



GROUP ON INTERNATIONAL AVIATION AND CLIMATE CHANGE (GIACC) THIRD MEETING

Montréal, 17 to 19 February 2009

Agenda Item 2: Review of aviation emissions related activities within ICAO and internationally

Opportunities for Mitigating Climate Impacts

(Presented by the U.S. Member)

SUMMARY

Alternative jet fuels produced from renewable sources may have reduced life-cycle greenhouse gas emissions (GHG) relative to jet fuel. As such, alternative fuels could play a central role in mitigating aviation's contribution to climate change. Although there are several challenges, including identifying appropriate feedstocks and processes, ensuring adequate performance, scaling production and assuring sufficient supply, and establishing life cycle impacts, substantial progress has been recently realized. This paper summarizes the findings of an analysis undertaken by the United States to contribute to the GIACC's considerations.

1. INTRODUCTION

1.1 Alternative jet fuel that is produced and created from renewable sources may have reduced life-cycle greenhouse gas emissions relative to jet fuel. Researchers sponsored by the U.S. undertook a well-to-wake, life-cycle analysis of some potential feedstocks for aviation alternative fuels. The analysis included all of the GHG emission that result from the creation of the alternative fuel—recovery, processing, and transport—as well as those resulting from its combustion. (A copy of the analysis is attached as Appendix A.)

1.2 The fuel options reviewed are considered “drop-in”. They have the potential to serve as a direct replacement for conventional jet fuel, requiring little or no modification to existing infrastructure or aircraft engines.

1.3 However, these fuels have varied life-cycle GHG emissions. The fundamental reason that biofuels present the opportunity for lower GHG emissions is that feedstocks absorb CO₂ for growth during photosynthesis in relatively short time scales. The growth of feedstocks offsets some, if not all, of combustion CO₂ emissions, resulting in reduced life-cycle GHG emissions.

1.4 Direct and indirect land-use changes are important aspects that must be evaluated when considering biofuels. Such changes include deforestation, conversion of grasslands to agricultural production, or diversion of agricultural production to fuel production. These may result in considerable GHG emissions, offsetting the gains from CO₂ absorption.

1.5 For a more detailed discussion of the issues please refer to Appendix A.

2. **FEEDSTOCKS AND FUELS CONSIDERED**

2.1 The analysis considered coal and biomass to liquid fuels (CBTL) and biomass to liquid fuels (BTL) via the Fischer-Tropsch process and hydroprocessed renewable jet (HRJ) fuels.

2.2 Feedstocks considered included corn stover (BTL and CBTL) and jatropha, soybeans, palm oil, and algae.

2.3 Fossil-to-jet fuel options (e.g., coal) have production potential but higher emissions than conventional jet fuel. With sequestration, GHG emissions could be comparable to jet fuel, but sequestration technology is not fully mature. Their use may therefore not reduce GHG emissions. BTL fuels have low GHG emissions but limited fuel production potential at this point. Blends of CBTL and BTL have both production and GHG emissions reduction potential.

2.4 Regarding HRJ fuels, excess palm and soy feedstocks (available after food needs are met) would lead to low GHG-emissions fuels, but there is little excess supply currently available. As such, large-scale soy oil and palm oil to HRJ production would have large GHG emissions resulting from the land-use changes of expanding production.

2.5 The algal HRJ, CBTL, and jatropha oil HRJ options all hold promise for reducing aviation's GHG emissions. Other options may be available as this field is rapidly developing, and the U.S. will continue to examine evolving options and provide results to the international community.

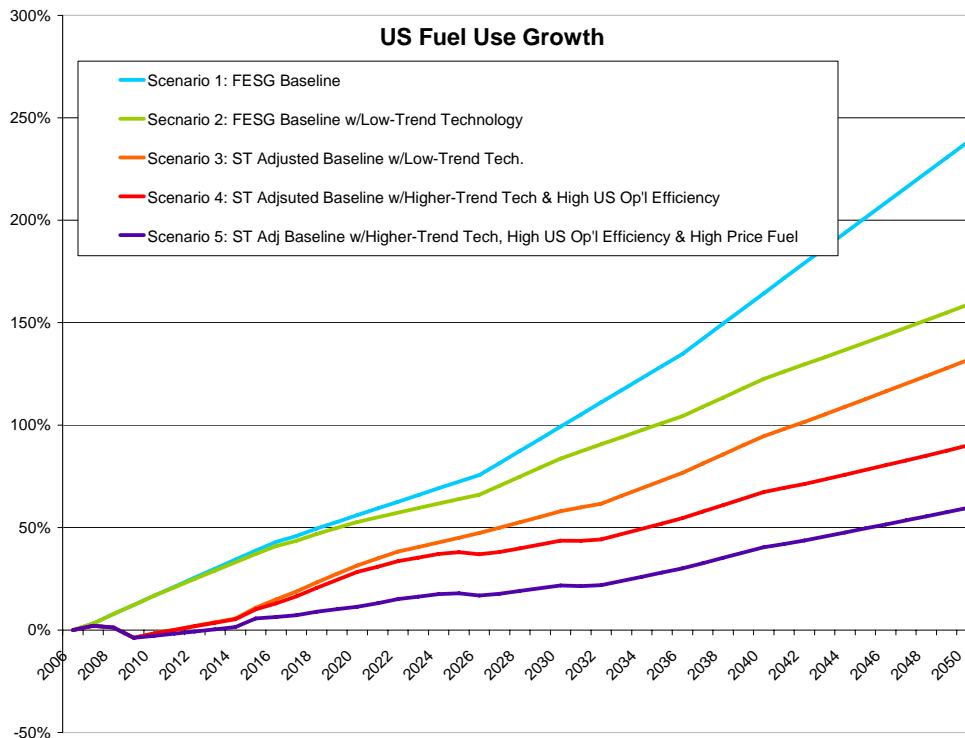
3. **CARBON-NEUTRAL GROWTH THROUGH BIOFUELS**

3.1 The analysis also sought to understand better fuel usage and the amount of land that would be required for carbon-neutral aviation growth in the U.S. market. To begin that analysis, a number of potential consumption scenarios for standard jetfuel use by U.S. commercial aviation from 2006 to 2050 were considered, as shown in Figure 1.¹ Using Scenarios 1, 3, and 5, our analysis sought to understand how much alternative fuel would be needed to bring aviation to carbon-neutral growth at the baseline years of 1990 and 2000.²

3.2 Table 1 indicates the average percentage of total life-cycle CO₂ emissions required from alternative fuel to achieve carbon-neutral growth in the U.S. through 2050 for two baseline years and three different fuel scenarios.

¹ The scenarios used here were developed in an analysis that is undergoing final review.

² We are also working on an analysis that would expand the assessment to world-wide commercial aviation.

Figure 1**Table 1**

| Baseline Year | Scenario | | |
|---------------|------------------------------|---|---|
| | Scenario 1: FESG Baseline | Scenario 3: Short-term Adjusted, Low-Trend Technology | Scenario 5: ST Adjusted Base-line, High-Trend Tech., High Operational Efficiency, High Fuel Price |
| 1990 | 71% | 57% | 38.% |
| 2000 | 70% | 56% | 36% |

3.3 For example, with the baseline year of 2000, the life-cycle CO₂ emissions level for the short-term adjusted, low-trend technology scenario would represent about 56 percent of total emissions in order to maintain carbon-neutral growth through 2050.

4. LAND-USE REQUIREMENTS FOR CARBON-NEUTRAL GROWTH

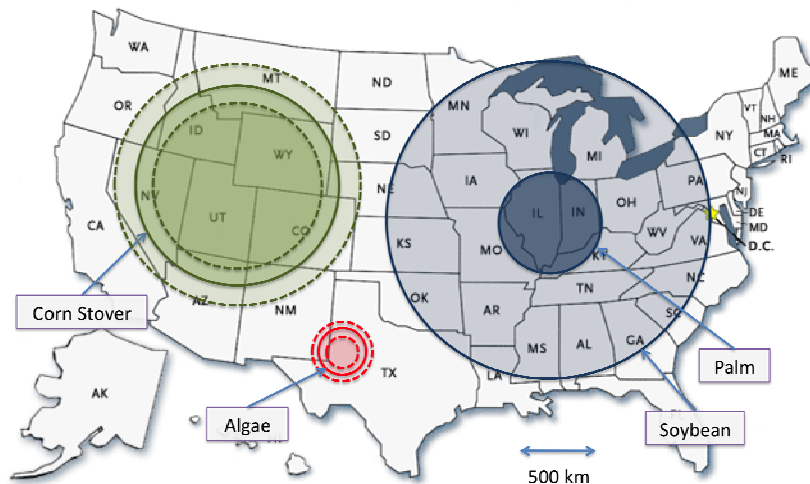
4.1 Taking the fuel-usage requirements for carbon neutrality and calculations of fuel yield per hectare for the various feedstocks evaluated, the analysis led to conclusions regarding the land area needed to sustain feedstocks for carbon-neutral aviation growth in the U.S. Figure 2 shows these landmass needs relative to the U.S.

4.2 The three, smallest red-shaded circles correspond to algae HRJ under the three fuel-use scenarios. The mid-sized green circles represent corn stover CBTL requirements. The largest blue circles represent soybean and palm oil. The soybean circle corresponds to the area needed to replace jet fuel. The soybean area corresponds to the landmass needed to achieve carbon neutrality.

4.3 Placement of the circles in no way indicates a preference or need for a specific region or climate.

Figure 2

Alternative Fuel Land Requirements Compared to the United States in 2050



5. CONCLUSION

5.1 Given their reduced life-cycle GHG emissions relative to conventional jet fuel, some alternative fuels could play a central role in mitigating aviation's contribution to climate change, including helping aviation to achieve carbon-neutral growth, particularly when combined with improved technology and more efficient operations. If appropriate renewable feedstocks are used, both Fischer-Tropsch (F-T) fuels and Hydroprocessed Renewable Jet (HRJ) fuel could provide aviation with modest (approximately 10%) to large (greater than 50%) reductions in emissions that contribute to global climate change.

5.2 A key factor in evaluating the benefits of feedstocks for alternative fuels includes the GHG emissions impacts of land used to produce them. Any feedstocks will need to be grown in a sustainable manner that does not compete with food production or have adverse land use impacts or result in the depletion of our fresh water resources. Since the growing conditions vary from feedstock to feedstock, there is a need for a balanced solution that uses multiple feedstocks. This is widely recognized and development programs are considering a wide variety of alternatives.

5.3 The most significant challenge is not in developing viable alternative fuels that could reduce aviation's GHG emissions -- the technology exists; rather, the challenge lies in development and commercialization of next generation feedstocks such as algae, jatropha, and halophytes. Although the economics of production need to be proven, these feedstocks may be able to produce sufficient jet fuel to achieve carbon neutral aviation growth through 2025 for U.S. aviation on a landmass comparable to 3% of U.S. cropland.

5.4 The U.S. is encouraged by the rapid progress being made in moving toward development and production of sustainable alternative aviation fuels. As is evident in the efforts of the Commercial Aviation Alternative Fuel Initiative (CAAFI) and work sponsored to date through various organizations, there is substantial progress being made. Plans are on track to certify a generic synthetic FT fuel blend as early as June 2009, and to follow this with certification of a HRJ fuel blend in 2010. Four highly visible

and successful renewable fuel flight tests were conducted in 2008. CAAFI sponsor ATA is advancing the concept of possible airline alternative fuel buying consortiums. Fuel producers, airlines and airports in the U.S. are discussing business synergies for deployment of alternative jet fuel production facilities. Significant U.S. Government funding for renewable fuel R&D and production facilities is being targeted by renewable jet fuel developers and their partners. CAAFI and other aviation efforts have made aviation visible as a viable renewable fuel customer.

5.5 There remain substantial challenges in research and development, commercialization, environmental assessment, or fuel qualification. We are continuing work in all these areas to help define a viable path forward in how such fuels may aid aviation in tackling the challenge of climate change. As this analysis shows, we are encouraged that renewable alternative jet fuels will have a significant role to play in addressing aviation's climate change impacts.

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Appendix A: Carbon Neutral Aviation Growth through Alternative Fuels

Life-cycle Analysis of Greenhouse Gas (GHG) Emissions – an Overview

The life-cycle analysis of alternative jet fuels encompasses emissions from the complete fuel cycle. This includes recovery and transportation of the feedstock from the well, field, or mine 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 steps of such a well-to-wake life-cycle analysis are shown schematically in Figure B.1. For each step of the life-cycle, emissions of GHG are assessed and reported on the basis of per-unit energy consumed by the aircraft. The GHG covered in this analysis are carbon dioxide, methane and nitrous oxide using their 100-year global warming potentials (IPCC, 2007). This analysis did not cover non-CO₂ or non-CO₂ equivalent combustion emissions from aircraft - for example NO_x, SO_x, soot, and water - that directly or indirectly impact global climate change. This study also did not consider energy or GHG emissions associated with the initial creation of infrastructure such as extraction equipment, transportation vehicles, farming machinery, processing facilities, etc. The impact of such emissions on the total life-cycle GHG emissions of the pathway is usually relatively small, and within the uncertainty range of the analysis. (Hill et al., 2006, EUCAR, 2007)

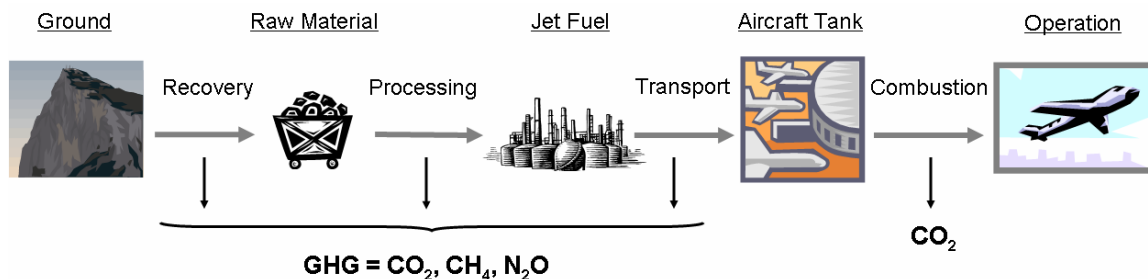


Figure B.1: Steps involved in the well-to-wake life-cycle analysis of alternative jet fuels created from fossil feedstocks.

Fossil feedstocks such as crude oil, coal or natural gas are created from geologically sequestered carbon sources, and the carbon is released as CO₂ when the fuel products are burnt. Such combustion CO₂ has to be taken into account in the life-cycle analysis (see Figure B.1). Biomass feedstocks absorb CO₂ from the atmosphere when they grow and the CO₂ emitted during fuel combustion is equal to that absorbed during biomass cultivation. Hence, biofuel combustion CO₂ is zero in the life-cycle analysis (see Figure B.2).

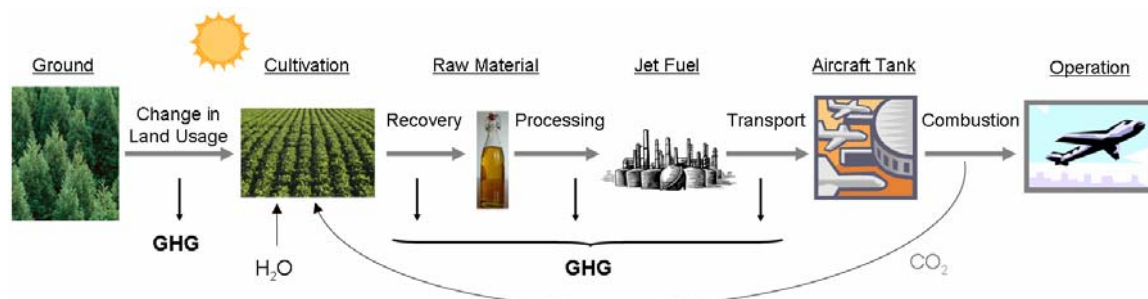


Figure B.2: Steps involved in the well-to-wake life-cycle analysis of bio-based alternative jet fuels.

Biomass feedstocks also have the potential for CO₂ emissions or CO₂ sequestration from changes in land use (see first step of Figure B.2). The CO₂ emissions or sequestration are due to changes in the biomass, soil and organic waste that are contained on and within the land. In some instances, these emissions can dominate the life-cycle GHG emissions of the biofuel pathway. The land use change can be a direct land conversion, (e.g., tropical rainforest being cleared for cropland to grow feedstocks), or it can be an indirect conversion resulting from land used for renewable oils or other food crops being diverted to fuel production. This would result in other land being converted to fill the void of renewable oils or food crops that are no longer being produced. In either case, it is assumed that a fixed quantity of biomass, (e.g.,

vegetable oil) needs to be supplied to global food markets and that additional production (for biofuel creation) is met by land that has been converted from some previous use. The magnitude of land use change emissions depends primarily on the type of land being converted to cropland and the type of crops being grown. For fossil feedstocks, where conversion of land (e.g. forest land, grass land) for extraction of fossil resources (e.g. extraction of bitumen) or siting of fuel processing facilities (e.g. oil refineries) takes place, land use change emissions per unit area are negligible compared to other components of the fuel pathway. This is because a large throughput of fuel volume or mass (as well as energy) is created per unit area of converted land.

For biofuels from algae, sufficient growth rates cannot be achieved without directly feeding CO_2 during growth. This is because the atmospheric concentration of CO_2 is too dilute to support an economically viable growth rate (Putt, 2007). The CO_2 that is used to feed the biomass must be abundant and come from an outside source. In this study, a fossil based electricity generation plant was chosen to meet these needs. One can imagine a coupled system, ideally but not necessarily geographically close to one another, where a fossil fuel is the primary input and both electricity and algal biofuel are primary outputs. This concept is shown schematically in Figure B.3 where the system boundary for a conventional biofuel pathway has been expanded to include an outside source of CO_2 . In addition, land use changes do not need to be incurred with algae because the necessary infrastructure can be created in wasteland and desert areas. Algae also have the capability to grow in high salinity levels, meaning that fresh water is not a necessity.

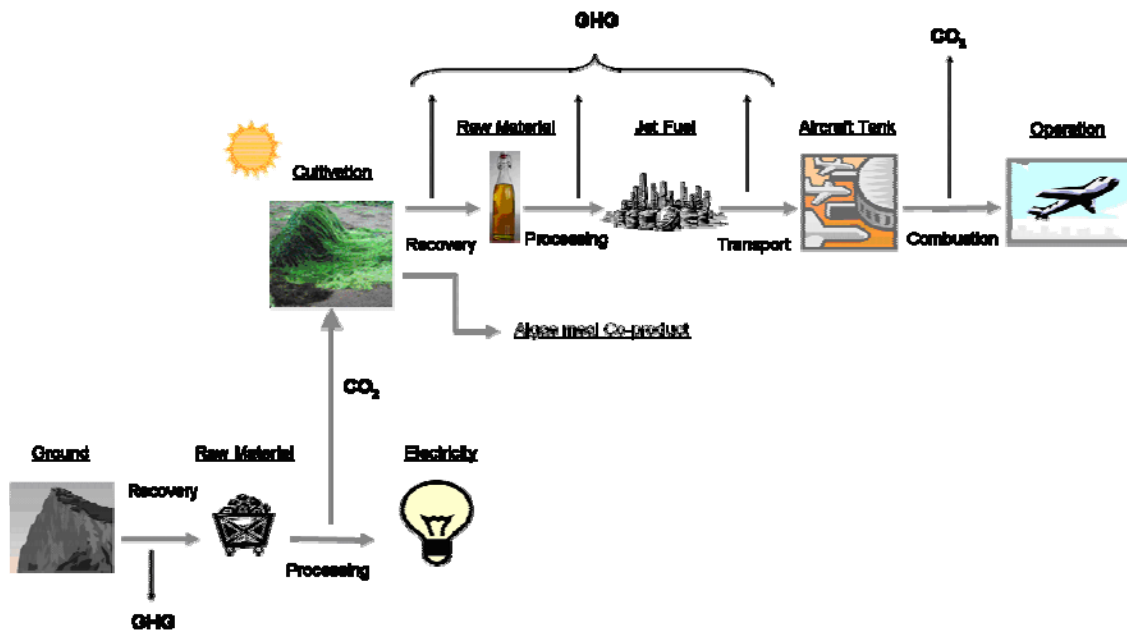


Figure B.3: Steps involved in the well-to-wake life-cycle analysis of hydroprocessed renewable jet fuel from algae.

Fuel production generally results in the creation of co-products in addition to the desired fuel. These co-products have a value that can be quantified based on their mass, energy content, or their ability to displace some other product that is being produced. Four methods have been used to allocate life-cycle emissions between the primary fuel product and any co-products that are created:

- Mass allocation
- Energy allocation
- Market-value allocation
- Displacement (or substitution, or system extension)

The mass and energy allocation approaches distribute the life-cycle emissions based on either the mass or energy content, respectively, of the co-products and the fuel. In this work, the energy allocation method was used to allocate energy and emissions between co-products of the Fischer-Tropsch process as well as those in the hydroprocessing of renewable oils to make Hydroprocessed Renewable Jet (HRJ); this is because these co-products have uses as energy sources.

The market allocation approach distributes the life-cycle emissions based on the market prices of the co-products and the fuel. Unlike the mass or energy allocation approaches, the market value allocation can change with time. The sensitivity to market forces could be particularly useful for co-products that could flood existing markets and drive the co-product price to zero. For example, if a fuel has a co-product that displaces some existing product, then the market value method will capture the diminished utility of creating additional co-product by allocating more of the emissions to the fuel being produced. This is because increasing alternative fuel production will not change the price of the alternative fuel as this is set by the price of conventional fuel net subsidies and taxes. Co-product creation does, however, have the capability to alter the price of similar commodities. In this work, the market allocation method was used to allocate emissions between the co-products in the extraction of oil from soybeans and palm for the HRJ pathways.

The displacement method assumes that the production of the incidental co-product displaces the production of a substitute product. As a result, an emissions credit from the non-production of this displaced product is given. Although this methodology is desirable because it is time-invariant and it could in theory be applied to any co-product, it is hard to implement. This is because of difficulties in identifying a suitable product to be displaced, calculating the life-cycle GHG emissions of that displaced product and determining the displacement ratio. (Huo et al., 2008) In the case of biofuels, the issue of how to appropriately allocate land use change emissions further complicates the application of the displacement method. The life-cycle analysis of algae in this work uses the displacement method to deal with the generation of electricity to sustain adequate growth rates.

The use of different approaches can lead to substantially different results, particularly in regards to biofuel pathways where significant quantities of co-products are being produced. The appropriate method may depend to a large extent on the type of question one seeks to answer in the analysis. Regardless of which method is applied by the LCA practitioner, it is important that those conducting LCA emission analyses clearly state the allocation approach adopted.

Analysis Procedure

The life-cycle GHG analysis was carried out based on available information in the scholarly and technical literature. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (version 1.8a) and its supporting data, both developed and maintained by Argonne National Laboratory, was the primary tool used in the well-to-wake life-cycle GHG analysis. A simulation year of 2015 was used and default GREET assumptions were used in the analysis of the pathways, except where specifically described below. For example, for all pathways, the average efficiencies of coal-fired power plants (utility boiler) and coal Integrated Gasification Combined Cycle (IGCC) plants were assumed to be 36 percent (Lower Heating Value) and 41.5 percent (Lower Heating Value), respectively¹ (Deutch and Moniz, 2007).

A key limitation of the GREET framework is that it is designed for land transportation fuels and vehicle systems and does not include jet fuel production pathways. Also, not all pathways analyzed in this work are available in GREET (e.g. jet fuel from oil shale). Hence, this work utilized data from the literature on jet fuel and jet fuel alternatives where available (e.g. fuel properties, refining efficiency) and incorporated them into the GREET framework in order to derive life-cycle GHG emissions. Where data specific to

¹ From Deutch and Moniz, 2007, the US coal fleet average generating efficiency is about 33% (HHV) and the generating efficiency for coal IGCC plants is 38.4% (HHV). Since the difference between HHV and LHV range from 2 to 4%, a 3% difference is assumed in this report. Hence, the efficiency of an average coal-fired power plant is assumed to be (33+3) 36% and the efficiency of a coal IGCC plants is assumed to be (38.4+3) 41.5%.

alternative jet fuels were not available, diesel fuel was used as a surrogate for jet fuel due to similarities in chemical composition².

In this work, the GREET framework was primarily used as a database and calculation platform where the quality of output energy and emission numbers obtained depended on the quality of input assumptions such as energy efficiencies, fuel properties, type and share of process fuels, and emission allocation method for co-products. Hence, a de novo approach was taken in identifying and reviewing key inputs and assumptions for each pathway. Specifically, default GREET input assumptions were examined for the fuel pathways available in GREET. Key parameters with a significant impact on the life-cycle GHG emissions of the pathway were identified. Default GREET values for these key parameters were updated wherever necessary through reviews of recent information available in the literature. Where a specific pathway was not available in GREET, the pathway was built from scratch within the GREET framework with all relevant input parameters gathered from the open literature.

To explore the impact of uncertainties in key parameters, three different scenarios – low GHG emissions, baseline or nominal GHG emissions, and high GHG emissions – were envisaged for each pathway. Key parameters were identified through examination of the GHG emissions that resulted from each of the individual steps of the life-cycle (see Figures B.1 through B.3). The engineering judgment of the authors was used to identify parameters that had both uncertainty as well as a considerable influence on the life-cycle GHG emissions. Input parameters such as process efficiency and biomass feedstock yield have both of these qualities in that they exert considerable influence on the life-cycle GHG emissions of the fuel pathway and their value a decade into the future is relatively uncertain; hence, these parameters were varied as part of the three scenarios. Input parameters that had a large impact on the life-cycle emissions but were well known and are not going to change in the future (such as the mass of CO₂ emitted per unit of fuel consumed by the jet engine) and parameters that may have relative uncertainty or variation but that will have a relatively small influence on the life-cycle emissions (such as the distance the feedstock needs to travel from the source to the refinery) were in general not examined.

By using the key parameters that define the low, baseline, and high emissions scenarios, a range of GHG emissions, rather than a single value, was derived for each fuel pathway. Appropriate values for the key parameters were determined through literature review and consultation with relevant experts. In general, industry average values, rather than marginal values, were sought. If a marginal value for a key parameter was found that fell outside of typical values and if the marginal value indicates a potential industry trend, then the value was examined as a case study for comparison to the low, baseline, and high emissions scenarios. Variation of the key parameter values across the three scenarios could arise from differences in time-frame (e.g. historical data versus future projections), different feedstocks (e.g. bituminous coal versus sub-bituminous coal), different technologies or changes in process designs. While the upper and lower bounds of values found in the literature were generally used in the low and high emissions cases, baseline values were usually those which were deemed most likely, most frequently occurring, or were the average or mid-point of the range of values reported in the literature.

Alternative Jet Fuel Pathways

The fuels analyzed in this work were jet fuel from conventional crude oil, jet fuel from Canadian oil sands, jet fuel from oil shale, Fischer-Tropsch jet fuel from natural gas, coal and biomass, and biojet from soy oil, palm oil and algal oil. For each pathway, three potential scenarios (low emissions case, baseline case and high emissions case) were identified and life-cycle GHG emissions were calculated for each of these scenarios. The fuel pathways are summarized in Table B.1.

² Diesel fuel and jet fuel belong to the same class of petroleum products, namely middle distillates, with “similar properties but different specifications as appropriate for their intended use” (Speight, 2002, p. 177).

Table B.1 Fuel Pathways Investigated

| Source | Feedstock | Recovery | Processing | Final product |
|---------------------|---|--|---|---|
| Petroleum | Conventional crude ³ | Crude extraction | Crude refining | Jet Fuel |
| | Canadian oil sands | Bitumen mining/ extraction and upgrading | Syncrude refining | Jet Fuel |
| | Oil shale | In-situ conversion | Shale oil refining | Jet Fuel |
| Natural gas | Natural gas | Natural gas extraction and processing | Gasification, F-T reaction and upgrading | F-T Jet Fuel (GTL) |
| Coal | Coal | Coal mining | Gasification, F-T reaction and upgrading (with and without carbon capture) | F-T Jet Fuel (CTL) |
| Coal and Biomass | Coal and Biomass | Coal mining and biomass cultivation | Gasification, F-T reaction and upgrading (with carbon capture) | F-T Jet Fuel (CBTL) |
| Biomass | Biomass | Biomass cultivation | Gasification, F-T reaction and upgrading | F-T Jet Fuel (BTL) |
| | Renewable oil (soy oil) | Cultivation and extraction of soy oils | Hydroprocessing | HRJ Fuel (Hydroprocessed Renewable Jet) |
| | Renewable oil (palm oil from South-east Asia) | Cultivation and extraction of palm oils | Hydroprocessing | HRJ Fuel |
| | Algae Oil | Cultivation and extraction of algae oils | Hydroprocessing | HRJ Fuel |

Alterations in Wong (2008) Pathways

The analysis for all of the pathways summarized in Table B.1, with the exception of the co-gasification of coal and biomass and algae, are based on Wong (2008) and much documentation can be found therein. The variations from the work of Wong (2008) are presented below. Details on the CBTL and algae HRJ pathways are presented in a subsequent section.

Conventional Jet Fuel Pathways

The conventional jet fuel pathway has been modified to reflect values from the recently released National Energy and Technology Laboratory (NETL) study on the life-cycle GHG emissions for conventional jet fuel (NETL, 2008). Because the depth and detail of their analysis was superior to that of Wong (2008), their well-to-tank emissions have been adopted for the baseline in this analysis. The tank-to-wake emissions from NETL (2008) were not used as they include methane emissions. The original value obtained by Wong (2008) was 85gCO₂/MJ_{Jet Fuel} and the refined value from NETL is 87.5gCO₂/MJ_{Jet Fuel}.

Two values for the life-cycle emissions of jet fuel from Canadian oil sands were given in Wong (2008). These values corresponded to surface mining and in-situ processes. To ease comparison with other fuel pathways, these individual values have been combined into a single value where 56.3% of the fuel comes

³ This was based on the 2005 mix of crude input to U.S. refineries assumed in the recent NETL study (NETL, 2008), and it included conventional crude oil, syncrude from oil sands and blended bitumen from Canada.

from surface mining processes and 43.5% comes from in-situ processes (AEUB, 2007). The low emissions case is set as the average emissions from surface mining while the high emissions case corresponds to the average for in-situ recovery. These bounding values do not correspond to a future scenario; instead, they provide approximate ranges of the emissions that are currently typical of oil sand recovery and conversion to jet fuel.

Land Use Change Emissions from Palm Oil and Soy Oil to HRJ

Land use changes can have a substantial effect on the life-cycle emissions of a biofuel, even when amortized over an extended time period. To allow for easier examination of this aspect of biofuel production, the analysis of the palm and soy oil pathways were each expanded from individual pathways that have different land use change scenarios for each of the low, baseline and high emissions cases to four unique pathways that represent various land use change scenarios. These pathways are summarized in Table B.2. The low, baseline and high emissions cases for each of these pathways are based on historical and projected variations in crop yield. For all of the pathways, the land use change emissions were amortized over a 30-year period, based on the engineering judgment of the author. The amortization is linear over the chosen time frame. A selection of a 20-year amortization period would result in 150% of the land use change emissions from a 30-year amortization while a 100-year amortization period would result in 30% of the land use change emissions from the 30-year amortization.

Table B.2 Land use change scenarios explored for HRJ pathways

| Soy oil to HRJ pathway scenarios | | Palm oil to HRJ pathway scenarios | |
|----------------------------------|---|-----------------------------------|---|
| LUC-S0 | No land use change | LUC-P0 | No land use change |
| LUC-S1 | Grassland conversion to soybean field | LUC-P1 | Logged over forest conversion to palm plantation field |
| LUC-S2 | World wide conversion of non-cropland | LUC-P2 | Tropical rainforest conversion to palm plantation field |
| LUC-S3 | Tropical rainforest conversion to soybean field | LUC-P3 | Peatland rainforest conversion to palm plantation field |

Fischer-Tropsch Fuel Pathways

The analysis of Wong (2008) used F-T plant efficiencies of 40%, 50%, and 60% for the low emissions, baseline, and high emissions scenarios of the CTL pathway. The lower value typifies older technologies that would not be used today while the upper value reflects the efficiency if the F-T plant is making considerable quantities of electricity. This range of values was narrowed to 47%, 50%, and 53% to reflect the expected efficiencies for modern F-T plants that would be designed to maximize liquid fuel production.

For the BTL pathway, Wong (2008) considered a range of feedstock options. For this analysis, a focus was placed on corn stover. This is because an industry already exists to provide the large quantities required for commercial scale production.

Life-Cycle GHG Emissions Analysis of Fischer-Tropsch Jet Fuel from Coal and Biomass

While both CTL and BTL hold promise as alternative jet fuels, they also have considerable flaws. Even with 85% carbon capture, a pure CTL plant has life-cycle GHG emissions that are 110% of conventional jet fuel (i.e., the life-cycle GHG emissions are 10% higher than conventional jet fuel). Without carbon capture, CTL has 220% of the emissions of conventional jet fuel. If the goal is to reduce emissions, then coal on its own is not an option. Biomass-to-liquids plants without carbon capture have life-cycle GHG emissions that are less than 10% of conventional jet fuel; however, there are considerable logistical challenges in obtaining sufficient quantities of biomass to operate at large scales because of the relatively low energy density of biomass. Because F-T plants are capital intensive, it is not economically feasible to build many small plants that are disbursed among the regions where biomass is being grown. Biomass must therefore be transported long distances to a large central plant, and the infrastructure to move the biomass becomes a limiting factor. Emissions from the transportation of the biomass to the processing facility are included in the life-cycle analysis but represent a fraction of the total that could be neglected. Since both biomass and coal are processed into an F-T fuel using similar technology, they could be

processed at a single F-T plant. The biomass offsets the high emissions from coal and coal offsets the low energy density and production limitations of biomass. In this work, a coal and biomass to liquid (CBTL) plant with carbon capture and storage (CCS) is considered since the primary goal is to reduce GHG emissions.

In order to be converted into an F-T fuel, the solid feed (either coal or biomass) must be first gasified into a synthesis gas (normally called syngas and composed mainly of H_2 and CO) and then converted with a catalyst to liquid fuel. The coal and biomass can either be gasified in the same unit (co-gasification), or in parallel with the syngases mixing together afterwards. This work examined only co-gasification as the parallel configuration is a superposition of CTL and BTL individually, which have each already been analyzed. Parallel processing also requires additional infrastructure, as separate gasifiers are needed for each feedstock.

Before entering the gasifier, biomass must be milled down to particles having a diameter of 1mm or less. Currently, the most energy efficient method of milling the biomass is via torrefaction. Torrefaction is a mild thermal treatment yielding a solid uniform product with lower moisture content and higher energy content. Efficiencies for this process range from 85% to 97%, with 90% being the most common.

There are no currently existing F-T plants that co-gasify coal and biomass; therefore, process efficiencies were estimated from existing CTL plant data. Because of the pre-processing of biomass, the overall F-T plant efficiency depends on the weight percent of biomass that is being co-gasified. This study explored a range from 0% to 50% biomass feed with 40%, 25% and 10% chosen for the low, baseline and high emissions cases, respectively. The pure CTL efficiencies were modified to account for the extra power consumption of pre-processing the biomass. In addition, it is assumed that the plant is designed to produce just enough electricity to sustain itself, but none to export to the grid. Higher efficiencies would be possible if additional electricity were generated for grid export. With the implementation of CCS, there is a cost of $250kWh/t_{CO_2}$ that must be generated from within the plant. This energy requirement is also accounted for in the process efficiency of the CBTL plant. Therefore, the low, baseline and high CTL plant efficiencies of 53%, 50% and 47% were lowered to 49.4%, 46.5% and 44.2%, respectively to account for biomass pre-processing and carbon capture within the CBTL plant.

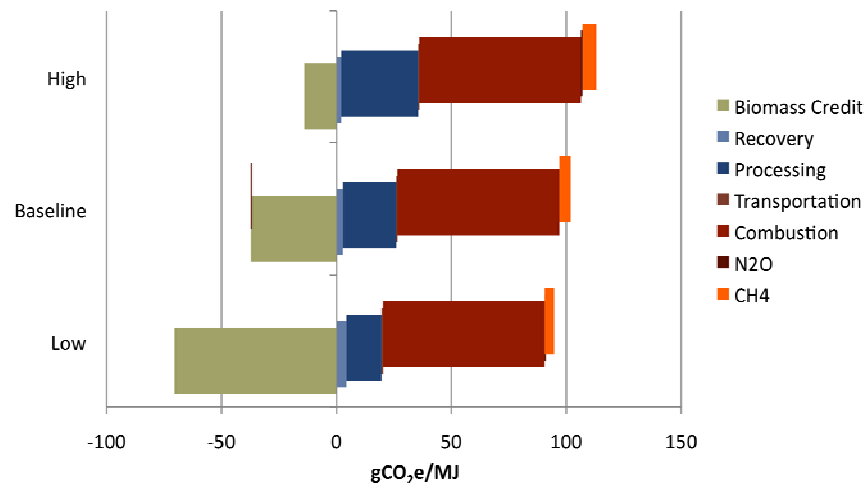


Figure B.4: Breakout of life-cycle emissions of CBTL by processing step for the low, baseline, and high emissions scenarios.

As was shown in Figures B.1 through B.3, the life-cycle of a fuel can be broken down into steps. Figure B.4 shows this emissions breakdown for the low, baseline and high emissions cases for CBTL. Note firstly that the diagram shows both positive and negative (e.g., from biomass growth) emissions contributions from each life-cycle step; note secondly that the negative N_2O emissions in the baseline case result from de-nitrification of corn stover and finally please note that the summation of positive and negative totals is

required for the cumulative total. The ‘biomass credit’ represents the CO₂ that is absorbed from the atmosphere during biomass growth and increasing biomass credit reflects the varied amounts of biomass being used in the three scenarios.

It was mentioned earlier that a range of 0% to 50% biomass weight fractions was explored. While Figure B.4 shows only three incremental values within this range, Figure B.5 shows continuous results for each of the cases. On the secondary axis is the quantity of biomass that is required for the production of 25,000 barrels per day of jet fuel (note that this is roughly the consumption for Boston Logan airport). Of note, a single typical railroad car can carry 26.5 tonnes of biomass (Mahmudi, 2006); therefore, 264 railroad cars would be needed to transport 7000 tonnes per day. This highlights the importance of considering GHG reductions for a high biomass wt% in conjunction with biomass feeding requirements.

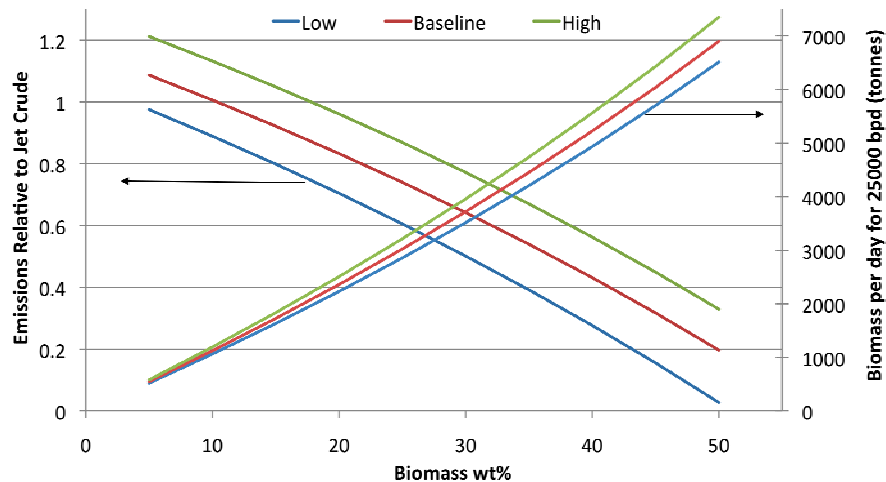


Figure B.5 Dependence of cumulative life-cycle emissions and biomass requirements for varied biomass utilization within CBTL.

Life-Cycle GHG Emissions Analysis of HRJ from Algae Oil

Using algae as a biofuel feedstock was first examined by the Department of Energy during the Aquatic Species Program (ASP) from 1978 to 1996. Algae are composed of protein, carbohydrates and lipids. Like other renewable oils, algal lipids can be used to make biofuels such as hydroprocessed renewable jet (HRJ). The ASP focused a great deal of attention on identifying a specific factor that would stimulate the algae to have a high weight fraction of lipids. There is still much discussion surrounding the possibility of genetically modifying certain strains of algae to produce more oils; however, the present analysis focuses only on strains that currently exist and have been documented. Furthermore, it is important to differentiate between micro-algae and macro-algae. Microalgae, as the name suggests, are tiny organisms which grow in water with concentrations ~0.2-0.4g/L and have the appearance of tinting the water green; these are the types of algae which are considered in this work. Macro-algae are the classical long strands that grow on the bottom of ponds and lakes (aka. seaweed). While some work has been performed using macro-algae as a fuel source, it is not considered here.

Algae can be grown in either an open pond setting or a controlled bioreactor. In the open pond approach, a pond in the shape of a raceway (oval) is constructed and a paddlewheel is used to circulate the water and mix the algae for even light exposure and growth. In bioreactors, the algae are grown in sheets or tubes allowing for much higher growth rates per unit area than open ponds. Bioreactors shield the algae from weather variations and facilitate growing in vertical geometries; however, these designs are cost intensive. Open pond technologies are examined in this analysis because of their reduced capital costs, the relative abundance of experimental documentation, and their increased technological readiness (relative to bioreactors). Given time, the capital costs of bioreactors could decrease as technological advances are made; and it is possible that a combination of bioreactor and open pond could prove to be an optimal system. These concepts will be further examined in this continuing research effort.

The two defining characteristics for algae as a biofuel are the growth rate (generally given in $\text{g/m}^2/\text{day}$) and lipid content (generally given as a weight percent of total). Both of these quantities vary within the literature as they depend on variables including algae type, weather conditions, among many others. The higher algal growth rates that are reported in the literature represent bioreactor technology and not open ponds. Recent presentations given by The Boeing Company employed yields that are 390% of the baseline value used in this work (Daggett, 2008). The current analysis is based on the engineering judgment of the authors based upon their literature review of open ponds. It was found that during peak periods of growth that $50\text{g/m}^2/\text{day}$ could be achieved while a yearly average of $20\text{g/m}^2/\text{day}$ appears reasonable (Seambiotic, 2008, NREL, 1998). A survey of algal strains also returned a range of lipid contents up to 40% (Becker, 2006). Assuming that technology will only improve in the future, $50\text{g/m}^2/\text{day}$ and 40% lipids by weight was adopted for the low emissions case, $25\text{g/m}^2/\text{day}$ and 25% lipids by weight was adopted for the baseline case and $20\text{g/m}^2/\text{day}$ at 15% lipids by weight was adopted for the high emissions case.

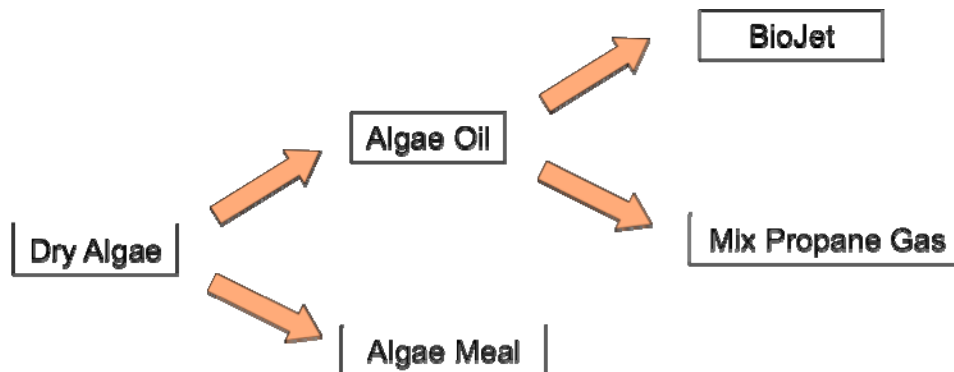


Figure B.6: Co-products that can be created from dried algae. It should be noted that this pathway is the same for palm oil, soybean oil, and many other renewable oil sources. For the allocation methodology used in this analysis, the algae meal is treated as animal feedstock; however, it could also be used for energy generation.

The extraction of oil from the algae and its processing into HRJ also results in the creation of marketable co-products (see Figure B.6). This is similar to the creation of HRJ from other renewable sources such as soy or palm. In all of these, the total emissions that are created need to be allocated among the co-products. For this analysis, as in Wong (2008), the emissions for algae oil and algae meal were allocated based on their market value while those from the HRJ and mix propane gas were allocated based on their energy allocation. This process is consistent with ISO guidelines on life-cycle analysis.

While much of the methodology for the analysis of algal HRJ is similar to that discussed for palm and soybean-based HRJ in Wong, 2008, the life-cycle is complicated by the need to feed CO_2 to the algae to sustain acceptable growth rates (see Figure B.3). The displacement (or system expansion) method is used to allocate emissions between the fuel and any electricity that is generated in providing the CO_2 required for growth. The system boundary is expanded to include both the electricity and emissions from a power plant somewhere else on the grid generating equal electricity to that generated in the production of the feed CO_2 from original system. The result is a CO_2 emissions credit (equivalent in meaning to the biomass credit of CBTL) given to the algal fuel related to the non-production of electricity somewhere on the grid. The ratio of the life-cycle GHG emissions from the electricity that is used to supply CO_2 for the algae and the type of electricity that is displaced has a large impact on the life-cycle emissions of the algal fuel. There is a significant degree of variation in the emissions per kilowatt-hour generated depending on the technology used, (i.e., utility boiler has higher emissions than integrated gasification combined cycle which has higher emissions than nuclear). The options in Table B.3 outline the effects on the life-cycle emissions that these choices can have. When 'dirty' electricity is used to feed the algae but 'clean' electricity is displaced then the CO_2 emissions credit is less than the CO_2 used to grow the algae; this results in a fuel that appears to be 'dirty'. When 'clean' electricity is used to feed the algae but 'dirty' electricity is displaced then the CO_2

emissions credit is greater than the CO₂ used to grow the algae; this results in a fuel that appears to be 'clean.' In this analysis, the electricity used to provide the CO₂ is always assumed to be the same as that which is displaced. For this configuration, the CO₂ emissions credit is approximately equal to the biofuel combustion emissions, which is the assumption used for biofuels that have not been 'fed' CO₂ for enhanced growth.

Table B.3: Impact of electricity choice on the biomass credit given to algal HRJ.

| Type of Electricity Coupled to Algae Growth | Type of Electricity Displaced | CO ₂ Credit Given to Algal Fuels |
|---|---------------------------------|---|
| Conventional Coal | Conventional Coal | Credit CO ₂ \approx Combustion CO ₂ (net combustion CO ₂ \approx 0) |
| | US Average Grid | Credit CO ₂ < Combustion CO ₂ (net combustion CO ₂ > 0) |
| | Nuclear (zero CO ₂) | Credit CO ₂ \approx 0 (net combustion CO ₂ >> 0) |
| US Average Grid | Conventional Coal | Credit CO ₂ > Combustion CO ₂ (net combustion CO ₂ < 0) |
| | US Average Grid | Credit CO ₂ \approx Combustion CO ₂ (net combustion CO ₂ \approx 0) |
| | Nuclear (zero CO ₂) | Credit CO ₂ \approx 0 (net combustion CO ₂ >> 0) |

When it is ready to be harvested, algae can represent as little as 1 part in 3000 in water. The task of extracting and drying the solid algae is the most energy intensive step of the cultivation process. Parameter variation was performed to investigate the influence of this step on the life-cycle emissions. If done inefficiently, drying can cause an algal HRJ to have life-cycle emissions that are 12% higher than jet fuel from conventional crude. This effect can be seen in the emissions from the recovery step of the high emissions case in Figure B.7. In a similar manner to Figure B.4, this figure shows both positive and negative (i.e., biomass usage) contributions from each life-cycle step with the summation of positive and negative contributions being the cumulative total. The counter intuitive trend in processing emissions from the low to high case occurs as a result of decreasing lipid content being assumed, and this lead to additional emissions being allocated to the algae meal.

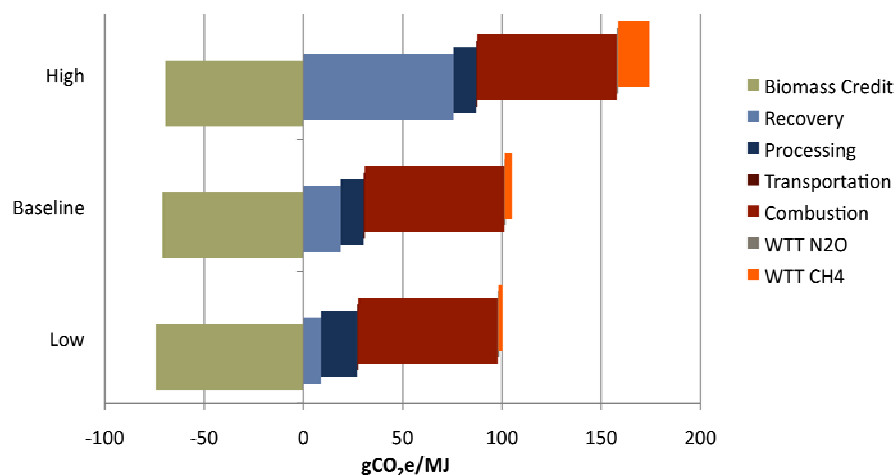


Figure B.7: Breakout of life-cycle emissions of algal HRJ by processing step for the low, baseline, and high emissions scenarios.

Summary of Life-Cycle GHG Emissions

The results from the CBTL and Algal HRJ pathways have been combined with the modified values from Wong (2008), to yield life-cycle GHG emissions from a wide range of potential alternative jet fuels as shown in Figure B.8. The presentation of these emissions is the same as Figures B.4 and B.7. It is important to note that this plot does not show cumulative totals, but rather it displays the emissions contributions from each step in the fuel life-cycle. The impact of the land use change scenarios, which were summarized in Table B.2, is included in the form of four pathways for both soy oil and palm oil HRJ. These results highlight the need to avoid land usage changes that result in GHG emissions. This method of presentation displays the ‘biomass credits’ that are given to biofuels because of the CO₂ that is absorbed during biomass growth; these credits are largely the reason why these fuels offer the potential for reduced GHG emissions. With the exception of BTL and CBTL, the biofuel pathways all have similar ‘biomass credits’ and the magnitude of these credits is equal in magnitude to the combustion emissions. The ‘biomass credit’ for CBTL is smaller because the fuel is created from a combination of coal and biomass. The ‘biomass credit’ for BTL is larger because biomass is being used to power the entire fuel production process.

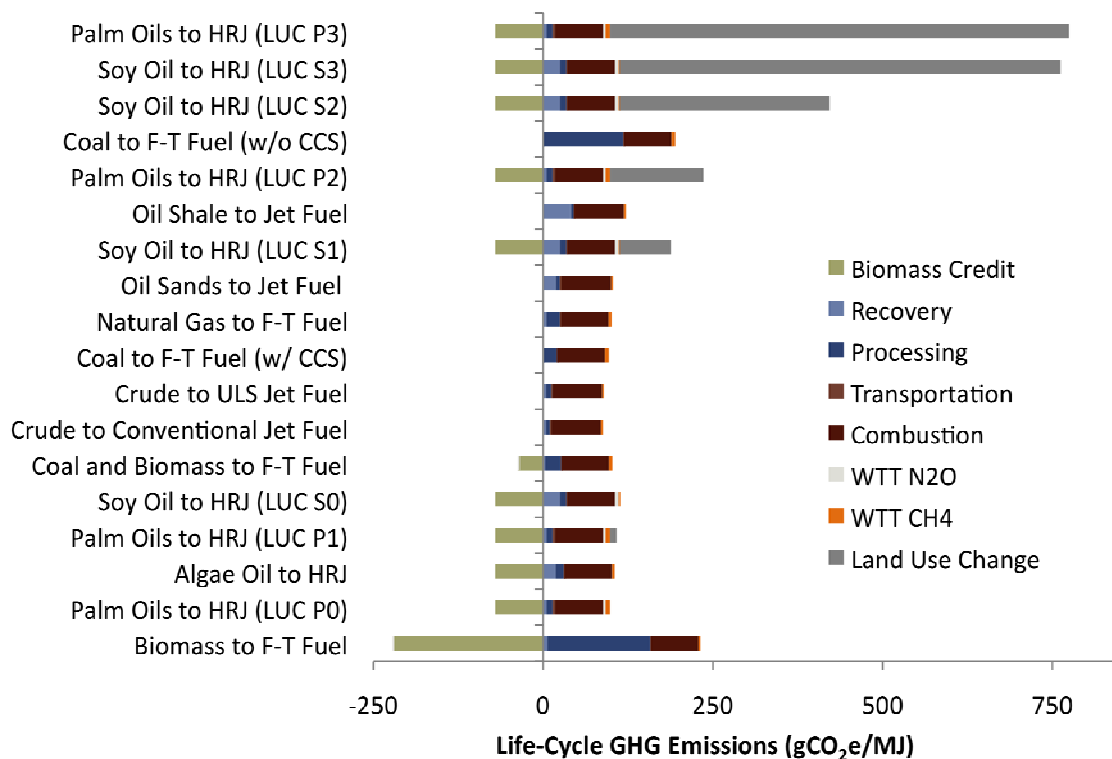


Figure B.8: Comparison of the life-cycle GHG emissions from a wide range of alternative fuel pathways.

The cumulative GHG emissions are given by the summation of the positive and negative contributions.

Note: CCS denotes Carbon Capture and Storage. Land Use Change (LUC) scenarios were defined in Table B.2.

Figure B.9 gives the cumulative totals for each of the pathways presented in Figure B.8 normalized by the life-cycle emissions for jet fuel from conventional crude. The uncertainty bars represent the range of emissions as given by the low and high emissions cases. Both CBTL and Algal HRJ have baseline life-cycle GHG emissions that are lower than conventional jet fuel; however, they both also have the potential to have GHG emissions that are higher than conventional jet fuel. For this reason, it is essential not to simply assume that biofuels are beneficial for the environment without knowing specifics.

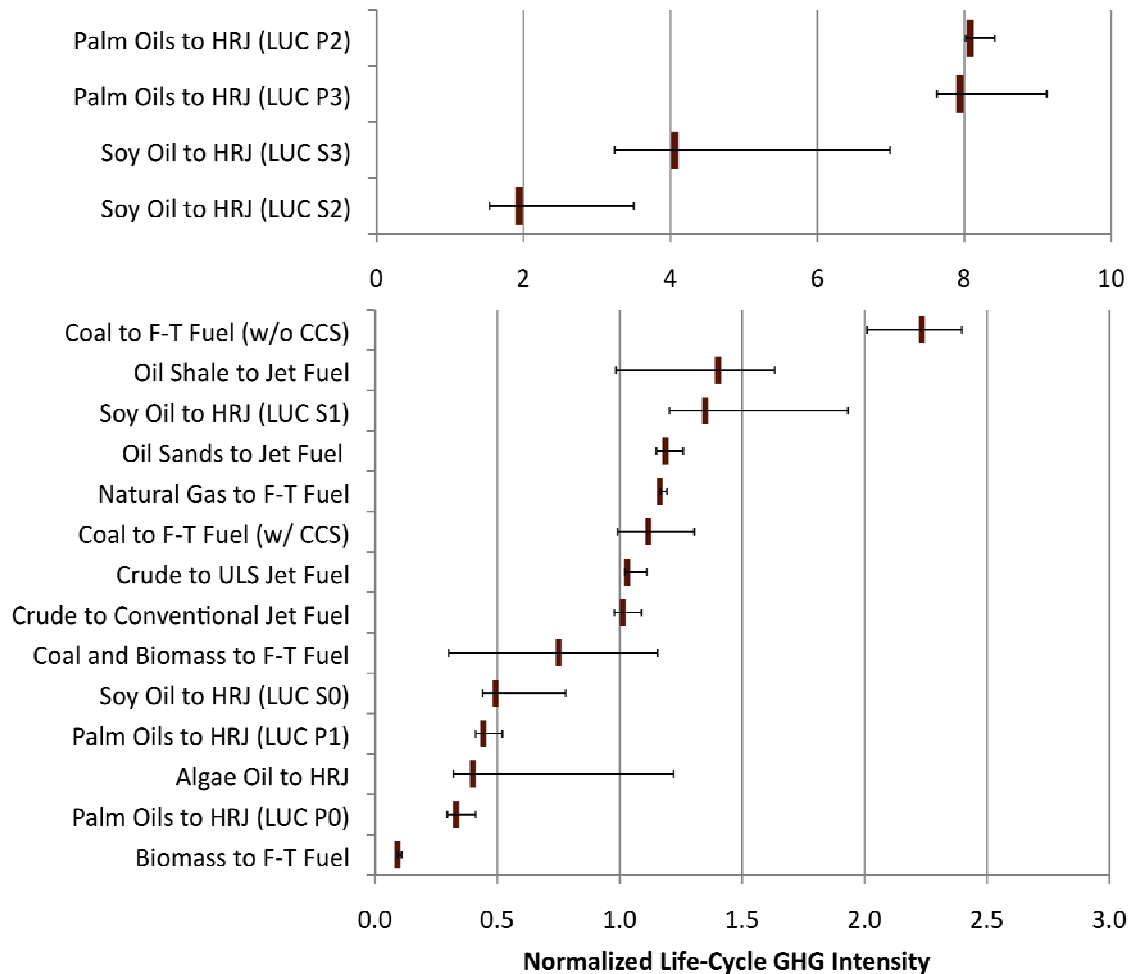


Figure B.9 Normalized life-cycle GHG intensity for the alternative jet fuel pathways under consideration. Uncertainty bars represent the low emissions, baseline, and high emissions scenarios. Please note the different scales for the top and bottom portions of the figure. Note: CCS denotes Carbon Capture and Storage and Land Use Change (LUC) scenarios are defined in Table B.2.

The focus of this work was to establish life-cycle GHG emissions inventories for a variety to alternative jet fuels and to determine the scales to which these fuels would need to be implemented in order to achieve emissions reduction targets. Table B.4 summarizes the fuel production potentials for all of the biofuel pathways presented in Figures B.8 and B.9. In addition, preliminary data on jatropha oil to HRJ have been gathered from the literature; this includes the fuel production potential in Table B.4. It merits noting that the life-cycle GHG emissions for jatropha HRJ have been estimated as approximately 30% of conventional jet fuel by Kalnes (2008). The range in yields of fuel per kilogram of jatropha/algae/palm/soy arises partially from the variation in oil fraction. Jatropha yields the most oil per kilogram (40%) followed by algae (25%), then palm kernels (22%) and finally soybeans (18%). Recall that there can be a great degree of variability in biomass oil yields as the Boeing Company have quoted a potential algal yield that is 390% of that used in this work.

A subtle but important point surrounding the F-T results is that only 25% of the fuel output from the fuel facility is assumed to be jet fuel. Using the first row as an example, there would be 976 (244×4) liters of liquid hydrocarbons produced for every hectare of corn stover, only 244 liters of which would be jet fuel (the rest could be used for fuels such as diesel, gasoline, and naphtha). The corn stover (or other terrestrial biomass) used as feedstock for pure BTL plants have very low energy densities. This causes a large quantity to be required in order to make small quantity of jet fuel (which has a relatively high energy density). Although the same feedstock is used for both pure BTL and CBTL, when supplemented by coal,

a reasonable output of fuel can be obtained from a smaller quantity of biomass. Herbaceous biomass or forest residue can also be used as a feedstock with the life-cycle GHG emissions staying within 7% of the value found using corn stover. Corn stover was the focus of this work because of its relative availability in large quantities.

Table B.4: Fuel production potential for various alternative jet fuels that could be derived from biomass.

| Process | Biomass Type | Biomass Requirements (kg _{Biomass} /MJ _{Jet Fuel}) | Biomass Yield (kg _{Biomass} /ha/year) | Land Requirements ⁽¹⁾ (ha/year/MJ _{Jet Fuel}) | Fuel Yields ⁽¹⁾ (L _{Jet Fuel} /ha/year) |
|--|--------------|--|---|---|--|
| BTL via Fisher Tropsch | Corn Stover | 0.542 | 4434.2 | 1.22E-04 | 244 |
| CBTL via Fisher Tropsch | Corn Stover | 0.090 | 4434.2 | 2.04E-05 | 1464 |
| UOP via Hydroprocessing | Jatropha | 0.080 | 4571.4 | 1.75E-05 | 1703 |
| UOP via Hydroprocessing | Soybeans | 0.154 | 2993.2 | 5.16E-05 | 579 |
| UOP via Hydroprocessing | Palm FFB | 0.121 | 19228.4 | 6.31E-06 | 4730 |
| UOP via Hydroprocessing | Algae | 0.112 | 91250.0 | 1.22959E-06 | 24265 |
| Notes: (1) F-T calculations assume that 25% of liquids output is jet fuel; May be lower in reality. (2) Hydroprocessing calculations assume use renewable diesel as a surrogate for biojet (3) Jatropha yield data from D1 Energy. | | | | | |

The life-cycle GHG emissions from Figure B.8 and B.9 and the production potentials that are summarized in Table B.4 can be combined to select fuel pathways that hold the most potential for reducing aviation's GHG emissions. This is because to reduce aviation's GHG emissions, fuel pathways having both low life-cycle GHG emissions as well as large fuel production potential are needed.

Fossil-to-jet fuel pathways have large production potential, but they have comparable or higher emissions than conventional jet fuel; therefore, their use will not reduce GHG emissions. BTL fuels have low GHG emissions, but they also have limited fuel production potential. With the use of excess palm or soy (available after food needs are met) for HRJ production, both palm to HRJ and soy to HRJ have low GHG emissions; however, there is little excess currently available. As such, large-scale soy oil and palm oil to HRJ production will have large GHG emissions resulting from the land use changes of expanding production. Hence, BTL as well as soy/palm to HRJ have limited potential for reducing GHG emissions. The algal HRJ, CBTL, and jatropha oil HRJ pathways all hold promise for reducing aviation's GHG emissions. There are other fuel pathways that hold the potential to reduce GHG emissions from aviation and merit study, (e.g., halophyte oil to HRJ). The authors will consider these as part of their ongoing work.

Achieving Carbon Neutrality through Biofuels

Because of the aforementioned limitations, fossil fuels, BTL, and soy/palm to HRJ pathways have limited or zero potential for reducing aviation's GHG emissions. However, other pathways present potential opportunities and should be considered further. These include algal HRJ, CBTL, and jatropha oil HRJ. In this section, various fuel pathways are considered along with conventional jet fuel to better understand the fuel usage and land mass that would be required for carbon neutral aviation growth.

It was estimated that the upper and lower bounds of possibility in fuel use are encompassed within the "FESG Baseline: Baseline Fuel Price" and the "Strong Plus: High Plus Fuel Price" projections respectively, as discussed in [Appendix A](#) of this document. The "Reduced Trend APO Baseline: Baseline Fuel Price, Low Trend Technology" projection, was used for demonstrative purposes in the carbon neutrality analysis discussed here as it falls between the two extremes. Life-cycle GHG emissions were estimated for this fuel use projection using the life-cycle GHG emissions from conventional jet fuel. Scenarios were then created to examine the potential for alternative fuels to help aviation reduce GHG emissions to some historical level (representative of some baseline year) by some future target year. Each scenario consisted of an alternative fuel choice, a baseline year (1990, 2000 and 2005 were examined), and a target year (2020, 2025 and 2050

were examined). Although alternative fuel use was estimated for all nine combinations of target and baseline years, only results from 2000 by 2050 are presented in this work.

Emissions from each of the fuel use projections using the current mix of jet fuel within the United States are shown in Figure B.10. The “Reduced Trend APO Baseline: Baseline Fuel Price, Low Trend Technology” projection will be referred to as the ‘baseline’ in later discussions because it lies in the middle of the projections. The “FESG Baseline: Baseline Fuel Price” will be referred to as the High Scenario and the “Strong Plus: High Plus Fuel Price” will be referred to as the Low Scenario.

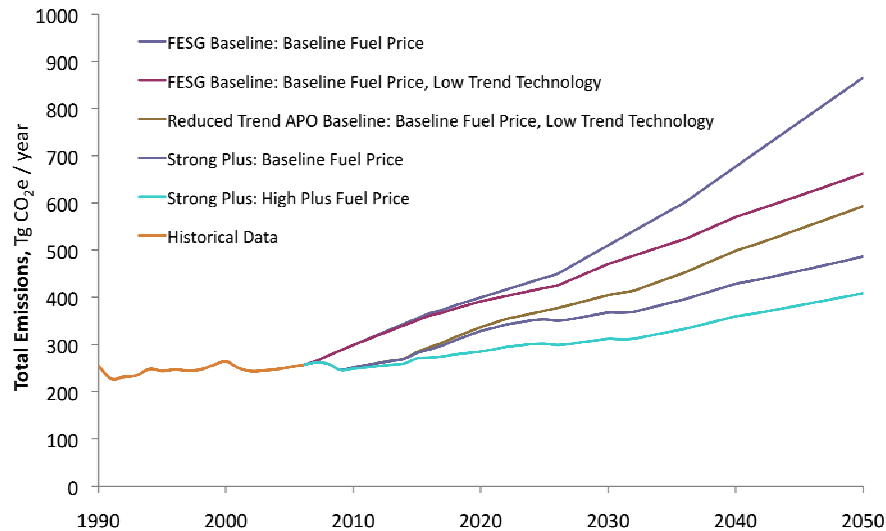


Figure B.10: Emissions from the projected fuel use cases developed by MVA for this analysis. The upper and lower extrema are taken as boundaries while the “Reduced Trend APO Baseline: Baseline Fuel Price, Low Trend Technology” projection has been chosen to demonstrate the development of carbon neutrality scenarios. Historical data is based on total jet fuel use (EIA, 2008) minus military jet fuel use (PQIS, 2008-1997). The baseline jet fuel life-cycle GHG emissions were used to estimate the total life-cycle emissions.

Carbon Neutrality Using Coal and Biomass

The life-cycle GHG emissions and fuel production potential from the baseline analysis of CBTL were combined with the projected fuel use from the “Reduced Trend APO Baseline” of Figure B.10 to create Figure B.11, which presents the life-cycle GHG emissions for two related scenarios. The first is a “Business-as-Usual” scenario where aviation continues to rely on conventional jet fuel. The second, labeled “CBTL Emissions,” is a hypothetical scenario in which aviation has an unlimited supply of alternative fuel available for its use (in this case, that fuel is CBTL). The scenario does NOT reflect a hypothetical production potential; in fact, the growth rate is almost certainly impossible. Instead, this scenario indicates the fuel quantities that would be needed to achieve carbon neutral aviation growth for each year in the future.

Each of the series contained within Figure B.11 are described in further detail below:

- The beige line represents the emissions that would occur if all fuel demands were met using conventional jet fuel, the “Business as Usual” scenario. Between 1990 and 2006, these emissions are based on historical jet fuel use; for years after 2006, the MVA fuel use scenario is used to estimate the emissions.
- The black line represents the emissions from the “CBTL Emissions” scenario; this includes both conventional jet fuel and the alternative fuel. The red dotted line is the target, which is the emissions level from the year 2000.
- The blue line represents the emissions coming from conventional jet fuel. Notice that this values tapers off to zero in order to try and meet the emissions target
- The green line represents the emissions coming from CBTL. Notice that after 2021, it is no longer possible to maintain the emissions level from the year 2000 using CBTL. For 2021 and subsequent

years, a fuel with life-cycle GHG emissions that is lower than CBTL is needed for carbon neutral aviation growth. This could be achieved by using higher biomass percentages within the CBTL fuel (this analysis assumed 25% biomass was used to create the fuel), or with a different fuel.

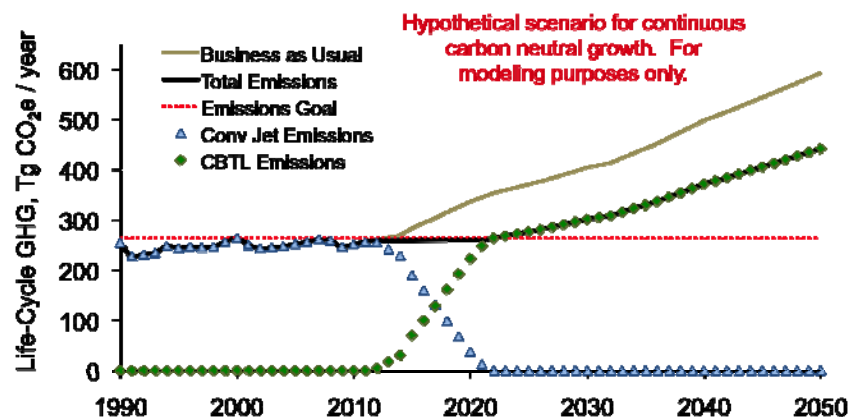


Figure B.11: Historical and future GHG emissions from aviation for scenarios representing business as usual use of conventional jet fuel and a hypothetical CBTL scenario whereby aviation maintains carbon neutral growth to the year 2021 through the extensive, and unrealistic, growth in the use of CBTL.

The analysis presented here uses CBTL created from corn stover because an industry currently exists for its creation and this waste resource would not incur land use change emission penalties. However, like all feedstocks, there are limitations on production. Figure B.12 provides guidance on these limitations. The current US production of corn stover is 54 billion kg per annum from 28.6 million hectares with 96 billion kg per annum being available using advanced tilling techniques (Graham et. al., 2007). In the future, it is projected that 343 billion kg per annum could be available from higher crop yields (Perlack et. al., 2005). As shown in Figure B.12, the biomass requirements presented in Figure B.11 would quickly outstrip current and future production potential. This underscores the need for a balanced solution that uses multiple feedstocks.

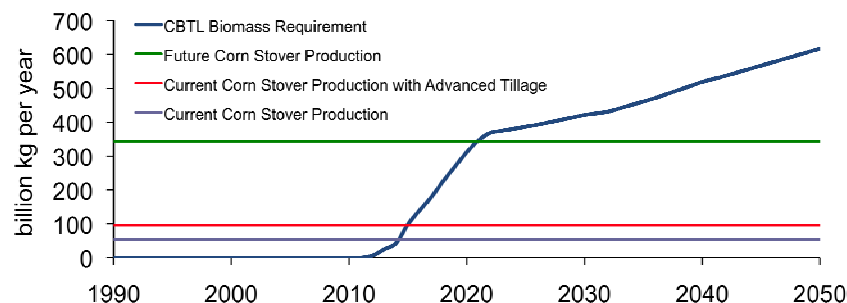


Figure B.12: Corn stover requirements to meet the CBTL production of Figure B.11 relative to current, and future production potential.

As shown in Figure B.12, the combination of coal and biomass will have difficulties reaching future emissions targets for carbon neutral aviation growth. This is true even with an unrealistic growth in both biomass production and facilities. However, assuming it does not provide greater utility in other sectors such as heating and electricity generation or ethanol production, CBTL holds promise for aviation. Even though coal and biomass is not a stand-alone solution for GHG reductions in the aviation sector, it could be supplemented by another form of cleaner, more available fuel, in order to meet emissions targets such as those being considered in this work.

Carbon Neutrality Using Algae

Using the data from the baseline analysis of algal HRJ and the projected fuel use from the “Reduced Trend APO Baseline” fuel usage projection, Figure B.13 was developed. It has the same form as Figure B.11 but the algal HRJ has sufficiently low life-cycle GHG emissions to maintain the emissions level of the year of 2000 through the year 2050. Since some conventional jet fuel usage in 2050 is not zero, a fully algal HRJ could sustain 2000 level emissions out past the year 2050.

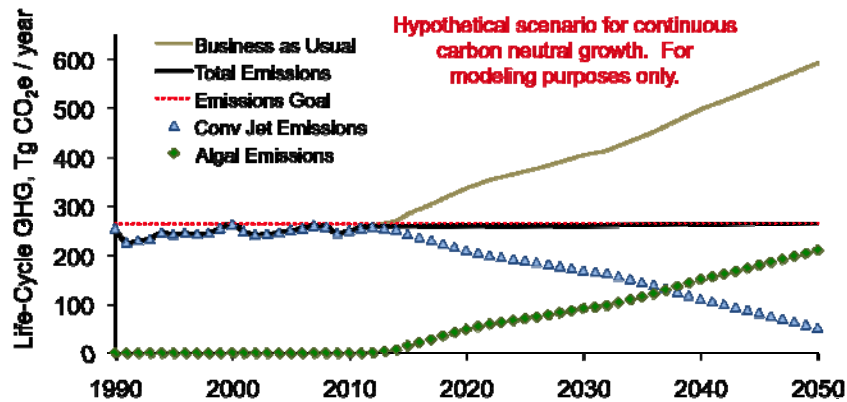


Figure B.13: Historical and future GHG emissions from aviation for scenarios representing business as usual use of conventional jet fuel and a hypothetical algal HRJ scenario whereby aviation maintains carbon neutral growth to the year 2050 through the extensive, and perhaps unrealistic, growth of algal HRJ.

Carbon Neutrality Limiting Cases

For scenarios with a baseline year of 2000, the threshold life cycle GHG emissions level for the average fuel being used was calculated to be 44.2% of conventional jet fuel. This value is not only dependent on the chosen baseline year but also on the fuel use scenario adopted. Table B.5 shows how the threshold of carbon neutrality changes depending on the baseline year and fuel use scenario (see [Appendix A](#) for details on other fuel use scenarios). Carbon neutral aviation growth (in 2050) cannot be achieved if the average life-cycle GHG emissions level from the US jet fuel mix exceeds these values. All values are given as percentages of the life-cycle GHG emissions from conventional jet fuel.

Table B.5: Life-cycle GHG emissions required to achieve carbon neutral aviation growth in 2050 for two different baseline years and three different fuel use scenarios. Emissions are given as a percentage of those for conventional jet fuel.

| Baseline Year | Scenario | | |
|---|-----------------------------------|---|----------------------------------|
| | Strong Plus: High Plus Fuel Price | Reduced Trend APO Baseline: Baseline Fuel Price, Low Trend Technology | FESG Baseline: Frozen Technology |
| 1990 | 61.9% | 42.6% | 29.2% |
| 2000 | 64.1% | 44.2% | 30.3% |
| Note: 1990 and 2000 are the most commonly referenced years for emissions benchmarking. The lowest emissions since 1990 occurred in 1992 when emissions were 4.2% less than those from 1990. | | | |

Land Usage Requirements for Carbon Neutrality

Given the fuel usage requirements for carbon neutrality from Figure B.13 as well as the fuel yield per hectare of land from Table B.4, the land area required to sustain the biomass needs for the carbon neutral algal HRJ scenario was estimated. Figure B.15 presents this landmass relative to a map of the United States, for reference. It is critical to note that the locations of the circles in no way indicate a preference or need for a specific region or climate. The blue circles of Figure B.15 correspond to the land area requirements for

soybeans and palm (for HRJ) while the green circles correspond to corn stover (for CBTL). For both corn stover and algae landmasses, the dashed line circles show how the areas required for growth change with the fuel use scenarios shown in Figure B.10. The data in Table B.6 indicates the volumes of fuel production and life-cycle GHG emissions that would correspond to these scenarios. The palm area corresponds to that which would be needed to achieve carbon neutrality, with the unrealistic assumption that land use changes would not be incurred. The soybean and corn stover areas correspond to that which would be needed to replace conventional jet fuel. As shown by the data in Table B.6, many of these scenarios exceed the carbon neutral target.

Figure B.14 graphically demonstrates the challenges of land mass requirements, growth and maintenance logistics as well as infrastructure limitations faced by biofuels; however, it does not tell the full story. The algae land area requirements would be sufficient to meet carbon neutral aviation growth in 2010, 2030, and 2050, all relative to 2000. The palm land areas would also be sufficient to meet carbon neutral growth; provided that it was actually possible to grow these quantities of palm. The volume of palm fruit required in 2050 would be 3.7 times current worldwide production (Flexnews, 2008). The corn stover acreage for CBTL and soybean land area for HRJ would not allow for carbon neutral growth, but it would be sufficient to replace all conventional jet fuel in 2050. However, the soybean volume requirement is over 4.7 times current global production (USDA, 2009) and the corn stover production requirements were described in conjunction with Figure B.12 (these also exceed current and forecast production).

Assuming the feedstock do become available, aviation will have to compete with other users of biomass resources. As an example, recent analysis by Hedegaard et al. (2008) indicates that the use of scarce biofuel resources may be more effective from perspectives of energy efficiency and CO₂ mitigation when used in heat and electricity rather than for transportation where the displaced petroleum would be used for transportation.

Table B.6: Comparison of conventional to alternative fuel use in the year 2050 using a baseline year of 2000. The percent of target emissions level achieved is relative to the emissions level from the year 2000.

| Fuel Source | Fuel Use Scenario | Total Fuel Use (billion kg/year) | Conventional Fuel Use (billion kg/year) | Alternative Fuel Use (billion kg/year) | Percent of Target Emissions Achieved |
|-------------|-------------------|-------------------------------------|--|---|--------------------------------------|
| Algae HRJ | High | 226.1 | 0.0 | 226.1 | 128 |
| | Baseline | 155.2 | 13.9 | 141.3 | 100 |
| | Low | 107.7 | 45.7 | 62.0 | 100 |
| CBTL | High | 226.1 | 0.0 | 226.1 | 244 |
| | Baseline | 154.9 | 0.0 | 154.9 | 167 |
| | Low | 106.7 | 0.0 | 106.7 | 115 |
| Soybean HRJ | High | 226.1 | 0.0 | 226.1 | 159 |
| | Baseline | 154.9 | 0.0 | 154.9 | 109 |
| | Low | 107.5 | 34.2 | 73.3 | 100 |
| Palm HRJ | High | 226.1 | 0.0 | 226.1 | 107 |
| | Baseline | 155.6 | 28.7 | 126.9 | 100 |
| | Low | 107.8 | 52.1 | 55.7 | 100 |

Alternative Fuel Land Requirements Compared to the United States in 2050

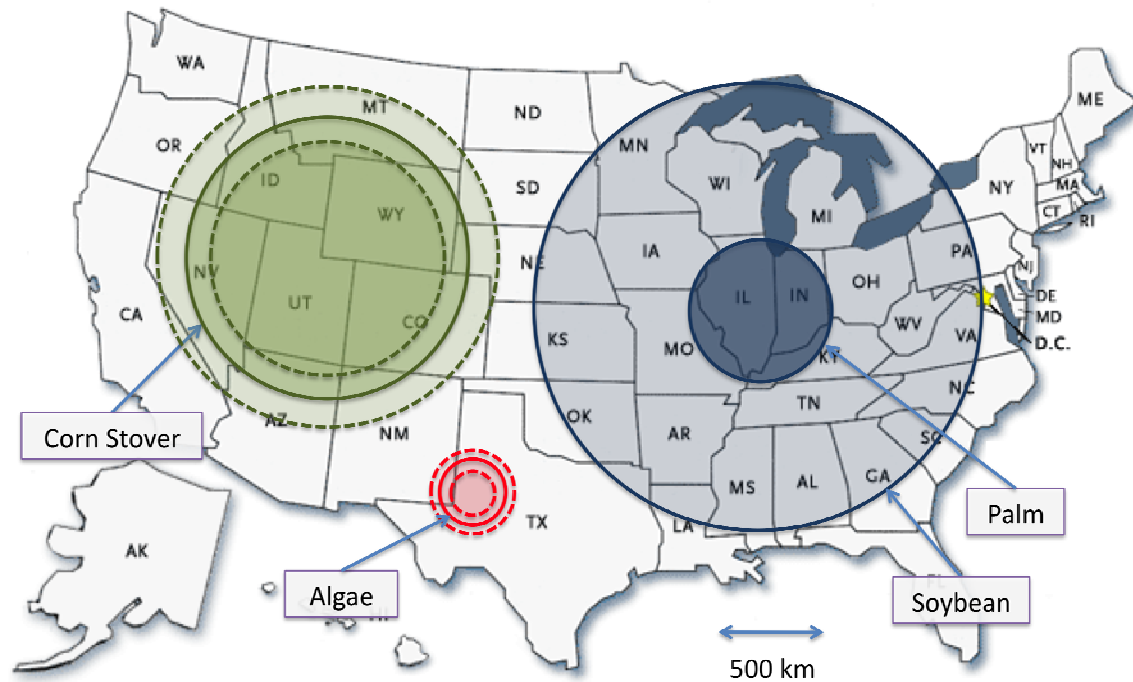


Figure B.14: Land area requirements for different biofuel use scenarios. The corn stover and algae areas reflect the low, nominal, and high fuel usage projections from Table B.6. The soy and palm HRJ scenarios reflect the nominal fuel usage projection from Table B.6. Of the scenarios presented in this figure, only the algal scenarios hold the potential for carbon neutral aviation growth.

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