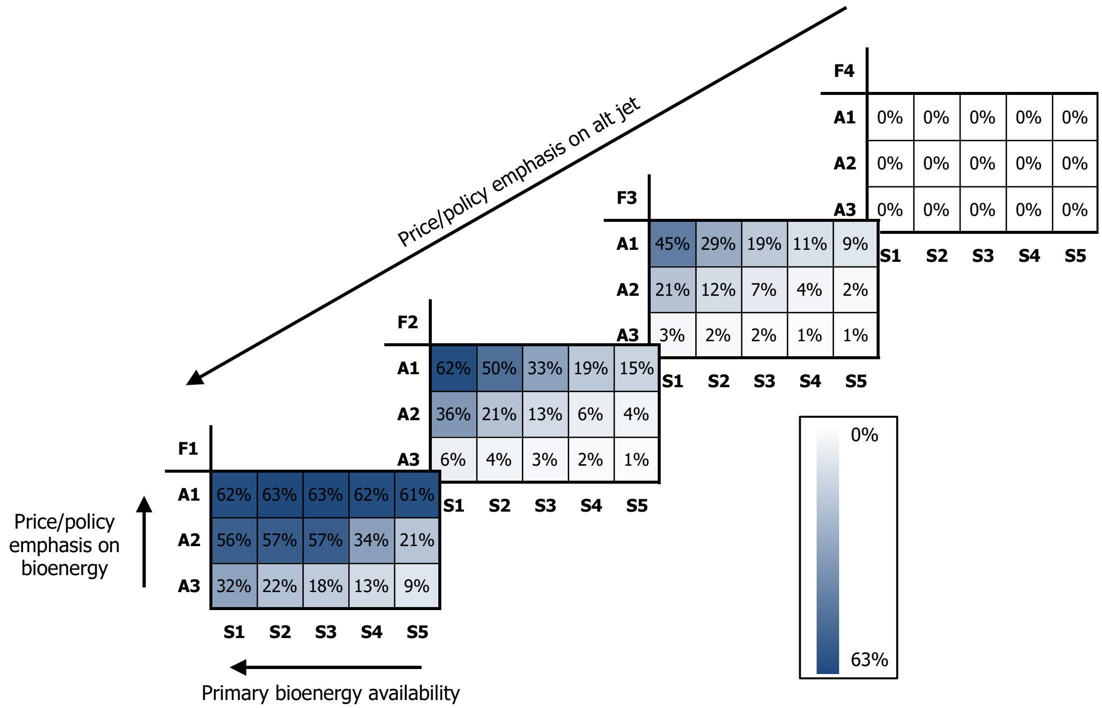

Figure 6. Low emissions case reduction in aviation CO_2e emissions from 100% petroleum-derived CAEP/10 Scenario 9 fuel burn projections, by AJF achievement scenario. The "S-dimension" refers to different sets of assumptions for the primary bioenergy potential, the "A-dimension" refers to different sets of assumptions for the bioenergy achievement, and the "F-dimension" refers to different sets of assumptions for the jet fuel achievement.

Aviation GHG emissions reduction	Required AJF production volume in 2050 (Mt/yr)	Requirements under linear growth		Requirements under exponential growth	
		Number of new biorefineries/yr	Capital investment/yr	Number of new biorefineries/yr	Capital investment/yr
2%	30	10	$1B - $3B	<5 (2025) to 30 (2050)	<$1B - $2B (2025) to $3B - $10B (2050)
10%	130	40	$3B - $14B	<5 (2025) to 200 (2050)	<$1B - $2B (2025) to $15B - $60B (2050)
17%	220	70	$6B - $25B	<5 (2025) to 300 (2050)	<$1B - $2B (2025) to $30B - $110B (2050)
40%	570	170	$15B - $60B	<10 (2025) to 1000 (2050)	$1B - $3B (2025) to $80B - $330B (2050)
63%	870	260	$20B - $90B	<10 (2025) to 1600 (2050)	$1B - $3B (2025) to $130B - $550B (2050)
Average historical global ethanol and biodiesel production		**Total annual volumes (Mt/yr)**		10 (years 1975 - 2000) to 45 (2001 - 2011)	
		Number of new biorefineries/yr		5 (years 1975 - 2000) to 60 (2001 - 2011)	
Projection for average annual investment in petroleum refining in 2035				$55B	

Table 1. Required fuel production volume in 2050 (based on total fuel demand projections of CAEP/10 Scenario 7), number of new 5000 bpd facilities required annually (assuming 50% jet fuel share in product slate) and range of annual capital investment required (jet-fuel portion only) for different GHG emission reduction percentages under the simplifying assumption of linear or exponential growth and low GHG intensity of AJF. AFTF expects the long-term development of AJF deployment to resemble an s-curve (see 3.6). Average historical growth for transportation biofuels in terms of annual production volumes and the number of new facilities per year (assuming a 5000 bpd scale for illustrative purposes) and projected petroleum refinery investment in 2035 shown for comparison purposes[2].

[2] International Energy Agency, Energy technology perspectives 2015.

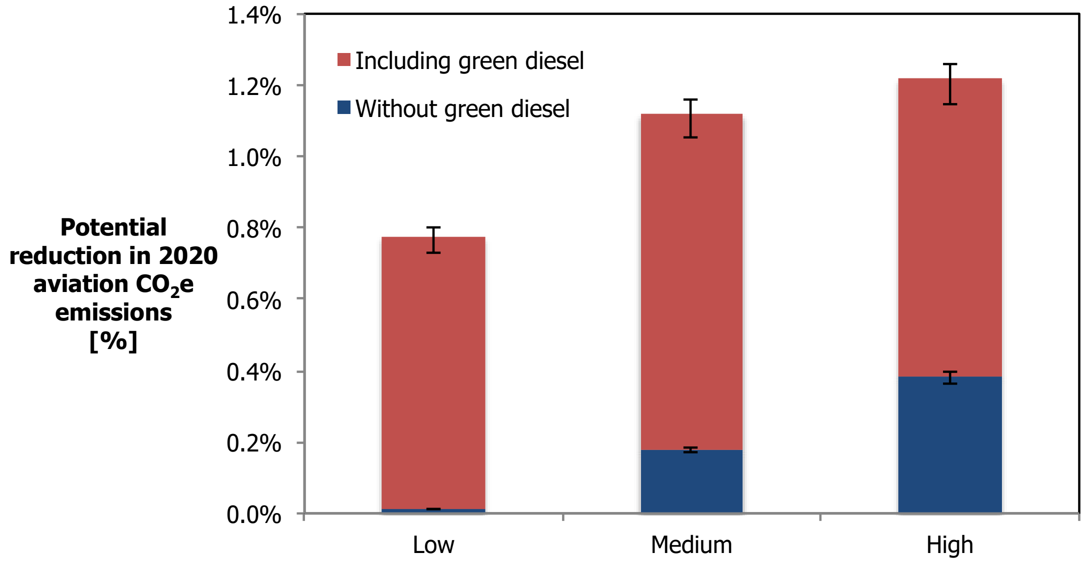

Figure 7. Potential reduction in 2020 aviation lifecycle CO_2e emissions using the low LCA emission factor case, compared to 100% petroleum-derived jet fuel baseline. Variability bars reflect different CAEP/10 fuel projections for 2020. Reduction is zero for all production scenarios under the high LCA emission factor case.

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