Impact of Non-CO_2 Combustion Effects from Aviation on the Environmental Feasibility of Alternative Jet Fuels

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Abstract

Alternative fuels represent a potential option for reducing the climate impacts of the aviation sector. The climate impacts of alternative fuels are traditionally considered as a ratio of life cycle greenhouse gas (GHG) emissions to those of the displaced petroleum product; however, this ignores the climate impacts of the non-CO_2 combustion effects from aircraft in the upper atmosphere. The results of this study show that including non-CO_2 combustion emissions and effects in the life cycle of Synthetic Paraffinic Kerosene (SPK) can lead to a decrease in the relative merit of SPK fuels relative to conventional jet fuel. For example, an SPK fuel option with zero life cycle GHG emissions would offer a 100% reduction in GHG emissions but only a 53% reduction in actual climate impact using a 100-year time window and the nominal climate modeling assumption set outlined herein. Therefore, climate change mitigation policies for aviation that rely exclusively on relative well-to-wake life cycle GHG emissions as a proxy for aviation climate impact may overestimate the benefit of alternative fuel use on the global climate system.

1 Introduction

Aviation plays a key role in the global economy and transportation systems. Projections indicate that over the next 2 decades, the demand for aviation within the US will grow at roughly 2% per annum (*1*). Mitigating climate change from the aviation sector can be simplified to consuming less energy, either through improvements in aircraft technology or operational efficiency, and reducing the climate impacts of the energy source, through the use of alternative fuels. Synthetic Paraffinic Kerosene, currently the most promising fuel composition for use in aviation, can be created via: 1) Gasification of coal, natural gas, or biomass to form synthesis gas, which is processed using Fischer-Tropsch (F-T) synthesis, and subsequently upgraded to a product slate that includes a synthetic jet fuel; and 2) Hydroprocessing of renewable oils, such as those created from jatropha, camelina, and algae, among many others, to create a Hydroprocessed Renewable Jet (HRJ) fuel (*2*). These fuels differ from conventional jet fuel in that they are comprised solely of paraffinic hydrocarbons and contain neither aromatic compounds nor sulfur (*3*).

The potential of a particular fuel to reduce greenhouse gas emissions (GHG) is generally assessed through a comparison of the life cycle GHG emissions inventory of the alternative fuel with that of the fuel it is intended to displace (*2*). A life cycle GHG emissions inventory encompasses emissions from recovery and transportation of the feedstock to the production facility, processing of these materials into fuels, transportation and distribution of the fuel to the aircraft tank, and finally, the combustion of the fuel in the aircraft. The term "well-to-wake" is used to describe the life cycle GHG inventory of aviation fuels. Life cycle analyses of bio-based, ground transportation fuels assume that the emissions from fuel combustion are equal and opposite to the emissions absorbed from the atmosphere during growth of the feedstock (*4, 5*). However, this approach neglects non-CO_2 combustion emissions and effects, namely, soot and sulfate aerosols, water vapor, and NO_X. Aviation also causes contrails and induced cirrus clouds called contrail cirrus. Such products will exist even if the net GHG emissions from the fuel life cycle are zero. Figure 1 schematically demonstrates the life cycle impacts pathway of aviation related climate change using a bio-based fuel starting with emissions from fuel production and fuel combustion in the engine and culminating in societal impacts.

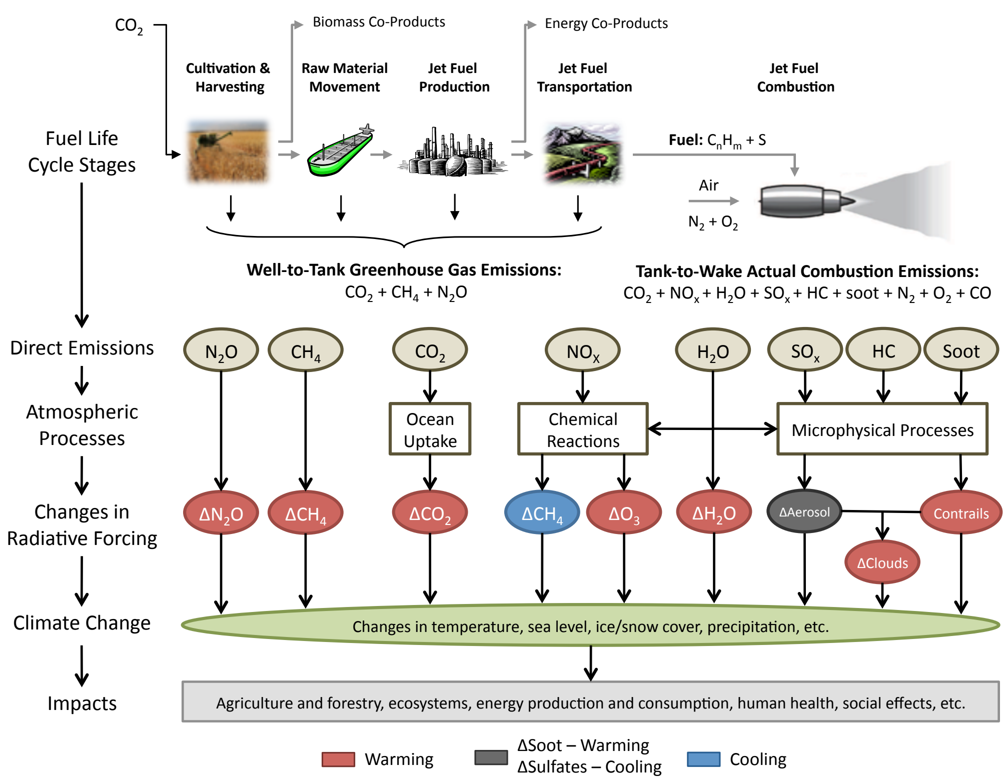

Figure 1: Aviation climate change impacts pathway (adapted from (*6*))

Soot and sulfate aerosols generate atmospheric warming and cooling, respectively, and have lifetimes on the order of days to weeks (*7*). Contrails and contrail cirrus sustain only for hours to days and cause atmospheric warming (*6,8*); however, their impact is the most uncertain of all aviation induced climate forcing (*6*). NO_X results in both short-term warming and long-term cooling. In the months following a pulse of NO_X in the upper atmosphere, ozone production is stimulated causing a short term warming. The NO_X also stimulates the production of additional OH, acting as a sink for CH_4. The corresponding reduction in CH_4, which is an important ozone precursor, leads to a long-term reduction in ozone. Both the long-term reduction in CH_4 and ozone cool the atmosphere and decay with a lifetime of approximately 11 years (*9*).

The purely paraffinic nature and lack of sulfur present in SPK fuels has been shown to cause changes in the combustion emissions from gas turbine engines (*10-13*); hence, the purpose of this paper is twofold: 1) develop ratios by which the CO_2 from combustion can be scaled to include the climate forcing from non-CO_2 combustion effects of conventional jet fuel and SPK, and 2) quantify how including non-CO_2 combustion species within the fuel life cycle changes the merit of alternative jet fuels relative to conventional jet fuel from the perspective of climate change. Select jet fuel life cycle GHG inventories developed by Stratton et al. (*2*) are subsequently leveraged as examples of how non-CO_2 combustion effects change the climate change mitigation potential of alternative fuel options; however, the conclusions of this work are independent of the life cycle GHG inventories to which the climate forcing from non-CO_2 combustion effects are added.

2 Methods

This paper implements a modified version of the climate impacts module of the Aviation Portfolio Management Tool (APMT) to establish a '*basis of equivalence*' between emissions of different species, such that the climate impacts of non-CO_2 combustion emissions and effects can be related to those of CO_2. This process is described in further detail in Sections 2.1 through 2.5.

2.1 **Functional Unit**

Well-to-wake GHG emissions are presented per unit of energy (lower heating value) consumed by the aircraft. The life cycle emissions of a fuel pathway can be presented either with or without the inclusion of climate impacts from non-CO_2 combustion emissions and effects. When non-CO_2 combustion emissions and effects are ignored, the emissions inventory is a pure GHG emissions inventory composed of CO_2, CH_4 and N_2O.

$$\left(CO_2e\right)_{\text{well-to-wake}} = \left(CO_2 + CH_4 \cdot GWP_{CH_4} + N_2O \cdot GWP_{N_2O}\right)_{\text{well-to-tank}} + \left(CO_2\right)_{\text{combustion}} \quad \text{Equation 1}$$

Merging non-CO_2 combustion emissions and effects into a fuel life cycle GHG inventory requires them to be presented per megajoule (LHV) of fuel consumed by the aircraft. This work developed non-CO_2 ratios to scale the CO_2 from combustion to account for the climate forcing from non-CO_2 combustion emissions and effects. This approach draws from the process and results developed for conventional jet fuel by Dorbian and Waitz (*14*). Although non-CO_2 combustion emissions and effects have climate impacts that have been represented in terms of CO_2, they are not themselves greenhouse gases (with the exception of water vapor). As such, integrating the non-CO_2 combustion emissions and effects into a GHG life cycle inventory results in a combination of a GHG inventory and an impact analysis. The terminology 'well-to-wake (+)' is presented here to identify the combination of CO_2 and non-CO_2 effects from fuel combustion in aircraft. This framework is shown in Equation 2.

$$\left(CO_2e\right)_{\text{well-to-wake (+)}} = \left(CO_2 + CH_4 \cdot GWP_{CH_4} + N_2O \cdot GWP_{N_2O}\right)_{\text{well-to-tank}} + \left(CO_2\right)_{\text{combustion}} \cdot \left(\text{non-}CO_2 \text{ ratio}\right) \quad \text{Equation 2}$$

2.2 Modeling Framework

The APMT climate module has been documented and tested in the literature (*15-17*). The model is based on the Bern carbon-cycle impulse response function with a simplified analytical temperature change model to estimate climate impacts for aviation CO_2 and non-CO_2 effects. The temporal resolution is limited to one year while the spatial resolution is an aggregated global mean level.

Inputs to APMT Climate are a background emissions scenario, a demand scenario for aviation fuel burn and corresponding emissions inventories for CO_2 and NO_X. Radiative forcing estimates for NO_X were obtained by linearly scaling radiative forcing estimates from the literature based on NO_X emissions because the short lived nature of the species inhibits a well defined gas-cycle like that for carbon (*9,18,19*). All short-lived effects (aerosols, H_2O, contrails and contrail cirrus) are scaled linearly with fuel burn levels based on radiative forcing estimates from the literature (*20-22*). Outputs from the model are temporal profiles of RF and change in global mean average temperature from each forcing agent.

2.3 Model Uncertainty

Monte Carlo methods are used to propagate uncertainties in inputs and model parameters to outputs. This requires expressing inputs and parameters as distributions where possible. As described by Mahashabde et al. (*16*), in order to extract meaningful insights about the possible costs and benefits of a policy, it is helpful if the analysis options are synthesized into a set of pre-defined combinations of inputs and assumptions. These combinations of inputs and model parameters each describe a particular point of view or perspective on analysis. Each of these combinations is designated as a *lens* as it symbolizes a particular viewpoint through which one can assess environmental and economic impacts. There are currently three lenses implemented in the APMT climate module; namely, low impacts, mid impacts and high impacts. Each lens corresponds to the use of different values or distributions for the most influential parameters in the climate module. Parameters captured in the lenses are the projected growth of aviation, climate forcing of each non-CO_2 effect, climate sensitivity and a climate damage coefficient. While APMT would normally allow the background CO_2 concentration to vary between lenses, this work uniformly adopted a constant background CO_2 concentration of 378 ppm to maintain consistency with existing IPCC GWP calculations. Sensitivity analysis using the APMT climate model has shown that using certain SRES background CO_2 concentrations can amplify the relative magnitude of non-CO_2 forcing agents by up to 20% relative to the constant background case; however, this sensitivity is not examined further within this work.

In a manner that parallels the lenses described above, Stratton et al. (*2*) developed a new methodological approach for constructing life cycle GHG inventories of transportation fuels. In it, key parameters were identified through examination of the GHG emissions resulting from each life cycle step. Optimistic, nominal and pessimistic sets of these key parameters were developed and used to formulate corresponding low GHG inventories, baseline or nominal GHG inventories, and high GHG inventories using attributional life cycle analysis (LCA). The low lens, mid lens and high lens of APMT, which were used to assess tank-to-wake combustion emissions, mirror the formulation of the low, baseline and high well-to-tank GHG emissions inventories.

2.4 Combustion of SPK Fuel Compared to Conventional Jet Fuel

The purely paraffinic nature and lack of sulfur in SPK fuels result in increased specific energy, decreased energy density and changes to the emissions characteristics of CO_2, H_2O, soot, sulfates and NO_X (*3, 10-13*). Therefore, independent non-CO_2 ratios are required for conventional jet fuel and SPK fuel. The changes in combustion properties between conventional jet fuel and SPK fuel are summarized in Table 1 and were implemented into the APMT climate impacts module.

Table 1: Emissions characteristics of SPK fuel relative to conventional jet fuel

Fuel Characteristics	**SPK relative to Conventional Jet Fuel**
Specific Energy (per kg_{fuel})	1.023
Energy Density (per L_{fuel})	0.963
CO_2 Emissions (per kg_{fuel})	0.98
H_2O Emissions (per kg_{fuel})	1.11
Sulfate Emissions (per kg_{fuel})	0.0
Soot Emissions (per kg_{fuel})	0.05-0.5
NOx Emissions (per kg_{fuel})	0.9-1.0
Contrails (per kg_{fuel})	1.0
Contrail cirrus (per kg_{fuel})	1.0

A detailed characterization of conventional and synthetic jet fuel by Hileman et al. (*3*) was used to determine changes in specific energy, energy density and CO_2 emissions. Water vapor emissions were modified based on the carbon to hydrogen ratio of Jet A and SPK fuel. Synthetic fuels contain negligible quantities of sulfur so all sulfate emissions were eliminated. Changes in soot and NO_X emissions were represented as probabilistic distributions to compliment the existing lens framework of APMT and reflect reduced certainty. The formation of contrails and contrail cirrus were assumed unchanged by the use of SPK fuel. Further characterization of combustion emissions and effects of SPK fuel relative to conventional jet fuel is available in Appendix A.

2.5 **Climate Metrics**

Global warming potentials (GWP) are commonly used to express the impact of long-lived gases such as CH_4 and N_2O in terms of a carbon dioxide equivalent (*22-24*). The time window over which the radiative forcing is integrated is a value judgment rather than a matter of science, although 100 years is commonly chosen. Other metrics are also available to relate the climate forcing of one substance to another (*23,24*). Clearly stating the chosen metric and time window is essential in all situations. This is particularly important when assessing the climate impacts of non-CO_2 combustion emissions and effects within a greenhouse gas inventory that includes CH_4 and N_2O. For example, the use of 100-year global warming potentials to express the CH_4 and N_2O in terms of CO_2 equivalent requires 100-year integrated radiative forcing to be used to assess the non-CO_2 combustion emissions effects.

The non-CO_2 ratios developed herein are designed to scale the CO_2 emissions from fuel combustion to account for the climate forcing from non-CO_2 combustion emissions and effects. The IPCC provides GWP values for CH_4 and N_2O over time windows of 20 years, 100 years and 500 years (*22*). Maintaining consistency with the treatment of life cycle CH_4 and N_2O limits the assessment of non-CO_2 combustion emissions and effects in this work to integrated-radiative forcing over 20 year, 100 year and 500 year time windows. The non-CO_2 ratio for a given time window, Δt, is given by Equation 3, where each RF is the aggregated radiative forcing from all direct and indirect mechanisms through which that species or effect influences the climate system.

$$\text{non-CO}_2\text{ ratio} = \frac{\int_{t_0}^{t_0+\Delta t}\left[RF_{CO_2}(t)+RF_{NO_x}(t)+RF_{soot}(t)+RF_{sulfates}(t)+RF_{contrails}(t)+RF_{cirrus}(t)+RF_{H_2O}(t)\right]dt}{\int_{t_0}^{t_0+\Delta t}\left[RF_{CO_2}(t)\right]dt} \qquad \text{Equation 3}$$

The challenge in treating non-CO_2 combustion emissions and effects lies in reconciling the wide range of atmospheric lifetimes ranging from centuries for CO_2 to hours for contrails. Long lived gases become well mixed in the atmosphere; however; short lived emissions can remain concentrated near flight routes, mainly in the northern mid-latitudes; hence, these emissions can lead to regional perturbations to radiative forcing (*25*). The impact of aircraft on regional climate could be important, but is currently beyond the capability of the models used in this work; hence, the results from APMT Climate may not be applied to individual flights. Despite these limitations, assessing short-lived effects on a globally averaged basis gives an indication of the total potential of mitigating climate change by including non-CO_2 forcing agents in climate policy (22).

3 Results

3.1 Non-CO_2 Ratios for Conventional and SPK Fuel

The non-CO_2 ratios derived for conventional jet fuel and SPK fuel are given in Figure 2 for time windows of 500 years, 100 years and 20 years. Each time window has ratios derived using the low, mid-range, and high impact lens to capture climate-modeling uncertainties. The bars correspond to results using the mid-range lens while the whiskers show the results using the low and high lens. Shorter time windows emphasize the climate forcing of short-lived effects.

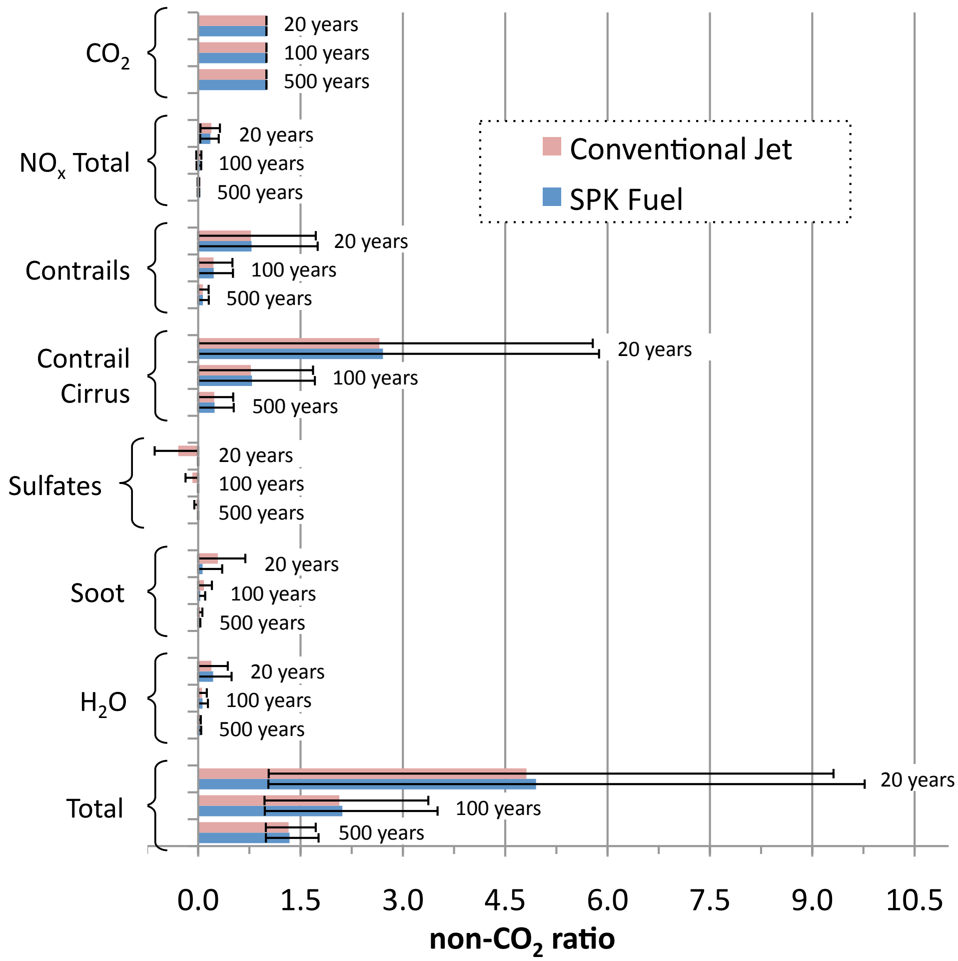

Figure 2: Non-CO_2 ratios disaggregated by species and time window for conventional jet fuel and SPK fuel

The combustion of conventional jet fuel emits 73.2 g CO_2/MJ. In the nominal case, the results from Figure 2 show that accounting for the climate impacts of all combustion products from aircraft is equivalent to emitting 2.07 times the amount of CO_2 actually produced from the combustion process, or 151.3 gCO_2e/MJ instead of 73.2 gCO_2/MJ.

Similarly, the combustion of SPK fuel emits 70.4 g CO_2/MJ. When compared to conventional jet fuel, the elimination of sulfates and the increase in water vapor lead to warming while the reduction in NO_X and soot lead to cooling. Using the low lens under the 100-year and 500-year time windows, the reduction in NO_X instead leads to a small warming effect. In the nominal case, Figure 2 shows that accounting for the climate impacts of the actual combustion products from aircraft consuming SPK fuel is equivalent to emitting 2.11 times the amount of CO_2 actually produced from the combustion process, or 148.8 gCO_2e/MJ instead of 70.4 gCO_2/MJ.

The contribution of contrails and contrail cirrus to the total non-CO_2 ratio is sufficiently large that even a small change of either is more significant than a large change in other species; hence, the total non-CO_2 ratios are most sensitive to error in these two forcing agents. The reader is reminded that the radiative forcing from contrails and contrail cirrus were assumed unchanged per unit mass of fuel burned. As discussed is Appendix A, more detailed models and empirical measurements are needed to determine what, if any, changes may actually occur to contrails and contrail-cirrus with a change in fuel composition.

3.2 Well to wake (+) Emissions Inventories

Using Equation 2, the results from Figure 2 can be combined with a well-to-wake GHG emissions inventory to complete the framework required to include non-CO_2 combustion emissions and effects in a fuel life cycle. The non-CO_2 ratios developed using the low, mid-range and high impact lenses of the APMT climate model were paired with select life cycle GHG inventories developed by Stratton et al. (*2*). These GHG inventories from were created by identifying key parameters through examination of the GHG emissions resulting from each life cycle step. Optimistic, nominal and pessimistic sets of these key parameters formed the basis for corresponding low GHG inventories, baseline or nominal GHG inventories, and high GHG inventories. The select fuel pathways used herein are conventional jet fuel, Fischer-Tropsch jet fuel from switchgrass, Fischer-Tropsch jet fuel from coal without carbon capture, and hydroprocessed jet fuel from rapeseed oil. All results and discussion in this section are limited to a 100-year time window because of its prevailing use in the scientific community for global warming potentials. The sensitivity of results to choice of time window is addressed in Section 3.3.

Life cycle analysis is fundamentally a comparative tool; hence, results are normalized by the life cycle GHG emissions of baseline conventional jet fuel. As noted in Table 1, the specific energy of SPK is 2.3% higher than that of conventional jet fuel. Therefore, the use of SPK leads to a reduced take-off weight and hence a reduced quantity of fuel needed to complete a given mission. Hileman et al. (*3*) quantified this effect on a fleet wide basis, finding that a 0.3% reduction in fleet wide fuel energy use would result from the use of all SPK; therefore, a 0.3% improvement in energy efficiency was applied to SPK fuels when normalizing by conventional jet fuel.

Figure 3 compares the well-to-wake and well-to-wake (+) emissions inventories normalized by the corresponding baseline of conventional jet fuel. The upper half shows only the well-to-wake inventories as presented by Stratton et al (*2*). The lower half shows the well-to-wake (+) version of the same GHG inventories. The solid error bars, which have lines on their ends, correspond to combining the 100-year mid-range non-CO_2 ratios with the well-to-wake low, baseline and high GHG emissions scenarios. The dashed error bars, which have circles on their ends, correspond to pairing the 100-year low impact, mid-range and high impact non-CO_2 ratios with the well-to-wake low, baseline and high GHG emissions scenarios, respectively. Presenting the results in this manner separates the variability introduced by the well-to-tank GHG inventories from the climate modeling uncertainty of the non-CO_2 ratios. The uncertainty of the non-CO_2 ratios has a larger influence than the internal variability of the GHG inventories on the range of normalized well-to-wake (+) emissions for each fuel pathway.

Relative to the normalized well-to-wake GHG inventories shown in the upper half of Figure 3, intra-pathway variability is increased with the inclusion of the non-CO_2 combustion emissions and effects while inter-pathway variability in normalized well-to-wake (+) emissions is reduced. For these select pathways, when only GHG emissions are considered, the range in baseline life cycle GHG emissions is 0.2 to 2.2 times those of baseline conventional jet fuel. When GHG emissions and non-CO_2 combustion emissions and effects are included, the range in baseline well-to-wake (+) emissions is reduced to 0.6 to 1.6 times those of baseline conventional jet fuel. Hence, the inclusion of non-CO_2 combustion emissions and effects in the fuel life cycle increases the absolute emissions range of each fuel pathway but reduces the overall range in the life cycle emissions of alternative fuels relative to conventional jet fuel.

Interest is primarily focused on fuel options with well-to-wake GHG emissions lower than those of conventional jet fuel. Because of the similar magnitude of the non-CO_2 combustion emissions and effects of SPK and conventional jet fuel, the normalized well-to-wake (+) emissions of fuels in this category are higher than their normalized well-to-wake GHG emissions. Hence, a percentage reduction in life cycle GHG emissions of the jet fuel mix is less than the actual percentage reduction in aviation related climate impacts. For example, an SPK fuel option with zero life cycle GHG emissions would offer a 100% reduction in GHG emissions but only a 53% reduction in actual climate impact using a 100-year time window and the mid-range lens. Therefore, aviation GHG reduction scenarios (e.g., emissions wedge charts) that rely exclusively on *relative* changes in GHG emissions may overestimate the benefit of alternative fuel use on the global climate system. Only a percentage reduction in fuel burn is equivalent to the same percentage reduction in aviation related climate forcing. The degree of overestimation is dependent on the assumptions used for the climate impact analysis of non-CO_2 combustion emissions and effects. Conversely, aviation GHG reduction scenarios that rely on *absolute* changes in GHG emissions (e.g. mass of CO_2e/MJ) will yield similar results for the impact of alternative fuel use on the global climate system regardless of whether well-to-wake or well-to-wake (+) emissions are used. The discrepancy between conventional jet fuel and SPK fuels caused by combustion CO_2 emissions and the non-CO_2 ratios is small by comparison to the variability in well-to-tank GHG emissions among the fuel options of Figure 3.

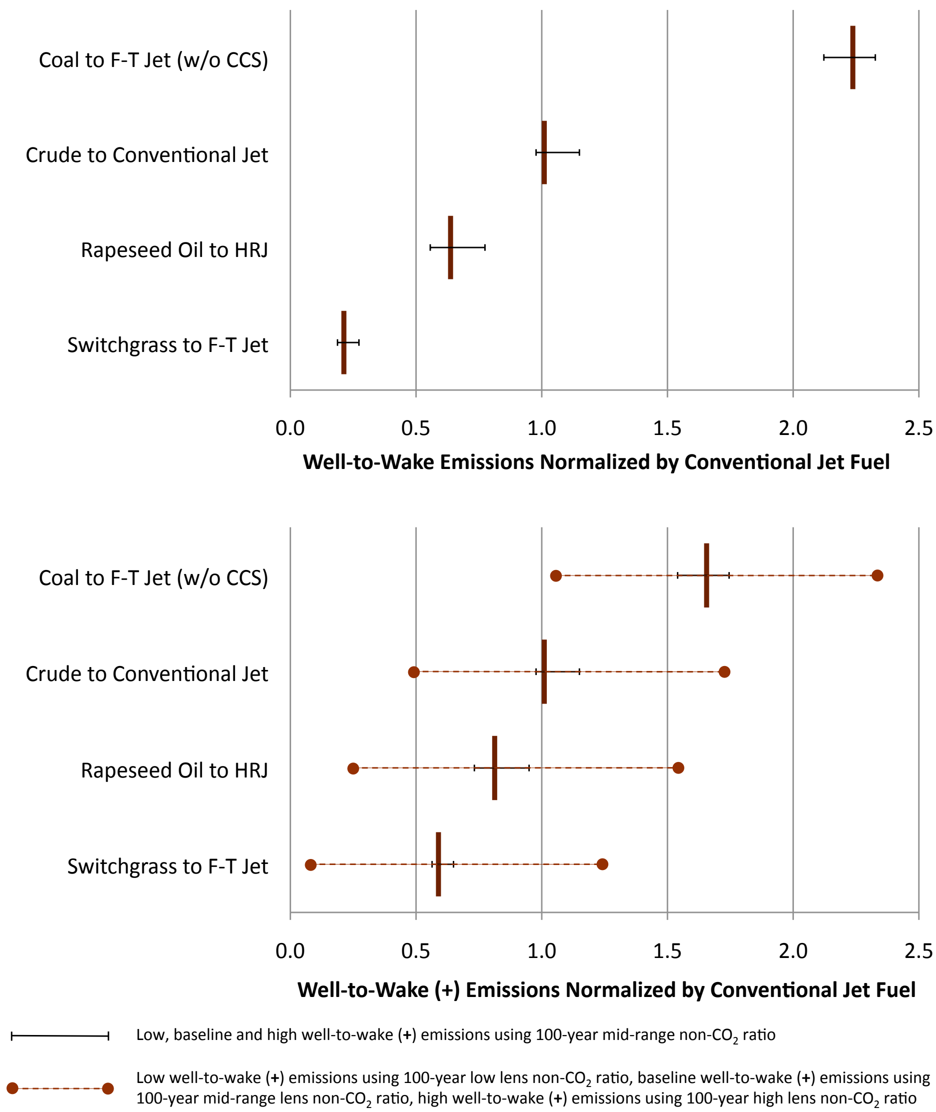

Figure 3: Well-to-wake (+) emissions for select alternative jet fuel pathways, normalized by conventional jet fuel

While the results of this work were developed using the current best available data, climate forcing from contrails and contrail cirrus remains uncertain, especially for SPK fuel; therefore, these results should be used with caution until further research is available on how SPK fuel use changes their impacts.

3.3 Sensitivity of Results to Time Window

The results of Figure 3 were created using a 100-year time window to express all species and effects in terms of carbon dioxide equivalent; however, other time windows (e.g., 500-year and 20-year) could have been chosen for the non-CO_2 ratios and GWP values of CH_4 and N_2O. The sensitivity of the well-to-wake and well-to-wake (+) emissions inventories to the choice of time window can be examined through the use of alternative jet fuel case studies. Specifically, the well-to-wake GHG emissions inventories of baseline conventional jet fuel from US crude oil, baseline conventional jet fuel from Nigerian crude oil and baseline rapeseed oil to HRJ were chosen to span a CO_2 dominated fuel, a CH_4 intensive fuel and a N_2O intensive fuel. Methane and nitrous oxide have atmospheric lifetimes of 12 and 114 years, respectively; therefore, a 20-year time window more heavily weights methane while a 100-year time window more heavily weights nitrous oxide. Additionally, the CO_2 and non-CO_2 combustion emissions and effects of conventional jet fuel were evaluated using the mid-range lens with 500-year, 100-year and 20-year time windows. The sensitivity of each GHG inventory and the combustion emissions and effects to time window selection is shown in Figure 4.

3.3.1 Baseline Conventional Jet Fuel from US Crude Oil

The life cycle GHG inventory of conventional jet fuel from US crude oil is largely composed of CO_2 emissions. Only a small fraction is CH_4 or N_2O; therefore, this inventory is insensitive to the choice of time window chosen to represent CH_4 and N_2O in terms of CO_2. The choice of time window causes only a 1.3gCO_2e/MJ change in the well-to-wake GHG emissions the fuel.

3.3.2 Baseline Conventional Jet Fuel from Nigerian Crude Oil

Substantial methane emissions result from the venting processes used in Nigeria for crude oil extraction. The global warming potential of CH_4 varies by approximately an order of magnitude when evaluated using a 20-year time window or a 500-year time window. This variation is carried through to the life cycle GHG inventories of fuels where CH_4 is an important contributor to the total. Choosing different time windows to assess the life cycle GHG emissions of baseline conventional jet fuel from Nigerian crude oil results in a range of 33.6 gCO_2e/MJ.

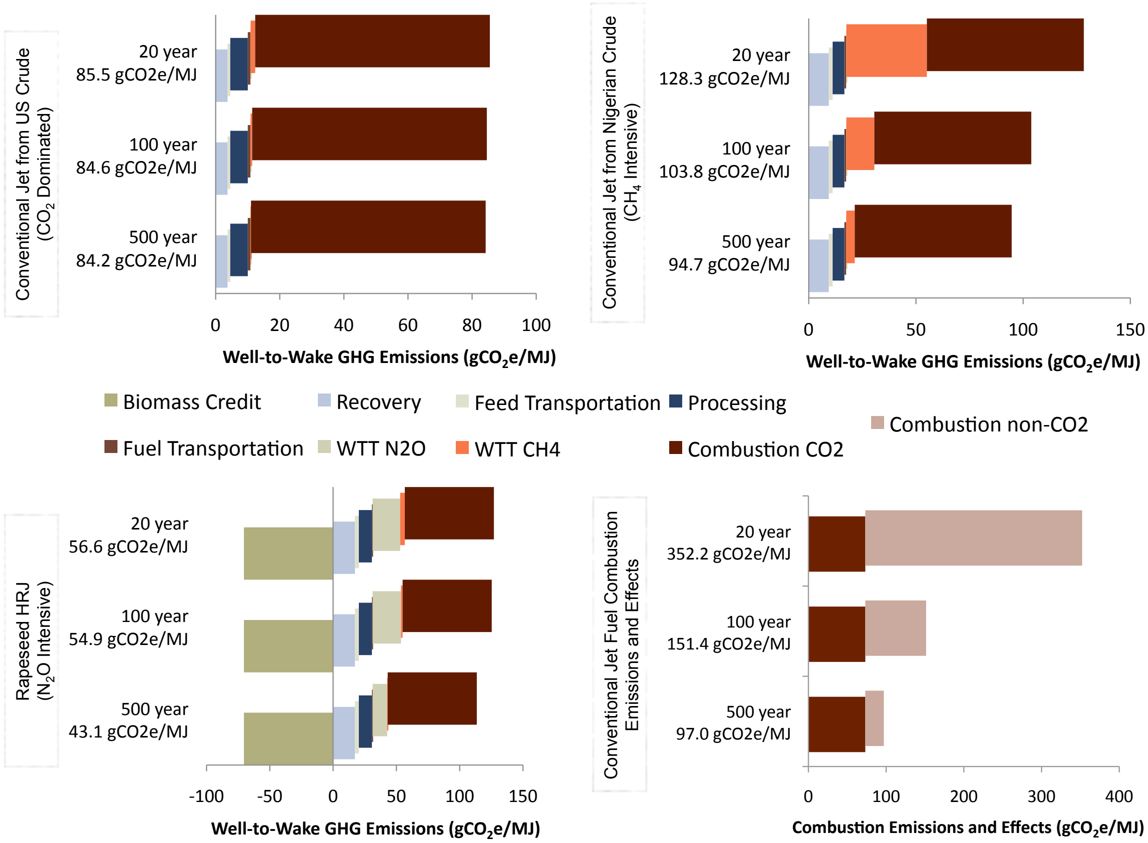

Figure 4: Sensitivity of well-to-wake GHG emissions inventories of baseline conventional jet fuel from US crude oil, baseline conventional jet fuel from Nigerian crude oil, baseline rapeseed oil to HRJ and the combustion emissions and effects of conventional jet fuel to 500-year, 100-year and 20-year time windows using the mid-range lens

3.3.3 Baseline Rapeseed Oil to HRJ Fuel

The life cycle GHG inventory of HRJ form rapeseed oil is strongly influenced by N_2O emissions from direct and indirect conversion of synthetic nitrogen applied to the field and nitrogen rich crop residues. The global warming potential for N_2O is less sensitive to time window than that of CH_4; however, it still varies by approximately a factor of 2 and this variation is carried through to the life cycle GHG inventories of fuels where N_2O is an important contributor. Baseline HRJ from rapeseed oil (assuming no GHG emissions from land use change) is subject to a range of 13.5 gCO_2e/MJ with the use of 500-year and 20-year time windows.

3.3.4 Combustion Emissions and Effects of Conventional Jet Fuel

While both the time horizon and choice of lens are important when assessing the climate impacts of non-CO_2 combustion emissions and effects, the focus of this section is the influence of the time window; therefore, the mid-range lens was used as a representative assumptions set. The combustion emissions and effects from conventional jet fuel vary by 255.2 gCO_2e/MJ, from 97.0 gCO_2e/MJ to 352.2 gCO_2e/MJ, with the use of a 500-year or 20-year time window, respectively. SPK fuels are subject to the same influence because of the similarity in the non-CO_2 ratios of SPK fuel and conventional jet fuel. As a result, all SPK fuels used by aviation are affected by the substantial influence of time window on well-to-wake (+) emissions. The scope is not limited to fuel pathways that are strong in a particular type of emissions and the magnitude is several times larger than that of CH_4 or N_2O. Despite this undesirable variability, the time window used to assess non-CO_2 combustion emissions and effects should be constrained to the same as that used in the global warming potentials of well-to-tank CH_4 and N_2O; hence, the need for consistency serves as a constraint in choosing the appropriate time window.

4 Discussion and Conclusions

This work implemented a modified version to the APMT climate impacts module to develop ratios to scale the CO_2 from fuel combustion to account for the additional climate forcing from the non-CO_2 combustion effects of SPK fuel and conventional jet fuel. The results indicated that including non-CO_2 combustion emissions and effects when comparing the emissions from SPK fuel to those of conventional jet fuel can lead to an important decrease in the relative merit of the SPK fuel. This is because contrails and contrail-cirrus clouds dominate the climate impact of the non-CO_2 effects from conventional fuel and the analysis herein assumed that SPK fuel use would not change the prevalence or impact of these effects. Additional work should be devoted to better understanding how changes in fuel composition affect the formation of contrails and contrail-cirrus clouds as their impact may be reduced with a change in fuel composition.

The decrease in relative merit of SPK fuels means that methods of tracking climate change mitigation that rely exclusively on relative well-to-wake life cycle GHG emissions as a proxy for aviation climate impact may overestimate the benefit of alternative fuel use on the global climate system. Furthermore, the variability introduced into the results by including non-CO_2 combustion emissions and effects highlights the broad challenges faced in collapsing multiple attributes into a single metric for comparison when assessing any new energy technology options. Determining an absolute 'better or worse' requires an evaluation system, which is usually accomplished through a weighting scheme, monetization or time windowing with one or more metrics. Greenhouse gases are a convenient metric of comparison because their cause and environmental effect are both important and readily quantified. Many other factors have less quantifiable impacts. The need for absolute comparisons often requires defining a '*basis of equivalence*' that introduces significant variability into the result.

This work indicates that aviation has an opportunity space extending beyond improving fuel efficiency and burning alternative fuels to reduce its climate impact. Technologies that reduce GHG emissions from fuel production, combustion CO_2 emissions, and non-CO_2 combustion emissions and effects can all be considered simultaneously. Currently, these areas are largely examined in isolation. A holistic analysis framework is needed that examines alternative fuels for reduced well-to-wake GHG emissions, aircraft design and operations for reduced fuel consumption, and changes to operational procedures for reduced contrails and contrail-cirrus impacts; however, enable an equitable comparison of the climate mitigation options for aviation requires accounting for the climate impacts of non-CO_2 combustion emissions and effects.

Acknowledgments

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Appendix A - Characterization of SPK Combustion Emissions and Effects

In maintaining the lens framework, the percentage reductions in soot and NO_X emissions attributed to the use of SPK fuel, as compared to conventional jet fuel, are given by distributions with functional forms and bounds shown in Figure A-1. Results with the low and high lenses reflect deterministic use of the low and high values while the mid-range lens reflects the results of Monte Carlo simulations using random variables drawn from the distributions of Figure A-1.

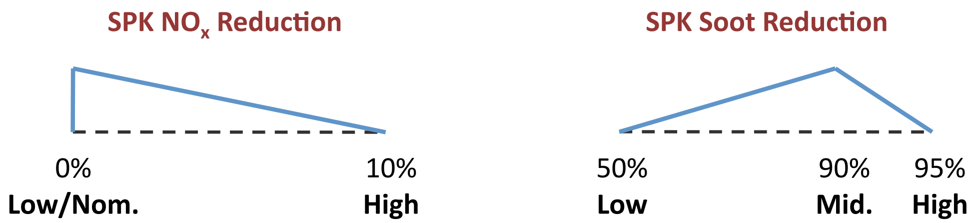

Figure A-1: Input distributions for NOX and soot reductions resulting from the use of SPK fuel

The upper and lower bounds of NO_X reduction were based on experimental results from Bester and Yates (*10*), Bulzan et al. (*11*) and Dewitt et al. (*12*). The functional form of the distribution was chosen to reflect a conservative estimate within the bounds of experimental data. NO_X emissions are strongly dependent on engine throttle setting, specific engine/combustor technology and ambient temperature; hence, it is little surprise that results of the aforementioned research efforts do not conclusively indicate a single value.

The upper and lower bounds of SPK induced soot reduction were based on experimental measurements from PW308 and CFM56 gas turbines. The data were reported by Donohoo (*13*) and are dependent on throttle setting. Soot reductions from SPK use in the PW308 varied from 95% at idle to 50% at 85% of full throttle; similarly, SPK fuel in the CFM56 led to a 98% reduction in soot at idle and a 70% reduction at 85% of full throttle. The mode of the distribution is consistent with measurements from Bester and Yates (*10*) and Bulzan et al. (*11*), who measured average reductions of 85% and 90% in soot emissions over the throttle range of a CFM-56-2C1 engine using coal based F-T jet fuel from Sasol and natural gas based F-T jet fuel from Shell, respectively.

SPK fuel was assumed to cause no change to the radiative forcing from aircraft contrails and contrail cirrus per unit of fuel mass relative to conventional jet fuel because no data has provided quantifiable evidence otherwise. Qualitatively, the magnitude of the atmospheric impact from contrails and contrail cirrus depends on details of plume evolution and the relative ability of aerosol particles to act as ice-forming nuclei (*6*). The presence of ice-forming nuclei may trigger the formation of contrail cirrus much later than the original emission if the background atmosphere has changed to a state allowing for cloud formation (*20*). Hence, the complete elimination of sulfate aerosols and the significant reduction of soot emissions caused by SPK fuel might serve to reduce contrail and contrail cirrus formation. Conversely, the increase in water vapor from SPK fuel may serve to stimulate additional contrails and contrail cirrus if their formation is more strongly dependent on background atmospheric aerosol concentrations rather than local concentrations in the exhaust jet. Wuebbles et al. (*6*) emphasize that improving the understanding of contrails and contrail cirrus formation requires coordinated regional-scale measurements to correlate the growth, decay, and trajectories of contrail ice particles with the ambient aerosols and gaseous aerosol precursor concentrations.

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