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

U.S. FUEL TRENDS ANALYSIS AND COMPARISON TO GIACC/4-IP/1

(Presented by the United States)

SUMMARY

The extent to which global aviation fuel consumption may change over time will be influenced by a number of factors, including improvements in aircraft technology and airspace management, and fluctuations in jet fuel availability and price. The extent to which global aviation carbon dioxide (CO_2) emissions may change overtime is influenced by the same factors as aviation fuel consumption, as well as the availability of renewable aviation fuels that offer CO_2 reductions over their life cycle. This paper summarizes the findings from an analysis of a range of potential scenarios undertaken by the U.S. to inform GIACC discussions regarding what fuel consumption CO_2 emissions savings may be achieved from a combination of measures. These findings are then compared to the results presented in GIACC/4-IP/1. The comparison of scenarios exemplifies that reflecting economic and aviation activity from 2006 to the present in the scenarios makes a marked difference in the projected 2050 levels.

1. INTRODUCTION

1.1 The prominence of aviation climate change issues and the associated debate during the 36th Session of the International Civil Aviation Organization (ICAO) Assembly led to the creation of the Group on International Aviation and Climate Change (GIACC). The mandate of GIACC is to develop and recommend to the ICAO Council a Programme of Action and common strategy consistent with Appendix K of Resolution A36-22. The work of GIACC involves consideration of options to limit or reduce greenhouse gas (GHG) emissions attributable to international civil aviation.

1.2 The U.S. has undertaken an analysis that reflects economic and aviation activity from 2006 to the present, and the projects fuel consumption and CO_2 emissions savings scenarios that the U.S. believes may be achieved from a combination of measures. That analysis documented in this paper was conducted to inform the GIACC deliberations.

1.3 The range of fuel price and aviation scenarios considered in the U.S. analyses covered – in broad terms – the following areas. Additional information appears in Appendix A.

a) Air Traffic Management: improvements in the movement of air traffic to further reduce fuel burn and CO_2 emissions from the aviation sector;

b) Technology: advances in engine performance and airframe design that would enhance the energy efficiency of the aviation sector;

c) Business Measures: efficiencies in the operation and maintenance of aircraft, airports and airlines; and

d) Market-Based Measures: options, such as emissions trading, that are cost-beneficial in managing aviation GHG emissions growth (modelled as adjustment to fuel price).

f) Alternative Fuels and their potential use in aviation to improve environmental performance were considered separately from the fuel burn scenarios analysis delineated immediately below. The alternative fuels analysis is covered in Section 5 and Appendix B.

2. SCENARIOS AND ASSUMPTIONS

2.1 The U.S. analysis was conducted using the Aviation Environmental Portfolio Management Tool for Economics (APMT-Economics), which has been approved by the ICAO Committee on Aviation Environmental Protection (CAEP) Forecasting and Economics Support Group (FESG) for use to conduct the CAEP/8 cost-effectiveness analyses.

2.2 The forecast analysis considers both ICAO and US Next Generation Air Transportation System (NextGen)[1] reference data. The initial point of reference for the projection of aviation growth is the FESG forecast from a 2006 base year data set (Datum) where forecasts of demand and supply for 2016, 2026 and 2036, by route-group and seat class were applied. The forecasts were projected out to 2050 by extrapolating the 2026 to 2036 aviation activity growth trends. The underlying aviation activity projections from FESG (which were formulated in June-2007) were then adapted for this analysis to account for actual aviation activities and the economic realities from 2006 to the present, based on information supplied by the U.S. Federal Aviation Administration (FAA). The following assumptions are included in the FAA Analysis Baseline scenario projection.

a) Aviation growth is relatively stagnant for the period 2006 to 2011, with a recovery in general economic growth and aviation activity in line with a historic elasticity of airline traffic growth to economic growth from 2012.

b) Cost components are unchanged through time; fuel price, labor costs, landing fees, route charges, volume-related costs and maintenance costs all remain the same.

c) Costs pass-through to fares; thus, both higher and lower (fuel) operating costs incurred by airlines are passed through to consumers such that unit profit margins are maintained.

d) Aviation-sector profitability and growth are assumed to be in a reasonable and sustainable continuing balance.

e) Aircraft are retired in accordance with the FESG retirement curves that were based on historic data.

[1] The Next Generation Air Transportation System (NextGen) is a long-term transformation initiative to increase the efficiency, safety, and capacity of the U.S. national airspace system and at the same time reduce aviation emissions, in part, by transforming the current air traffic control system. This effort involves new technologies and air traffic procedures that will contribute to reducing aviation emissions and incorporates research, development and maturation of emissions-reduction technologies.

f) Aircraft technology improvement related to fuel use is considered through a low trend-based new aircraft technology improvement, which is assumed to be available at no additional cost to the industry and that equates to an average 1% per annum improvement in fuel use for new aircraft entering service over the entire forecast period.

g) Penetration of new aircraft technology into the operational fleet is assumed to occur over a period of time; specifically, a single one-time technology improvement would take fifteen years to achieve 50% penetration.

h) Enhanced airspace management and operational improvements that ensure airborne delays remain at the 2006 base year levels.

2.3 The underlying aviation activity for the analyses was a one-week sample of 2006 passenger aircraft operations drawn from the ICAO-CAEP Modelling and Database Task Force (MODTF) Common Operations Database, which excluded passenger aircraft with fewer than 20 seats.[2] The base year data is described as the Datum. This data provided the starting point for considering various assumptions that lead to the FAA Alternative Scenario A and Scenario B forecasts, which are covered in this paper.

2.4 Scenarios A and B include a combination of assumptions for: air transport growth, new aircraft fuel use technology, airspace operational efficiency, market-based options and fuel prices. A summary of the input assumptions is provided in Table 1; additional information appears in the subsequent text and in Appendix A.

Table-1 Scenario Input Summary

Core Scenario	Air Transport Growth	New Aircraft Fuel Use Technology	Operational Efficiency	Fuel Price
FAA Analysis Baseline	Short-term demand adjusted to reflect economic downturn	Low Trend-based new aircraft improvement (average 1% per annum)	No Additional Delays	None/EIA Low
FAA Analysis Baseline with Alternative Scenario A	Short-term demand adjusted to reflect economic downturn	Optimistic trend new aircraft improvement (average 1.5% per annum)	High for US, with a 5 year lag before equivalent global improvement	None/EIA Low
FAA Analysis Baseline with Alternative Scenario B	Short-term demand adjusted to reflect economic downturn	Optimistic trend new aircraft improvement (average 1.5% per annum)	High for US, with a 5 year lag before equivalent global improvement	High-plus phased over 5 years

Assumptions for new aircraft fuel use technology are further described in paragraph 2.5; operational efficiency in paragraph 2.6 and fuel price in paragraph 2.7.

2.5 New aircraft fuel use technology for FAA Alternative Scenarios A and B were considered through a further level improvement, beyond the Baseline, that equates to an average 1.5% per annum improvement in fuel use for new aircraft entering service over the entire forecast period.

[2] The underlying data was drawn from a development version of the CAEP MODTF 2006 Common Operations Database. Some detailed aspects of this underlying database have since been revised for use in CAEP/8 analysis; however, the revised data were not available in time to be incorporated as the underlying aviation activity database for this analysis using APMT-Economics.

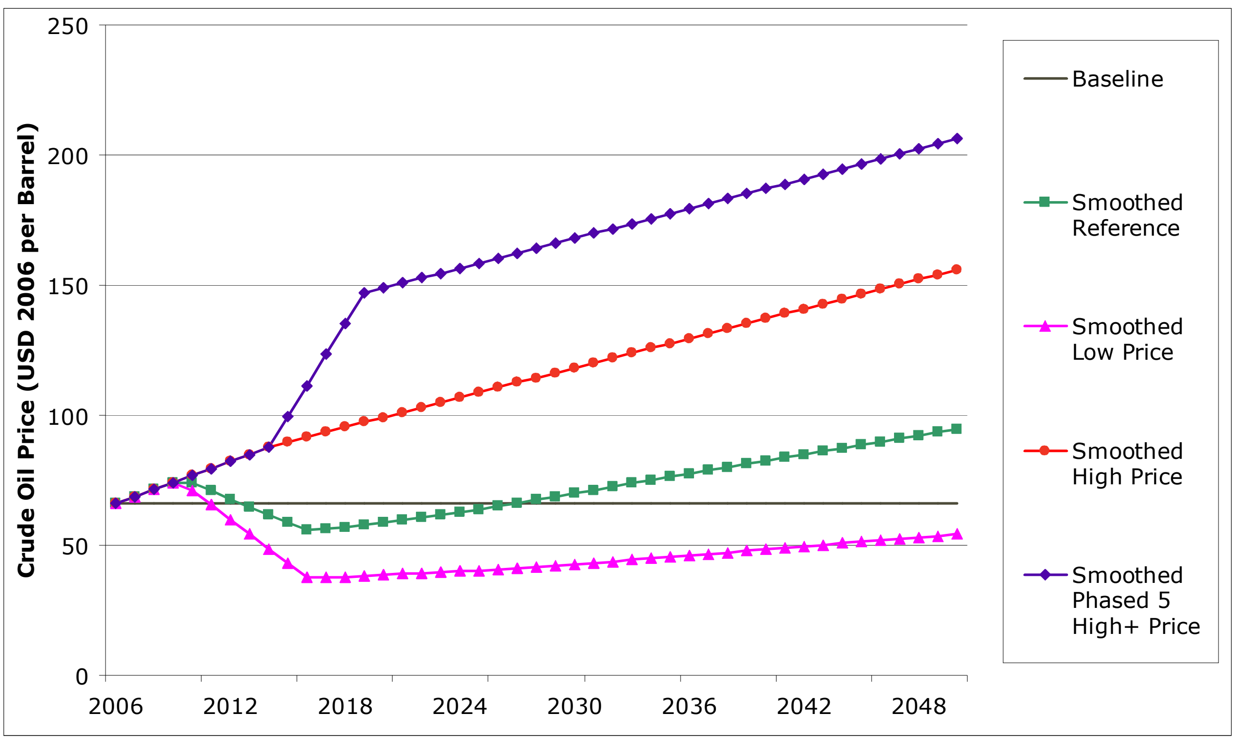
2.6 The airspace operational improvements for Scenarios A and B were based on those used in the NextGen High Density[3] case, which as applied in this analysis is summarized in Table 2. It was assumed that these airspace improvements were implemented at no additional cost to the industry.

Table-2 Airspace Operational Improvement Assumptions Relative to the Baseline

Geographic Scope	Operational Efficiency Improvement
United States	Flight distance was assumed to be reduced by 3% at 2015 and by 10% at 2025
Rest of World	Flight distance was assumed to be reduced by 3% at 2020 and by 10% at 2030

2.7 The fuel price scenarios used for the FAA Baseline, A and B scenarios were drawn from the US Energy Information Administration (EIA) International Energy Outlook for 2008. The Baseline Scenario and Scenario A uses the 2006 base year (Datum) fuel price, which equates to the EIA low scenario. The fuel price for Scenario B began by assuming the EIA High Price trend, and then the price was increased to represent additional market-based GHG measures phased in over five years. The fuel price scenarios are illustrated in Figure 1 in terms of the real price per barrel to 2026, which were then extrapolated out to 2050.

Figure-1 Fuel Price Scenarios



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[3] The NextGen High Density solution set involves airports and adjacent airspaces that require all the capabilities of the NextGen flexible terminals and airspace, plus integrated tactical and strategic flow capabilities. They may require higher performance navigation and communications capabilities for air traffic and the aircraft to support these additional operational requirements. http://www.faa.gov/about/initiatives/nextgen/resources/sol_sets/hd/index.cfm

3. PROJECTIONS

3.1 The projected global fuel burn in 2050 ranges from 473 Mt for Scenario B to 690 Mt for the FAA Analysis Baseline, as shown in Figure 2. For the U.S. the projected fuel burn in 2050 ranges from 115 Mt for Scenario B to 167 Mt for the FAA Analysis Baseline. Data resulting for both the U.S. and global projected fuel burn is presented in Table 3.

3.2 Global passenger km growth, as projected from 2006 to 2050 for scenarios A and B, ranges between 460% and 550%, as shown in Figure 3. The projections for U.S. passenger km growth from 2006 to 2050 for scenarios A and B range between 235% and 290%; which equates to the average fuel use per passenger kilometer reducing between 36% and 50%.

Table-3 Annual global aviation fuel burn for the FAA Analysis scenarios, million tonnes (Mt)

	U.S. Operations			Global Operations		
	FAA Analysis Baseline	FAA Analysis Baseline with Alternative Scenario A	FAA Analysis Baseline with Alternative Scenario B	FAA Analysis Baseline	FAA Analysis Baseline with Alternative Scenario A	FAA Analysis Baseline with Alternative Scenario B
2006	68	68	68	174	174	174
2012	71	71	69	193	193	188
2016	79	77	73	224	221	207
2020	90	87	76	267	262	225
2025	101	96	82	312	297	253
2026	103	95	81	321	303	257
2036	129	113	95	448	392	329
2050	167	137	115	690	565	473

Figure 2: Global Fuel use Projected to 2050

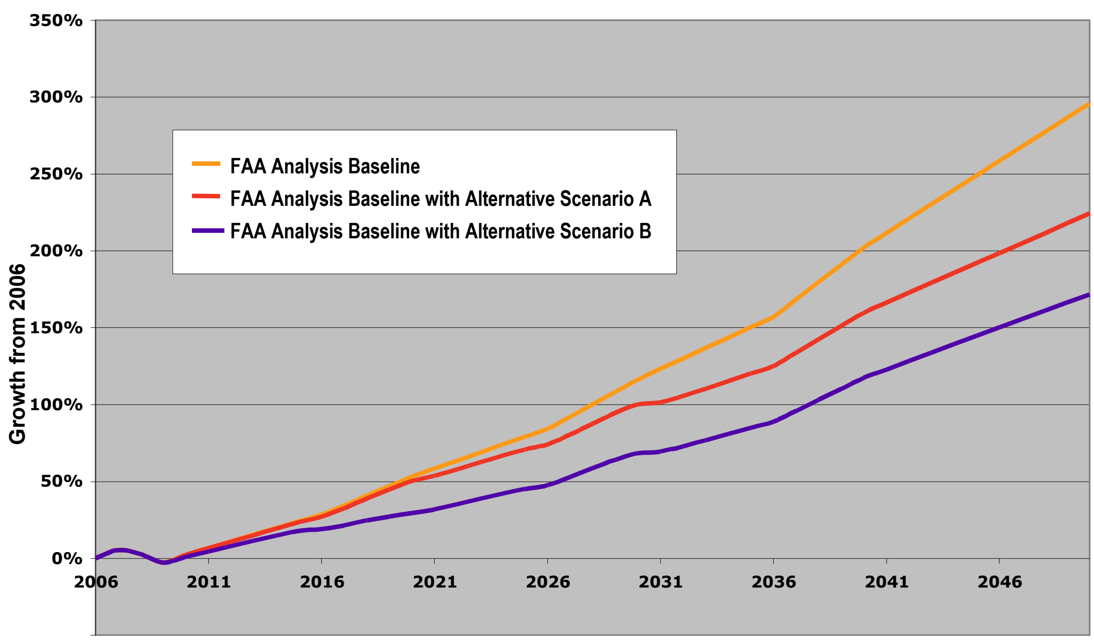
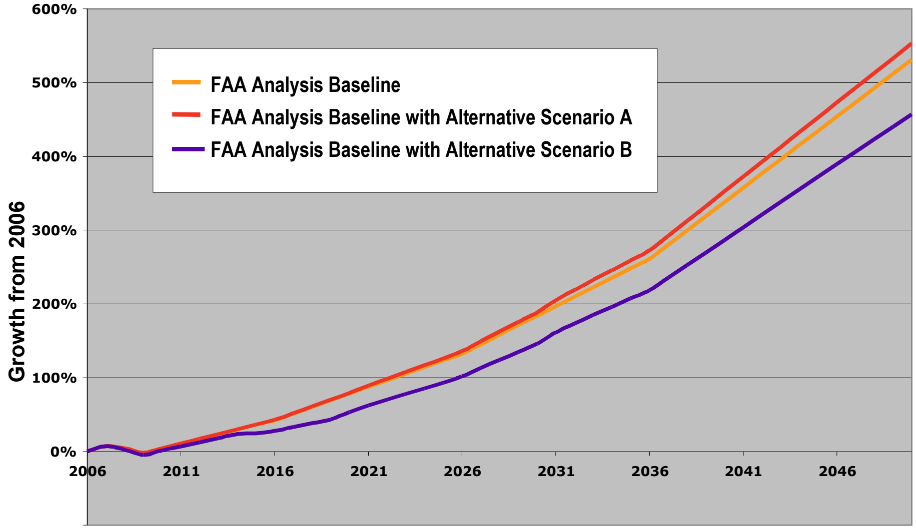


Figure 3: Global Passenger km Projected to 2050



4. PROJECTIONS COMPARED

4.1 Work conducted by the ICAO-CAEP FESG Projections Task Group (PTG) and MODTF in response to a request by the GIACC resulted in GIACC/4-IP/1, entitled *Global Aviation CO_2 Emissions Projections to 2050*. Data from that paper are compared with the FAA Analysis Baseline, Scenario A and Scenario B in Table 4 and Figure 4.[4] Table 5 contains a summary of the MODTF scenario assumptions.

Table-4 Annual Global Fuel Burn for MODTF and FAA Analysis Scenarios (million tonnes of fuel)

Year	MODTF Scenario 3^	MODTF Scenario 4^	MODTF Scenario 5^	MODTF Scenario 6^	FAA Analysis Baseline	FAA Scenario A	FAA Scenario B	MODTF S3 + FESG central demand	MODTF S4 + MMU A1 demand scenario	MODTF S4 + FESG central demand	MODTF S4 + CONSAVE A1_ULS demand scenario	MODTF S5 + FESG central demand	MODTF S5 + MMU B1 demand scenario	MODTF S3 + MMU A2 demand scenario	MODTF S5 + CONSAVE B1_DtE demand scenario
2006	**187**	**187**	**187**	**187**	**174**	**174**	**174**	**187**	**187**	**187**	**187**	**187**	**187**	**187**	**187**
2012	*240*	*240*	*238*	*238*	**193**	**193**	**188**								
2016	**276**	**276**	**273**	**271**	**224**	**221**	**207**								
2020	*316*	*314*	*310*	*305*	**267**	**262**	**225**								
2025	*372*	*368*	*361*	*351*	**312**	**297**	**253**								
2026	**385**	**397**	**372**	**361**	**321**	**303**	**257**								
2036	**542**	**523**	**503**	**477**	**448**	**392**	**329**								
2050	*883*	*835*	*790*	*730*	**690**	**565**	**473**	**795**	**760**	**741**	**738**	**693**	**452**	**443**	**282**

The MODTF and FESG-PTG data derived from GIACC/4-IP/1 are *pending review and acceptance by CAEP/8.*
^Data for MODTF Scenarios 3 through 6 came from GIACC/4-IP/1, Table 1 and are based on the FESG consensus (central) forecast. The data in *italics* were interpolated by MODTF to meet the years requested by the GIACC. MODTF Scenario 6 "goes beyond the improvements based on industry-based recommendations."
+ Data for the FESG-PTG developed scenarios came from GIACC/4-IP/1, Table A2.1

[4] MODTF scenarios 1 and 2 are not included in Table 4 or Figure 4 in this document since GIACC/4-IP/1, paragraph 20 noted "the assumptions used in these scenarios (1&2) regarding fuel burn improvements are not considered to be a realistic outcome."

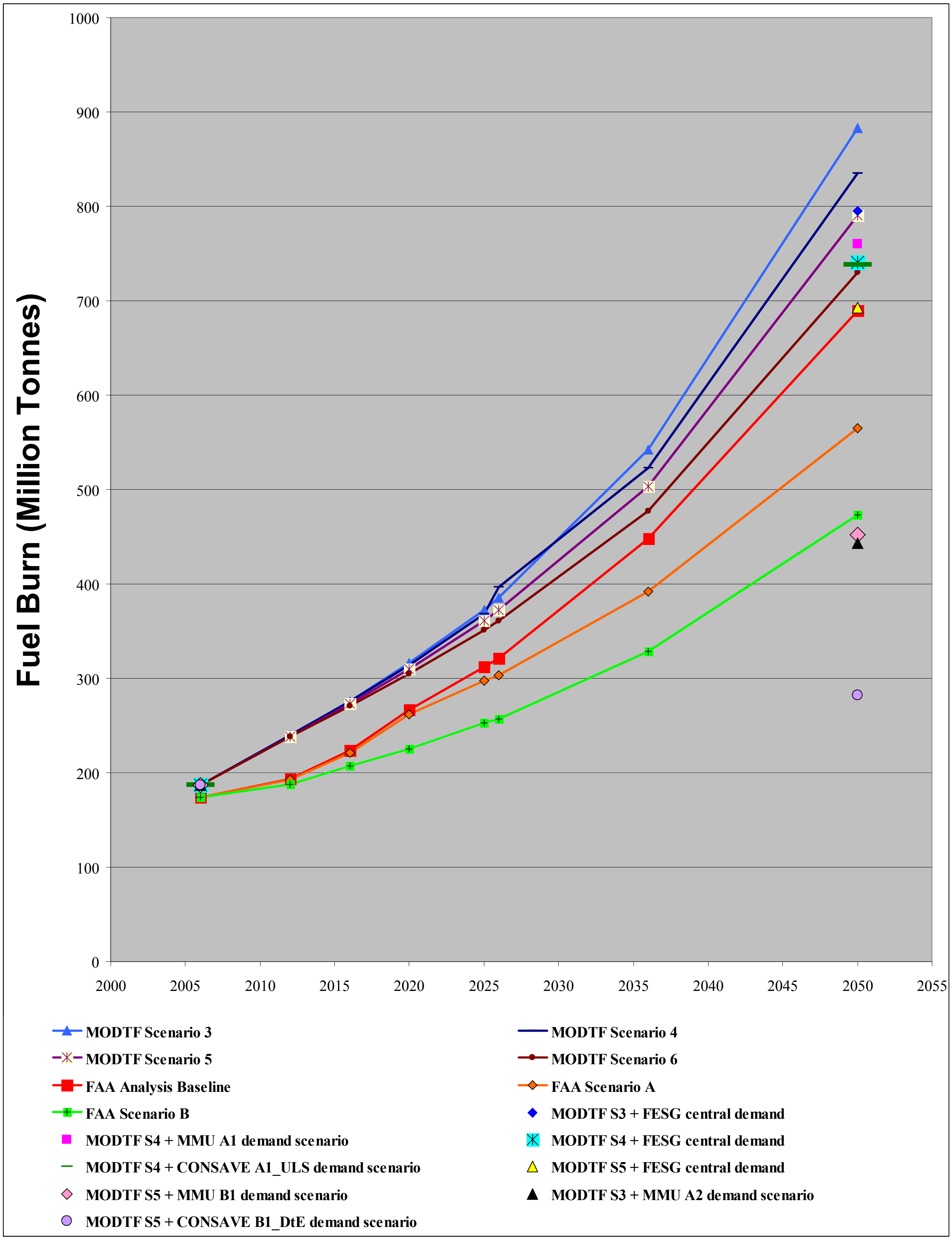
Table-5 Summary of MODTF Scenario Assumptions

	Forecast	CNS/ ATM	Fleet-Wide Operational improvements in 2016	Fleet-Wide Operational improvements in 2026	Fleet-Wide Operational improvements in 2036	New Aircraft technology entering the fleet 2006> <2015	New Aircraft technology entering the fleet 2015=>2036	New Aircraft technology entering the fleet 2006>2036
MODTF Scenario 1	FESG consensus	No improvements beyond those available today	0	0	0	no improvements beyond those available today		
MODTF Scenario 2	FESG consensus	Only improvements to maintain current ATM efficiency levels	0	0	0	no improvements beyond those available today		
MODTF Scenario 3	FESG consensus	Fleet-Wide Moderate Operational Improvement	0.5 percent	1.4 percent	2.3 percent	0.95 percent per annum	0.57 percent per annum	
MODTF Scenario 4	FESG consensus	Fleet-Wide Moderate Operational Improvement	0.5 percent	1.4 percent	2.3 percent			0.96 percent per annum
MODTF Scenario 5	FESG consensus	Fleet-Wide Advanced Operational Improvements	1.0 percent	1.6 percent	3.0 percent			1.16 percent per annum
MODTF Scenario 6	FESG consensus	Fleet-Wide Optimistic Operational Improvements	3.0 percent	6.0 percent	6.0 percent			1.5 percent per annum

Information contained in this table was derived from GIACC/4-IP/1, *Global Aviation CO_2 Emissions Projections to 2050*.
MODTF Scenarios 1 and 2: "assumptions… regarding fuel burn improvements are not considered to be a realistic outcome."
MODTF Scenario 6: "goes beyond the improvements based on industry-based recommendations."

4.2 MODTF computed global aviation fuel burn (and hence CO2 emissions) for 2006, 2016, 2026 and 2036 consistent with the FESG CAEP/8 central traffic forecast (developed at the global level for passenger and freight services) for a range of modelling scenarios, summarized in Table 5. MODTF results are currently only available for the FESG CAEP/8 central forecast. It is anticipated that application of the FESG CAEP/8 low scenario will reduce results by 15 to 20%. In addition, the MODTF extrapolation approach does not allow the effects of market maturity to be captured, which would constrain the growth in global aviation demand and hence in emissions.

Figure 4: MODTF and FAA Analysis Scenarios Compared for Global Aviation Fuel Burn Projections to 2050 (million tonnes of fuel used)
(MODTF/FESG-PTG results are pending review and acceptance by CAEP/8)



4.3 MODTF scenarios presented in GIACC/4-IP/1 were accompanied by the following note: *"Results presented in (the GIACC/4-IP/1) paper should be considered illustrative. They demonstrate the order of magnitude of global aviation CO2 emissions in 2050 under a range of assumptions. The uncertainties when looking out to 2050 must be acknowledged when interpreting the results presented."*

4.4 The APMT-Economics tool, used to model the FAA Analysis Scenarios, was developed to work with the Aviation Environmental Design Tool (AEDT); and, when used together AEDT generates the fuel burn and emissions. For this analysis, however, APMT-Economics modeled the fuel burn based on aircraft specific fuel burn characteristics extracted from an AEDT generated 2005 global inventory.[5] While the fuel burn component within APMT-Economics is primarily used to establish a reasonable estimate for the fuel cost component of total aircraft type-specific operating costs, the ability of APMT-Economics to estimate fuel burn was verified against AEDT and found to be within the range of other MODTF models.

4.5 As depicted in Figure 4, the FAA Analysis Baseline level at 2050 approximately coincides with the FESG-PTG modelled MODTF Scenario 5 with FESG central demand. FAA Scenarios A and B show higher global fuel burn projections at 2050 than the following three FESG-PTG modelled scenarios: MODTF Scenario 5 with MMU B1 demand scenario, MODTF Scenario 3 with MMU A2 demand scenario, and MODTF Scenario 5 with CONSAVE B1_DtE demand scenario.

5. ALTERNATIVE FUELS

5.1 Appendix B presents an update on the research that was presented in GIACC/3-IP/4. The major changes are an update on the life cycle greenhouse gas emissions of Hydro-treated Renewable Jet bio fuel created from algae, an analysis of jatropha as a Hydro-treated Renewable Jet bio fuel feedstock, and a revised examination of the potential for bio fuels to replace 50% and 100% of jet fuel in the year 2050.

6. CONCLUSIONS

6.1 Results presented in this paper should be considered illustrative. They attempt to demonstrate the order of magnitude of global aviation CO_2 emissions in 2050 under a range of assumptions. The uncertainties when looking out to 2050 must be acknowledged when interpreting the results presented.

6.2 While the results of the FESG-MODTF work and the FAA Analysis Scenarios are considered illustrative, the comparison of scenarios exemplifies that the FAA scenario results are within the range projected by the FESG-PTG, and will likely be in the range of the FESG CAEP/8 low forecast. In addition, the results from the FAA Analysis Scenarios demonstrate that reflecting more up to date information on the economic and aviation activity from 2006 to the present makes a marked difference in the projected 2050 fuel burn levels. For example, compared to earlier MODTF projections, global fuel burn by 2050 could be 20-50% lower under some alternative scenarios. This is potentially significant as it could make it either more feasible to use alternative fuels (less supply required) or less costly for market measures (fewer charges or emission permits to purchase) to offset fully aviation's carbon growth in the longer-term.

[5] APMT-Economics analyses for CAEP/8 incorporate inputs from the 2006 reference data set.

6.3 We offer this information to GIACC to consider as it discusses the range of potential aspirational goals being developed in the medium and long term for the international aviation sector.

— END —

Analysis of Aviation & Fuel Price Scenarios for U.S. Participation in the ICAO Group on International Aviation and Climate Change

Report for the U.S. Federal Aviation Administration, Office of Environment and Energy

May 2009

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Contents

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Summary

Background and Objectives

In September 2008, the U.S. Federal Aviation Administration (FAA) Office of Environment and Energy (FAA-AEE) commissioned work to analyse global fuel burn trends through 2050, given a range of aviation and fuel price scenarios.

An FAA Analysis Baseline scenario has been generated to account for the impacts of fuel burn technology improvements for new aircraft, airspace operational efficiency improvements and demand projections. This Baseline demand projection was derived from the CAEP/8 central case forecast,[1] which was adjusted to account for recent aviation market conditions and extrapolated from 2036 out to 2050.

Analysis Approach

The Aviation Environmental Portfolio Management Tool for Economics (APMT-Economics)[2] was used to analyse global fuel burn and CO_2 emissions trends, given a range of aviation and fuel price scenarios and considering the potential for aircraft fuel use technology and aviation operational efficiency improvements. ***Only passenger aircraft operations and demand were addressed in this analysis.***

The APMT-Economics tool is designed to model aviation market responses, focusing on the decisions that would be made by airlines in response to the introduction of a range of environmental policy measures that directly affect the aviation industry. It operates at a relatively disaggregate spatial level of detail, but includes a detailed representation of individual aircraft types, aircraft ages and fleets.

The APMT-Economics Model produces a set of internally consistent forecasts of **Baseline** (demand and supply projections with a default set of scenario assumptions) and **Scenario Responsive** (demand and supply projections with alternative scenario assumptions, including policy measures) situations, allowing for a wide range of aviation industry and consumer responses to the potential introduction of environmental policy measures.

APMT-Economics was developed to work with the Aviation Environmental Design Tool (AEDT); and, when used together AEDT generates the fuel burn and emissions. For this analysis, however, APMT-Economics modelled the fuel burn based on aircraft specific fuel burn characteristics extracted from an AEDT generated 2005 global inventory. While the fuel burn component within APMT-Economics is primarily used to establish a reasonable estimate for the fuel cost component of total aircraft type-specific operating costs, the ability of APMT-Economics to estimate fuel burn was verified against AEDT and found to be within the range of other ICAO CAEP models.

1 Prepared by the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) Forecasting and Economics Support Group (FESG).

2 APMT-Economics is part of a comprehensive suite of software tools under development by the FAA Office of Environment and Energy, in collaboration with Transport Canada and NASA, which allow for thorough assessment of the environmental effects and impacts of aviation. APMT-Economics, previously known as the APMT Partial Equilibrium Block (PEB), has been approved by ICAO-CAEP-FESG for use to conduct CAEP/8 cost-effectiveness analyses. As part of the wider research programme, the scope and details of the APMT-Economics tool and underlying analysis assumptions continue to be updated; and, therefore, the analysis reported for any study reflects a snapshot of the model and its forecasting capability.

In this analysis we have used APMT-Economics to conduct a large number of model tests with a range of assumptions around a core set of Baseline and scenarios. The tests have been used to demonstrate the effects for a number of aviation market stakeholders regarding aviation fuel use, demand, operations, fleet, consumer surplus, airline profitability and fuel efficiency in response to the following:

- potential improvements to aircraft technology, operations and fuel efficiency gains;
- consideration of recent economic and aviation industry downturn impacts; and
- higher fuel costs through a combination of higher commodity prices and a phased introduction of market-based GHG measures that were modelled as an additional fuel cost.

Analysis Inputs and Assumptions

The underlying aviation activity was a one-week sample of 2006 passenger aircraft operations drawn from the ICAO-CAEP-MODTF[3] Common Operations Database, which excluded passenger aircraft with fewer than 20 seats.[4] The base year data is described as the **Datum** situation and a validation of the APMT-Economics Datum input levels of aviation activity and the associated operating costs and revenues was undertaken against available data from ICAO and from fuel use estimates from AEDT. The APMT-Economics Datum year inputs and calculated values demonstrated a good validation against data at a global level and a satisfactory representation of the recorded information for the United States[5]. This data provided the starting point to which the demand and supply forecasts were applied to establish the alternative scenario forecasts.

The forecast analysis considers both ICAO and U.S. Next Generation Air Transportation System (NextGen)[6] reference data. The initial point of reference for the projection of aviation growth is the FESG forecast from a 2006 base year Datum where forecasts of demand and supply for 2016, 2026 and 2036, by route-group and seat class were applied. The forecasts were projected out to 2050 by extrapolating the 2026 to 2036 aviation activity growth trends. The underlying aviation activity projections from FESG (which were formulated in June-2007) were then adapted for this analysis to account for the variance of recent economic and aviation activity relative to the assumptions underpinning the FESG forecasts. The underlying Baseline scenario projection, referred to as the **FAA Analysis Baseline**, includes the following assumptions.

- **Aviation growth** is relatively stagnant for the period 2006 to 2011, with a recovery in general economic growth and aviation activity in line with a historic elasticity of airline traffic growth to economic growth from 2012.
- **Cost components** are unchanged through time; fuel price, labour costs, landing fees, route charges, volume-related costs and maintenance costs all remain the same.

3 ICAO Committee on Aviation Environmental Protection (CAEP) Modelling and Database Task Force (MODTF)

4 The underlying data was drawn from a development version of the CAEP MODTF 2006 Common Operations Database in August 2008. Some detailed aspect of this underlying database have since been revised for use in CAEP/8 analysis but were not available in time to be incorporated as the underlying aviation activity database for this analysis using APMT-Economics.

5 In the timeframe for this analysis no attempt was made to separately calibrate the APMT-Economics Model at a regional level, yet the values compared suggested agreement to within 10%.

6 The Next Generation Air Transportation System (NextGen) is a long-term transformation initiative to increase the efficiency, safety, and capacity of the U.S. national airspace system and at the same time reduce aviation emissions, in part, by transforming the current air traffic control system. This effort involves new technologies and air traffic procedures that will contribute to reducing aviation emissions and incorporates research and development on emissions-reduction technologies.

- **Costs pass-through to fares**; thus, both higher and lower (fuel) operating costs incurred by airlines are passed through to consumers such that unit profit margins are maintained.
- **Aviation-sector profitability** and growth are assumed to be in a reasonable and sustainable continuing balance.
- **Aircraft are retired** in accordance with the FESG retirement curves that were based on historic data.
- **Aircraft technology improvement** related to fuel use is considered through a low trend-based new aircraft technology improvement, which is assumed to be available at no additional cost to the industry and that equates to an average 1% per annum improvement in fuel use for new aircraft entering service over the entire forecast period.
- **Penetration of new aircraft technology** into the operational fleet is assumed to occur over a period of time; specifically, a single one-time technology improvement would take fifteen years to achieve 50% penetration.
- **Enhanced airspace management** and operational improvements that ensure airborne delays remain at the 2006 base year levels.

The scenarios tested with the APMT-Economics tool have considered alternative combinations of assumptions for: air transport growth, new aircraft fuel use technology, airspace operational efficiency, market-based options and fuel prices. Table S.1 is summary of the input assumptions, which are defined further below.

Table S.1: Scenario Input Summary – Core Tests

Core Scenario	Air Transport Growth	New Aircraft Fuel Use Technology	Airspace Operational Efficiency	Fuel Price Change
FAA Analysis Baseline	Short-term demand adjusted to reflect economic downturn	Low Trend-based new aircraft improvement (average 1% per annum)	No Additional Delays compared to Datum	None/ EIA Low
FAA Analysis Baseline with Alternative **Scenario A**	*Short-term demand adjusted to reflect economic downturn*	Optimistic trend new aircraft improvement (average 1.5% per annum)	High for U.S., with a 5 year lag before equivalent global improvement	*None/ EIA Low*
FAA Analysis Baseline with Alternative **Scenario B**	*Short-term demand adjusted to reflect economic downturn*	Optimistic trend new aircraft improvement (average 1.5% per annum)	High for U.S., with a 5 year lag before equivalent global improvement	High-plus phased over 5 years

The common assumptions for each alternative scenario relative to the Baseline case are shown in italics.

New aircraft fuel use technology for FAA Alternative Scenarios A and B were considered through a further level improvement, beyond the Baseline, that equates to an average 1.5% per annum improvement in fuel use for new aircraft entering service over the entire forecast period.

The **airspace operational improvements** for Scenarios A and B were based on those used in the NextGen High Density[7] case, which as applied in this analysis is summarized in Table S.. It was assumed that these airspace improvements were implemented at no additional cost to the industry.

Table S.2 Airspace Operational Improvement Assumptions

Geographic Scope	Operational Efficiency Improvement
United States	Flight distance was assumed to be reduced by 3% at 2015 and by 10% at 2025
Rest of World	Flight distance was assumed to be reduced by 3% at 2020 and by 10% at 2030

The **fuel price scenarios** used for the FAA Baseline, A and B scenarios were drawn from the US Energy Information Administration (EIA) International Energy Outlook for 2008. The Baseline Scenario and Scenario A uses the 2006 base year (Datum) fuel price, which equates to the EIA low scenario. The fuel price for Scenario B began by assuming the EIA High Price trend, and then the price was increased to represent additional market-based GHG measures phased in over five years. The fuel price scenarios are illustrated in Figure S.1 in terms of the real price per barrel to 2026, which were then extrapolated out to 2050.

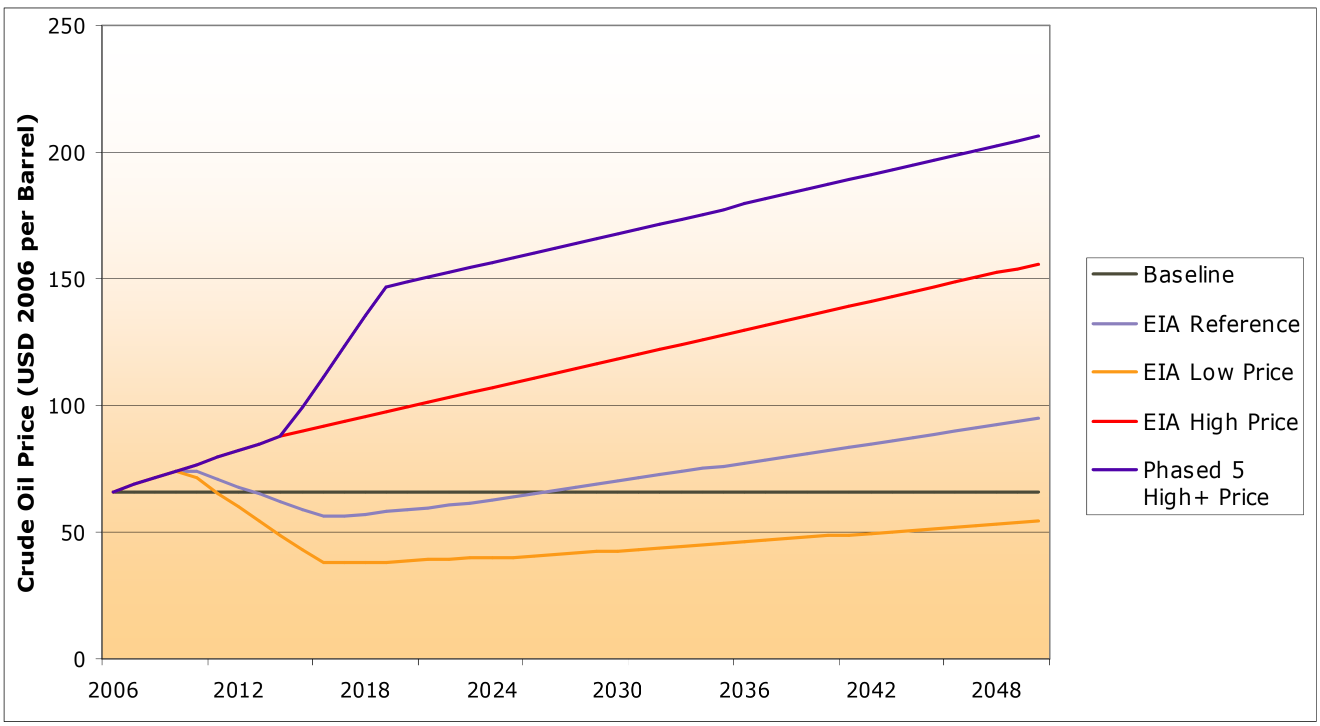


Figure S.1: Fuel Price Scenarios

7 The NextGen High Density solution set involves airports and adjacent airspaces that require all the capabilities of the NextGen flexible terminals and airspace, plus integrated tactical and strategic flow capabilities. They may require higher performance navigation and communications capabilities for air traffic and the aircraft to support these additional operational requirements. http://www.faa.gov/about/initiatives/nextgen/resources/sol_sets/hd/index.cfm.

Projections

Projections for **U.S. passenger km growth** from 2006 to 2050 for scenarios A and B range between 235% and 290%; which equates to the average fuel use per passenger kilometre reducing between 36% and 50%, as shown in Figure S.2. Projections for **U.S. fuel burn in 2050** ranges from 115 Mt for Scenario B to 167 Mt for the FAA Analysis Baseline, as shown in Figure S.3.

Global passenger km growth, as projected from 2006 to 2050 for scenarios A and B, ranges between 460% and 550%, as shown in Figure S.4. Projected **global fuel burn in 2050** ranges from 473 Mt for Scenario B to 690 Mt for the FAA Analysis Baseline, as shown in Figure S.5. Data resulting for both the U.S. and global projected fuel burn are presented in Table 3.

Table S.1 Annual global aviation fuel burn for the FAA Analysis scenarios, million tonnes

	US Operations			Global Operations		
	FAA Analysis Baseline	FAA Analysis Baseline with Alternative Scenario A	FAA Analysis Baseline with Alternative Scenario B	FAA Analysis Baseline	FAA Analysis Baseline with Alternative Scenario A	FAA Analysis Baseline with Alternative Scenario B
2006	68	68	68	174	174	174
2012	71	71	69	193	193	188
2016	79	77	73	224	221	207
2020	90	87	76	267	262	225
2025	101	96	82	312	297	253
2026	103	95	81	321	303	257
2036	129	113	95	448	392	329
2050	167	137	115	690	565	473

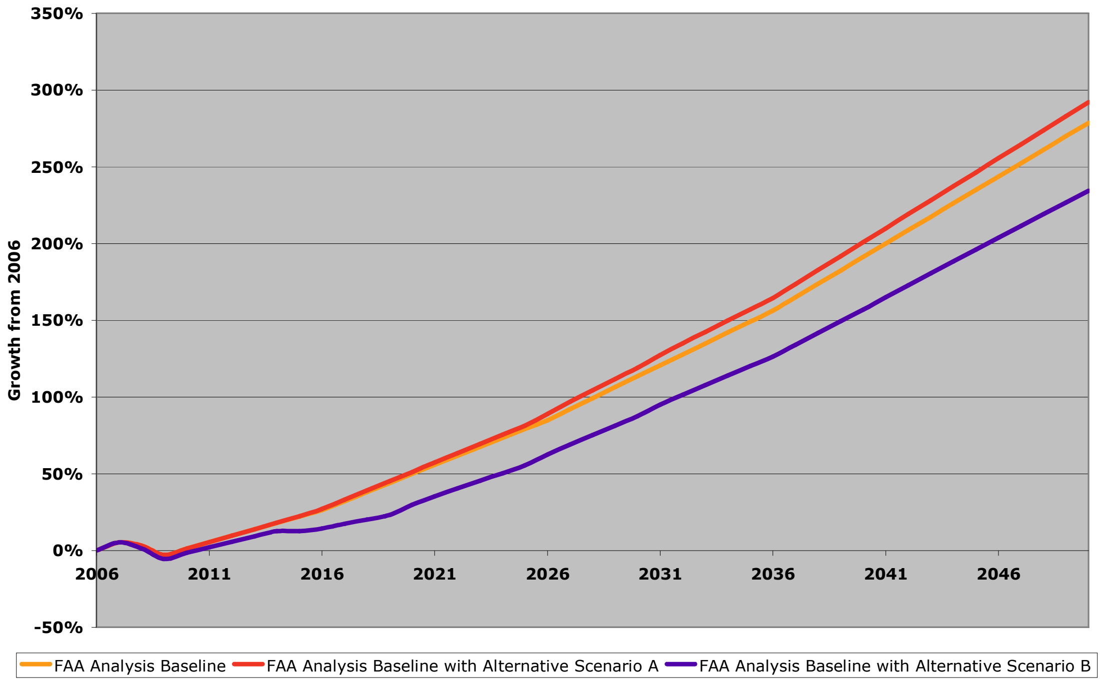


Figure S.2: Projected Growth in United States Passenger km under Alternative Scenarios

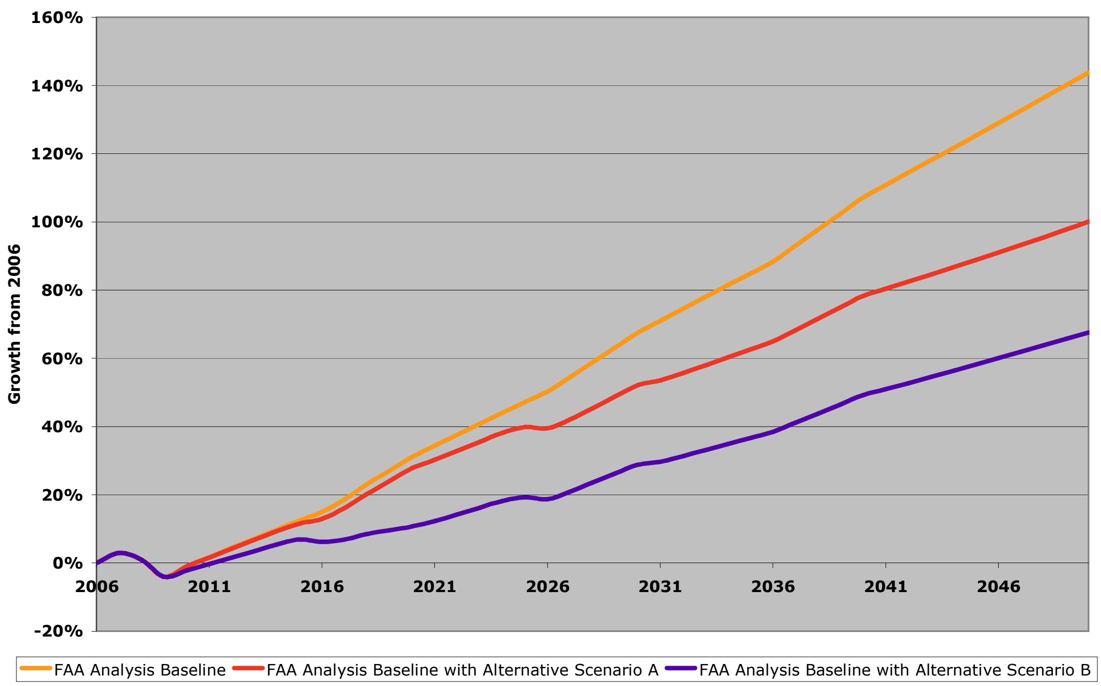


Figure S.3: Projected Growth in Fuel use for the United States under Alternative Scenarios

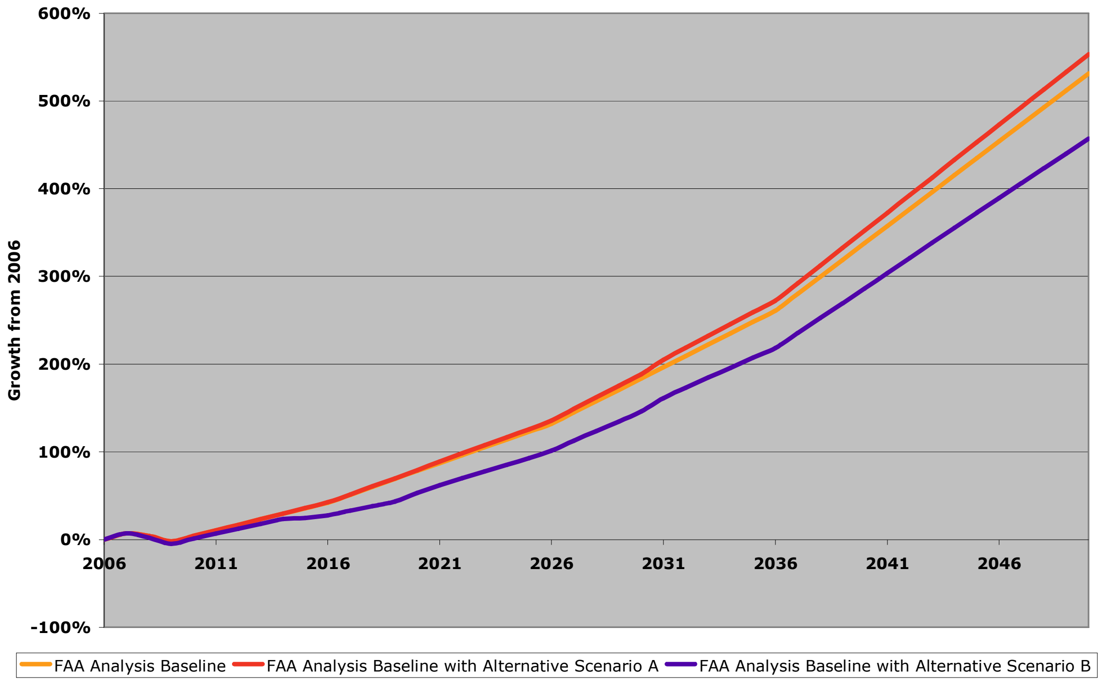


Figure S.4: Projected Growth in <u>Global</u> Passenger km under Alternative Scenarios

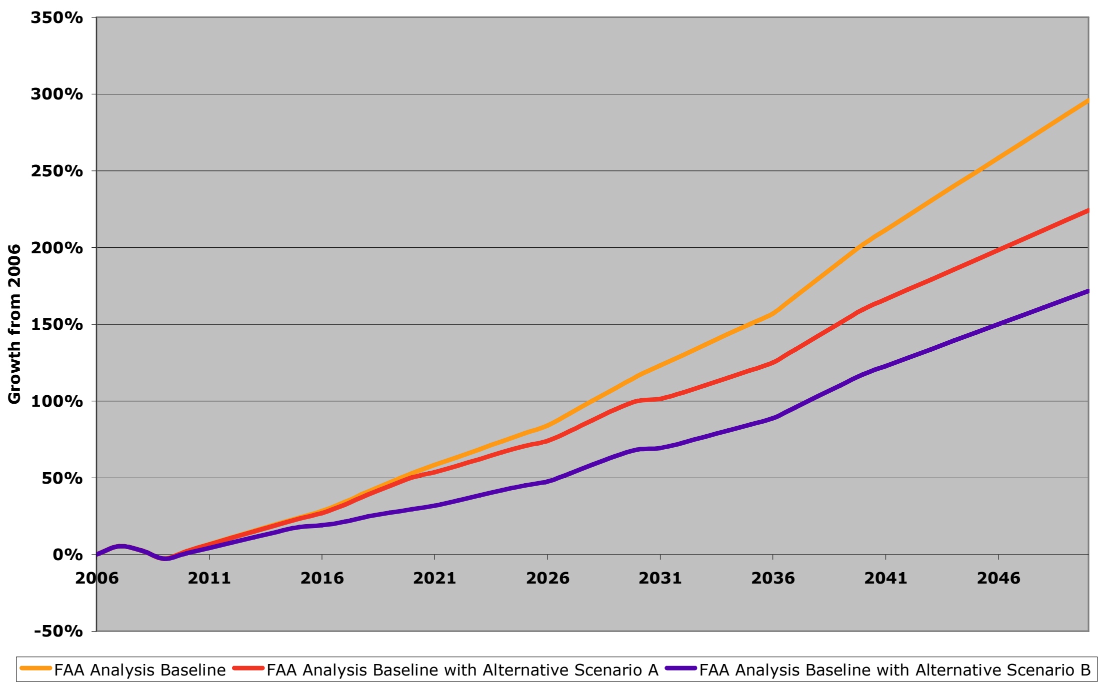


Figure S.5: Projected Growth in <u>Global</u> Fuel use under Alternative Scenarios

1 Introduction

1.1 Background and Objectives

1.1.1 In September 2008, the U.S. Federal Aviation Administration (FAA) Office of Environment and Energy (FAA-AEE) commissioned work to analyse global fuel burn trends through 2050, given a range of aviation and fuel price scenarios.

1.1.2 An FAA Analysis Baseline scenario has been generated to account for the impacts of fuel burn technology improvements for new aircraft, airspace operational efficiency improvements and demand projections. This Baseline demand projection was derived from the CAEP/8 central case forecast, which was adjusted to account for recent aviation market conditions and extrapolated from 2036 out to 2050.

1.2 Report Structure and Status

1.2.1 This report documents the analysis work that has been undertaken using the Aviation environmental Portfolio Management Tool for Economics (APMT-Economics), which is a component of the Aviation Environmental Tools Suite. The structure of the report is:

- Chapter 1 – Introduction and overview of the analysis tool;
- Chapter 2 – Validation of Datum and Baseline Situation;
- Chapter 3 – Scenarios and Assumptions; and
- Chapter 4 – Results.

1.2.2 This report provides the supporting documentation for the analysis and air transport projections using the APMT-Economics tool that are reported in the U.S. Information Paper to the Group on International Aviation and Climate Change (GIACC), meeting 4 (May 2009). The analyses reported in this paper consolidates the analyses reported to the FAA in draft in December 2008, and the further analyses to take account of the recent economic and market conditions affecting aviation. Subsequent to the initial exploratory work, MVA Consultancy undertook further research and analysis that was specifically in support of the U.S. FAA contribution to the GIACC.

1.2.3 As part of the overall research effort being conducted by the FAA, the APMT-Economics tool remains under development and refinement, as does the model input data. In particular, refinements to the model input data and assumptions have been defined in parallel work that are relevant to this analysis consequently, the analysis outputs reported here are now updated from that originally underlying the U.S. Information Paper on Aviation and Alternative Fuels for the GIACC meeting 3. In doing so, we ensure that the current best analysis projections are now reported. The current outputs are less than 10% different at 2050, well within the bounds of uncertainty that we would have placed on the original scenario projections to 2050 that were derived from this analysis.

1.2.4 It should be noted that ***only passenger aircraft operations and demand*** *were addressed in this analysis*.

1.2.5 A Glossary of key terms is included at the end of the document.

1.3 The Aviation Environmental Tools Suite

1.3.1 The FAA-AEE, in collaboration with Transport Canada, is developing a comprehensive suite of software tools that will allow for thorough assessment of the environmental effects and impacts of aviation. The main goal of the effort is to develop a new critically needed capability to characterize and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operational, and market scenarios.

1.3.2 Figure 1 is a simplified schematic of the Aviation Environmental Tools Suite[8]. The main functional components of the Tools Suite are as follows:

- Environmental Design Space (EDS): estimates source noise, exhaust emissions, and performance for potential future and existing aircraft designs;
- Aviation Environmental Design Tool (AEDT): currently estimates global, regional and local noise, fuel burn and emissions from aircraft;
- Aviation environmental Portfolio Management Tool for Impacts (APMT-Impacts): estimates the environmental impacts of aircraft operations for technological, operational and policy options; and
- Aviation environmental Portfolio Management Tool for Economics (APMT-Economics): an economic model of the aviation industry for considering environmental policy options.

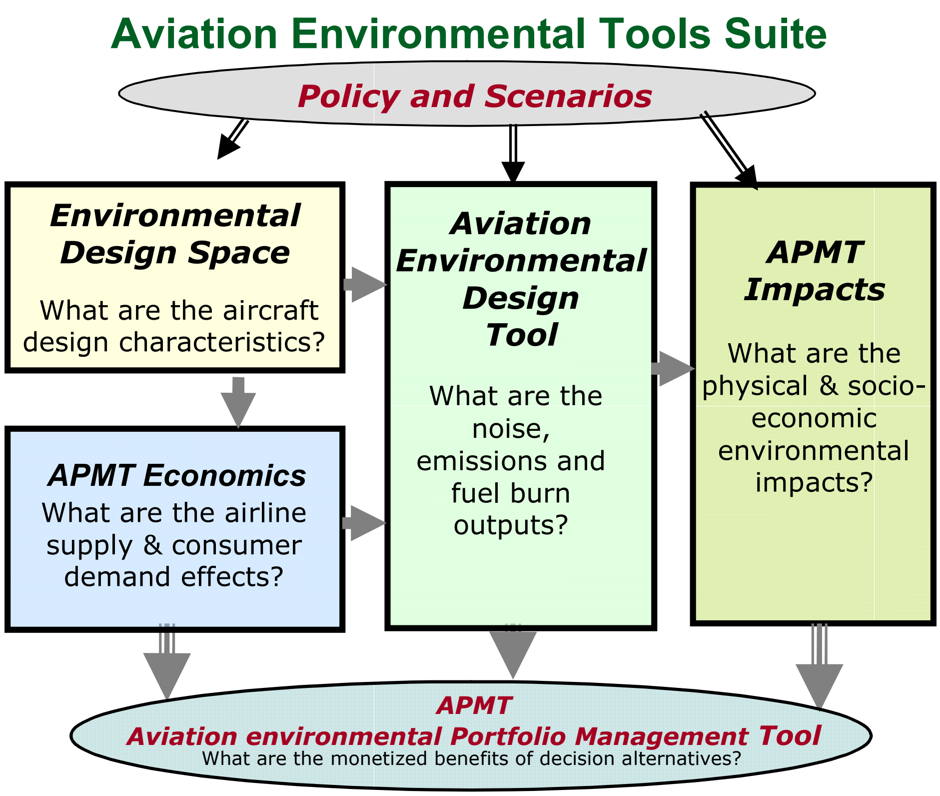


Figure 1.1: Modelling Blocks within the Aviation Environmental Tools Suite

8 APMT and EDS development is through the Partnership for AiR Transportation Noise and Emission Reduction (PARTNER) program.

1.4 APMT-Economics

1.4.1 APMT-Economics is designed to model aviation market responses to a range of aviation scenarios and environmental policy measures that directly affect the aviation industry. The model is centred on the decisions that would be made by airlines in response to future market conditions where these decisions lead to changes in aviation demand, supply and environmental factors. It operates at a relatively disaggregate spatial level of detail, but includes a detailed representation of individual aircraft types, aircraft ages and fleets.

1.4.2 From an established Datum (Base) year database of air transport demand, supply and costs, APMT-Economics projects the future aviation:

- operating costs;
- demand projections and capacity requirements;
- fleet development projections; and
- fleet assignment to an aggregate set of operations.

1.4.3 APMT-Economics produces a set of internally consistent forecasts of the Baseline (projection without scenario measures) and Policy (projection with scenario measures) situations, allowing for a wide range of aviation industry and consumer responses to the potential introduction of environmental policy measures.

1.4.4 A number of different types of main policy responses are distinguished, specifically:

- **supply side responses**: airlines changing their fleet mix and/or characteristics of aircraft in their fleet and measures considered as evasive responses such as responses of airlines or airline clients to avoid payment of a charge or taxation;
- **demand side responses**: changes in air transport demand through fare increases following from cost increases; and
- **operational responses**: airlines changing their flight operation to off-set policy induced cost increases.

1.4.5 The main objective of APMT-Economics is to establish a comprehensive projection of air transport demand and supply, while taking into account:

- the need for additional future aircraft capacity, given the projected air transport demand and the retirement of aircraft from the existing fleet;
- a scenario and policy sensitive selection of fleet replacement and flight operations; and
- the cost-driven relationships between demand and supply.

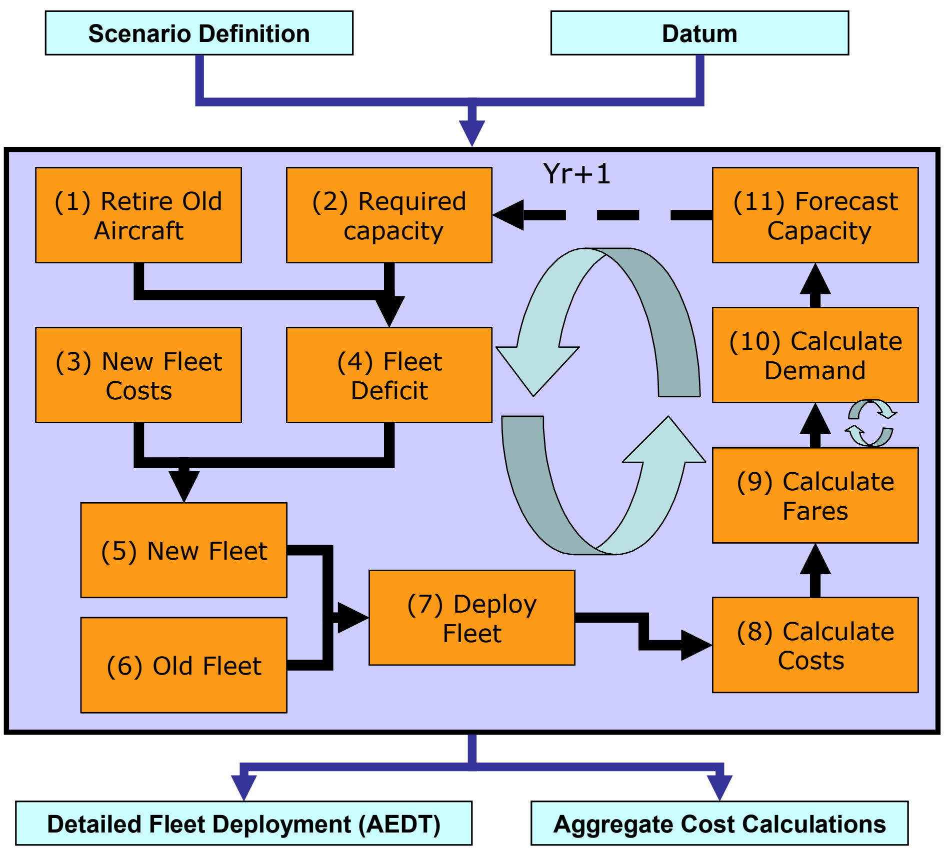
1.4.6 The matching of demand and supply within APMT-Economics is based on a so-called partial equilibrium approach. In this approach, the analysis of changes is limited to the market for air transport only, without directly taking into consideration how changes in the air transport market might imply changes in other markets. In the context of APMT, this means that a new equilibrium is brought about in the market for air travel after a change in policy, and the impact of that change on the travelling public and air carriers. Within the APMT-Economics functionality, changes in costs to air carriers are translated into changes in air fares, leading to an adjustment of air transport demand. Where appropriate, exogenous impacts that are consistent with the scenario specification can also be input to the model; for example, some research has shown that higher fuel prices could lead to lower GDP and while APMT-Economics would not compute the GDP impacts directly, these could be input to the model as part of the scenario specification.

1.4.7 Main functional requirements of APMT-Economics include:

- the handling of different **Baseline** projections of relevant factors affecting air transport demand (passengers and freight) and air transport supply (fleet development and flight operations);
- the assessment of alternative aviation scenarios and the impact of a variety of different air transport related environmental policy measures;
- the provision of a coherent and detailed description of present and future air transport activities (flight operations) on global, regional, national and local scale; and
- the provision of a detailed set of inputs for the computation of the economic impacts on relevant actors in terms of costs, revenues and other direct economic effects.

Figure 1.2 is a diagram of the main steps in the APMT-Economics tool.

Figure 1.2 Main processes in APMT-Economics



1.4.8 Given the present air transport demand and operations for a set reference or Datum year, an aggregate future air transport demand projection (in terms of passengers and freight by country pair) is provided from external sources. Future fleet capacity is adjusted to match demand requirements, taking into account the retirement of aircraft from the existing fleet. Newly purchased aircraft to replace and expand existing fleet capacity are drawn from a set of candidate aircraft designs based on both existing and new technology.

1.4.9 The actual selection of newly purchased aircraft depends on the set of eligible candidate designs and a comparison of unit aircraft operating costs (costs per seat). In this selection process, the effects of policies (such as operating restrictions or charges that increase certain cost components) are taken into account. Changes in aircraft operating costs due to the effects of policies may lead to a change in fares, subsequently leading to a change in demand. Based on a translation of changes in unit costs to changes in fares, the partial equilibrium between air transport demand and supply is approximated within the APMT-Economics module.

1.4.10 Following the achievement of the partial equilibrium, the (adjusted) information on demand projection, aircraft retirements and aircraft replacements for the forecast situation is provided to AEDT. In contrast with the APMT-Economics module, which operates on a country-pair[9] level of spatial aggregation, AEDT works on the level of individual airport pairs with fully specified aircraft flight characteristics. Given the specification of the detailed flight operations in the present situation (based on the information in the Current Air Transport Database), the information provided by the APMT-Economics module is used to make the detailed future flight operations projection as required by the AEDT. The detailed forecasts are generated by applying a series of distributions to the APMT-Economics aggregate forecasts. These distributions apply splitting factors for country pair to city pair, engine family to UID and carrier region to carrier code.

1.4.11 Within the APMT-Economics module, detailed computations of aircraft operating costs take place for all relevant aircraft types, as well as computations of air fares and revenues. The information on costs and revenues generated in the APMT-Economics module provides the basis for the assessment of actor specific direct economic impacts. In addition to the air carriers, relevant actors might include: manufacturers, airports, the air traffic management operators, and the repair, overhaul and maintenance sector, as well as consumers and governments. Direct economic effects may include: (changes in) operating costs, revenues and results, employment effects, loss in fleet value, income from charges and consumer surplus.

1.4.12 Further details of the functionality of APMT-Economics are contained in the Algorithm Design Document (ADD).

9 Each country-pair flow is disaggregated into groups of routes with common stage lengths and the combination of country-pairs and stage lengths are referred to as 'schedules'.

2 Validation of the Datum Situation

2.1 Overview

2.1.1 This chapter summarises the validation of the Datum and Baseline for the version of APMT-Economics used for the analysis of global fuel burn and CO_2 emissions trends for the aviation industry. It is important that the model validates well against available data in order that it may be considered to be a reliable basis from which to analyse the impact of introducing aviation policies.

2.1.2 The 2006 Datum was developed from a one week sample of operations from AEDT[10]. The data was processed to remove freighter operations and passenger aircraft with fewer than 20 seats. The data was then matched to fleet data for 2006 from the ICAO CAEP Forecasting and Economics Support Group (FESG) to provide the characteristics of the fleet undertaking the operations. This data provided the starting point to which the FESG demand and supply forecasts were applied to establish the Baseline.

2.2 Supply and Demand

2.2.1 The validation of the Datum was undertaken against available data from FESG, ICAO and AEDT. Table 2.1 contains a summary of the supply and demand validation at a global level.

Table 2.1 Datum Year Validation/Calibration at 2006 Global Supply and Demand

Metric	APMT-Economics	Observed	Δ	% Δ	Observed Data Source
Total Aircraft	18773	18773	0	0%	FESG Passenger Fleet
Operations (m)	25	27	-2	-7%	ICAO (includes freight)
Distance (bn km)	34	34	0	0%	ICAO
Passenger km (bn km)	4404	4222	181	-1%	ICAO
Passenger load factor (%)	75	76	-1	0%	FESG
Fuel (kg) per km	5.07	5.07	0.00	0%	AEDT

2.2.2 The average aircraft utilisation rates (aircraft hours per annum) have been calibrated so that APMT-Economics matches the number of aircraft in the FESG fleet. The calibration has been undertaken on a seat class basis, so each seat class replicates the corresponding FESG value.

2.2.3 Data from ICAO suggests that there were approximately 27 million movements per annum in 2006. The current version of APMT-Economics contains only passenger operations on aircraft with greater than 20 seats. APMT-Economics uses operations data from the CAEP Modelling and Database Task Force (MODTF) 2006 Common Operations Database (COD), which contains 25

10 The underlying data was drawn from a development version of the CAEP MODTF 2006 Common Operations Database in August 2008. Some detailed aspects of this underlying database have since been revised for use in CAEP/8 analysis, but were not available in time to be incorporated as the underlying aviation activity database for this analysis.

million passenger flights and other data received indicates that there are around 2 million freight operations. Therefore the number of operations in APMT-Economics closely represents the observed data from ICAO.

2.2.4 The number of aircraft kilometres (34 billion km) operated in 2006 according to ICAO is replicated by APMT-Economics. The passenger demand estimates in APMT-Economics have been taken directly from the FESG observed data. APMT-Economics has slightly higher passenger kilometres in the Datum than the ICAO equivalent.

2.2.5 The average fuel per km has been calibrated to match the data for AEDT.

2.2.6 This study included results that isolated the impact to the United States, and therefore the validation at this level is also important. APMT-Economics was calibrated at a global level but ICAO does produce a small amount of data for the North America region that can be used for validation. Table 2.2 contains a summary of the validation of North American operations in APMT-Economics against the data available from ICAO.

Table 2.2 Datum Year Validation at 2006 North American Supply and Demand

Metric	APMT-Economics	Observed	Δ	% Δ	Observed Data Source
Operations (m)	10	11	-1	-5%	ICAO (includes freight)
Distance (bn km)	14	14	0	2%	ICAO
Passenger km (bn km)	1509	1387	122	9%	ICAO

2.2.7 The North American data from APMT-Economics again validates well against the data published by ICAO. The passenger operations in this region in APMT-Economics may be higher than in the ICAO data as there are only 5% less operations than the combined freight and passenger total in ICAO and the passenger kilometre value is 9% greater than the ICAO value.

2.3 Costs and Revenues

2.3.1 ICAO also produces cost and revenue data that was used for validation and calibration of the Datum representation in APMT-Economics. A summary of the validation is shown in Table 2.3.

2.3.2 Validating against costs and revenues is not as straightforward as validating against supply and demand data, given different reporting of the data by aircraft type. Average operating costs for individual aircraft types in APMT-Economics are based on Form 41, reported regional variations in labour costs, aircraft prices from AVMARK, fuel use from AEDT, and the average Quarter 1 fuel price for 2006. Fares were calibrated so that the global profit margin reported by ICAO for 2006 was achieved.

Table 2.3 Datum Year Validation/Calibration at 2006 Global Costs and Revenues

Metric	APMT-Economics	Observed	Δ	% Δ	Comment
Crew costs ($bn)	32	32	0	0%	ICAO (APMT-Economics excludes freight)
Maintenance costs ($bn)	39	42	-3	-8%	ICAO (APMT-Economics excludes freight)
Depreciation & Finance ($bn)	59	62	-3	-5%	ICAO (APMT-Economics excludes freight)
Landing costs ($bn)	15	16	-1	-7%	ICAO (APMT-Economics excludes freight)
Route costs ($bn)	9	10	-1	-9%	ICAO (APMT-Economics excludes freight)
Total fuel cost ($bn)	104	106	-2	2%	ICAO 2005 factored to 2006 prices
Operating expenses ($bn)	400	439	-39	-9%	ICAO (includes freight)
Unit costs (Op exp/ATK) U.S. cents	76.0	71.0	5.0	7%	ICAO (includes freight)
Operating revenues ($bn)	413	452	-39	-9%	ICAO (includes freight)
Yields (Op rev/RTK) U.S. cents	100.9	96.0	4.9	5%	ICAO (includes freight)

2.3.3 The results that airlines report to ICAO are open to considerable interpretation about the data items that go into each category and therefore we have allowed a higher deviation from the validation data. Table 2.3 shows that APMT-Economics is within 10% on all items which is considered to be an acceptable level of validation, given a level of uncertainty in the reported aggregate data.

2.3.4 The validation against crew costs is very close as the overall unit labour costs have been adjusted downward on a regional basis to meet the overall target. The data from ICAO includes freighter crew so the APMT-Economics crew costs may be around 1% high.

2.3.5 The maintenance costs in APMT-Economics are lower than the reported level from ICAO, which does include freight. Freight fleets are typically older than passenger fleets and therefore require more maintenance, so the APMT-Economics value would increase once the freighter operations are added.

2.3.6 Capital, landing and route costs in APMT-Economics are close to, but slightly less than the ICAO equivalents. Capital costs in APMT-Economics include all ownership and leased costs since it is not possible to separate these costs, and they must all be included for the fleet selection algorithm in APMT-Economics.

2.3.7 APMT-Economics uses fuel consumption data from AEDT and an average fuel price of 60 U.S. cents/kg, with regional variation from ICAO data. The resulting overall fuel cost in APMT-Economics is very close to that published by ICAO.

2.3.8 Overall Operating Expenses and Revenues in APMT-Economics are of a similar magnitude but slightly less than the data reported by ICAO. The yields and unit costs in APMT-Economics are 5-7% higher than the ICAO data which is again driven by the current exclusion of freight operations which have considerably lower yields and unit costs than passenger operations. The inclusion of freight operations to APMT-Economics should lead to a further improvement in the validation.

2.3.9 At a global level, the cost and revenue results of APMT-Economics appear to validate well against the ICAO data.

2.3.10 Only a small number of cost and revenue metrics were available from the ICAO data for the North American region. A comparison of corresponding data from APMT-Economics is provided in Table 2.4.

Table 2.4 Datum Year Validation at 2006 North American Costs and Revenues

Metric	APMT-Economics	Observed	Δ	% Δ	Comment
Operating expenses ($bn)	131	156	-25	-16%	ICAO (includes freight)
Unit costs (Op exp/ATK) U.S. cents	76.1	78.0	-1.9	-2%	ICAO (includes freight)
Operating revenues ($bn)	135	163	-28	-17%	ICAO (includes freight)
Yields (Op rev/RTK) U.S. cents	99.8	111.0	-11.2	-10%	ICAO (includes freight)

2.3.11 As with the global data, the APMT-Economics cost and revenue data for North America is less than the ICAO published data. The operating expenses and revenues would be increased in APMT-Economics with the addition of freight operations, however, the yields and unit costs would decrease slightly from their current values.

2.4 Summary

2.4.1 In this chapter we have summarised the APMT-Economics Datum year validation against data published by ICAO. This validation has shown that at a global level, APMT-Economics validates well against the published data. The model was calibrated at the global level however the validation at the North American regional level is also satisfactory.

3 Scenarios and Assumptions

3.1 Overview

3.1.1 APMT-Economics, from the Aviation Environmental Tools Suite, was used to analyse global fuel burn and CO_2 emissions trends, given a range of aviation and fuel price scenarios and considering:

- The potential for aircraft technology improvements and the potential for air traffic management operational improvements (both global and U.S. only);
- Impacts of fuel prices on disposable income and hence the demand for aviation; and
- Air transport demand projections based on the recent and current economic conditions.

3.1.2 The APMT-Economics analysis considers the following responses:

- Exogenous impact of energy prices on GDP and underlying aviation demand growth;
- Internally consistent scenarios reflecting the extent to which airlines could raise capital and pass increasing costs onto consumers through fare increases;
- Demand responses to increasing airline costs and fares;
- Purchase of improved technology aircraft designs (where these are available);
- Availability of improved airspace management technology to reduce airborne delays; and
- Accelerated retirement of least fuel efficient aircraft designs.

3.1.3 The underlying traffic growth for this analysis is derived from the CAEP/8 FESG central case scenario. However, it is recognised that the FESG scenario, with its basis in 2006, does not take into account the recent economic and market impacts on the aviation industry. In particular, traffic growth over the past two years has been low, as a combination of high fuel prices and economic conditions. Short-term forecasts now anticipate that traffic may fall in 2009 and 2010 with a recovery to 2006 demand and traffic levels not likely until 2011/2012. We have sought to capture these impacts in some of our scenarios by adjusting the FESG forecasts in the short term on the basis of the most recent (November 2008) U.S. FAA Aviation Policy Office projections.

3.1.4 The FAA Analysis Baseline case scenario assumes no rise in fuel prices or other aviation costs is considered from the Datum situation. We calibrated the APMT-Economics inputs to ensure that the FESG forecast trends in load factors, trip lengths and fleet development by seat class are reproduced in the FAA Analysis Baseline Case.

3.1.5 The further scenarios that we have modelled build upon the Baseline by constructing alternative, but consistent, sets of assumptions to demonstrate the potential impacts of:

- Technology impacts, and this analysis effort was also conducted with consideration of both CAEP FESG, Working Group 3 and U.S. Next Generation Air Transportation System (NextGen)[11] reference data; and

11 The Next Generation Air Transportation System (NextGen) is a long-term transformation initiative to increase the efficiency, safety, and capacity of the U.S. national airspace system and at the same time reduce aviation emissions, in part, by transforming the current air traffic control system. This effort involves new technologies and air traffic procedures that will contribute to reducing aviation emissions and incorporates research and development on emissions-reduction technologies.

- A Future trend where there is a rise in fuel prices and market-based GHG measures are introduced.

3.2 Aircraft Technology

3.2.1 Future technology assumptions are based on CAEP Working Group 3 scenarios. Two levels of improvements to fuel use efficiency technology are considered that are assumed to be available at no additional cost to the industry reflecting:

- a *low trend-based* new aircraft technology improvement, which equates to an average 1% per annum improvement in fuel use for new aircraft entering service over the entire forecast period.
- An *optimistic* trend in new aircraft technology improvement, which equates to an average 1.5% per annum improvement in fuel use for new aircraft entering service over the entire forecast period.

3.2.2 APMT-Economics has been constructed to operate with discrete aircraft types which it is assumed would be introduced to reflect potential step changes in aircraft technology and therefore the trend-based assumptions need to be incorporated into the model as discrete steps.

3.2.3 The low trend-based new aircraft technology assumption is employed in the FAA Analysis Baseline Case.

3.3 Air Transport System Operational Improvements

3.3.1 The potential for **aircraft operational efficiency improvements** are based on those used in the NextGen High Density analysis, and their application in this analysis is summarised in Table 3.1. As with the aircraft technology improvements, it has been assumed that the improvements to operational efficiency have been at no additional cost to the industry.

Table 3.1 Operational Improvement Assumptions

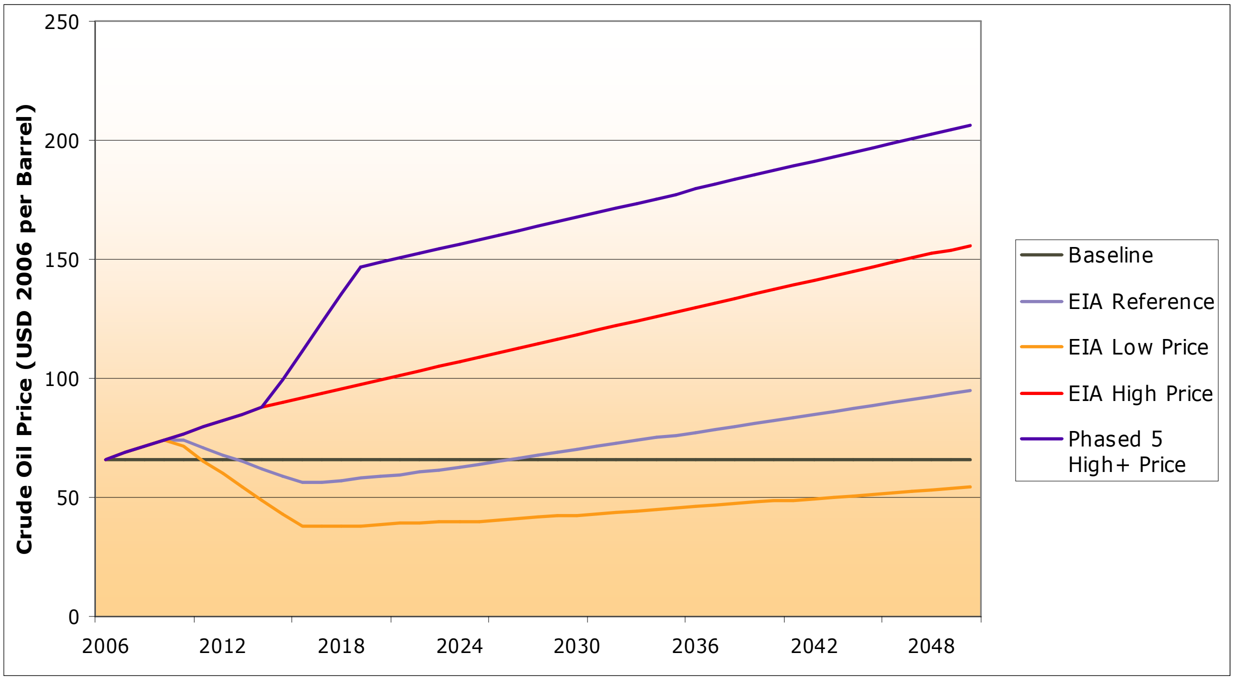
Geographic Scope	Airspace Operational Efficiency Improvement
United States	Flight distance was assumed to be reduced by 3% at 2015 and by 10% at 2025
Rest of World	Flight distance was assumed to be reduced by 3% at 2020 and by 10% at 2030

3.3.2 No airspace operational efficiency improvements are assumed for the FAA Analysis Baseline Case beyond those which would be required to maintain the current level of delay and routing.

3.4 Fuel Price Scenarios

The U.S. Energy Information Administration (EIA) International Energy Outlook for 2008 presents a number of energy price and consumption scenarios. The "High" price scenario defined in this document was used as the basis for the **fuel price scenarios** in this analysis. In addition to this scenario, we considered no change in price in the Baseline, and a "High-plus" scenario containing additional market based GHG measures, phased in over 5 years[12]. The scenarios are illustrated in terms of the real price per barrel in Figure 3.1. The values up to 2050 have been generated by extrapolating the trends from 2026 to 2036.

Figure 3.1 Fuel Price Scenarios Considered



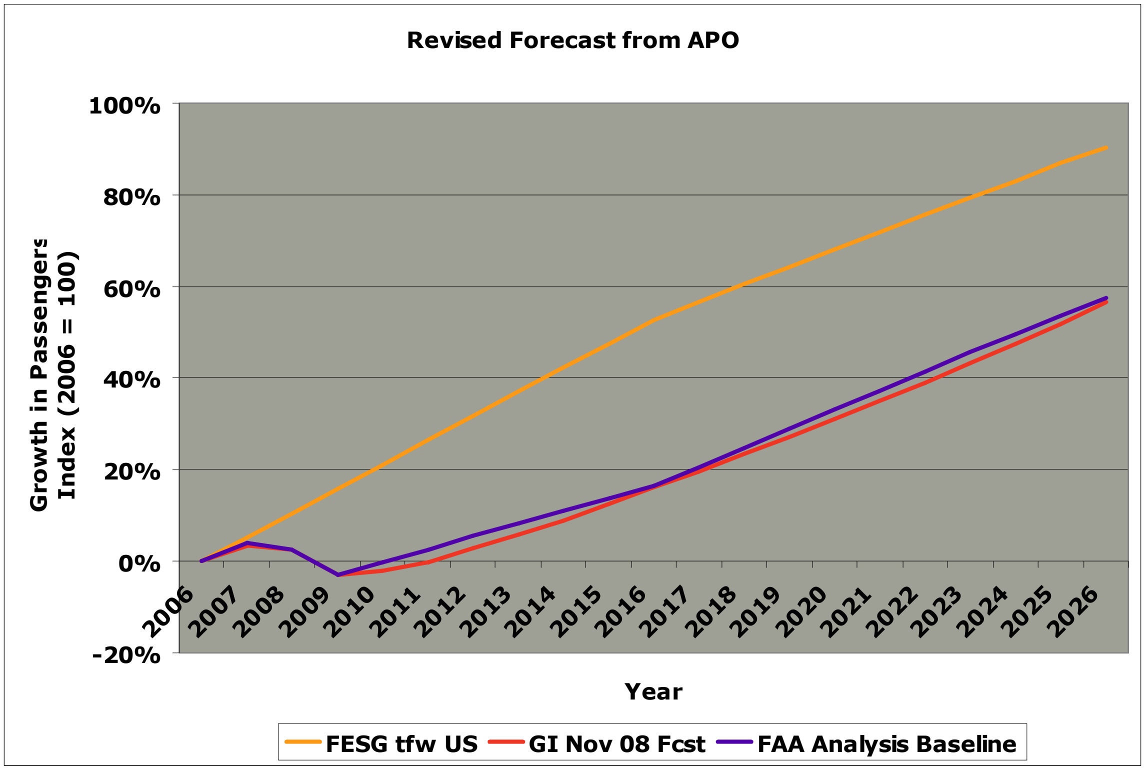
3.4.2 The FAA Analysis Baseline Case is based on a default assumption of no real change in energy or aviation fuel prices for the whole of the forecast period.

3.5 FAA Analysis Baseline Demand Forecasts

3.5.1 As noted above the FAA Analysis Baseline is derived from adjusting the underlying CAEP/8 FESG forecast to account for the current economic climate and aviation market. The short term element of the projection for aviation activity used in APMT-Economics is based on the FAA's U.S. air passenger demand forecasts from November 2008. These forecasts suggest that there would be fewer passengers in 2009 and 2010 than there had been in 2006, with the 2006 level of patronage only exceeded in 2011/2012. Figure 3.2 compares the FAA November forecasts and the CAEP/8 central case FESG forecast for passengers travelling on U.S. operations. This figure also shows the outturn U.S. passenger growth resulting from implementing the FAA Baseline in APMT-Economics based on a combination of information from FESG and U.S. FAA.

12 Noted on the chart as "Phased 5 High+ Price"

Figure 3.2 Comparison of FAA Forecasts and Recent Year Observed Data



3.5.2 The FAA Analysis Baseline follows the profile of the FAA November 2008 passenger growth curve in the short term to 2012, including reported traffic for 2007 and 2008. For the remaining years the FESG demand growth curves were essentially shifted by around 5 years such that the growth in the period 2012 to 2016 is consistent with the growth from 2006 to 2011 in the Baseline forecast. On the basis of available data, the same pattern of adjustment was made to both the U.S. and Global projections used by APMT-Economics. The FAA Baseline results from extrapolating the ICAO FESG CAEP/8 central case forecast from 2036 out to 2050.

4 Analyses and Results

4.1 Introduction

4.1.1 The preceding chapters present an overview of APMT-Economics, the background to the analysis and the analysis assumptions and scenarios. Each test from APMT-Economics produces a range of metrics across the forecast period of 2006 to 2050 and these outputs can also be analysed at a spatially disaggregate level[13]. For each test there is therefore a vast amount of detailed information that we can draw upon in describing the results of the analysis and to support its conclusions.

4.1.2 In conducting the analysis we have undertaken a large number of tests to explore the contributions of technology improvements, various demand and economic scenarios and the impact of a range of future fuel price assumptions. In this report we have focused on presenting the results from just three key tests where the aim of the analysis and reporting is to illustrate a potential range of growth in demand, supply (fleet and operations) and fuel burn. The key tests presented are:

- **The FAA Analysis Baseline**;
- The FAA Analysis Baseline with **Alternative Scenario A**: the Baseline with an assumption of an optimistic scenario for the development of new aircraft fuel burn technology and high levels of airspace operational efficiency; and
- The FAA Analysis Baseline with **Alternative Scenario B**: the Baseline with the optimistic and high airspace operational technology scenario with the assumption of higher fuel prices plus and an environmental charge on fuel use.

4.1.3 We have concentrated on providing the following metrics as being indicators of the percentage (and absolute) impacts stakeholders in the aviation industry relative to the Baseline projections and to the 2006 Datum year:

- **Airlines**: Seat Km to indicate volume of supply and network growth, Total Cost, Cost per Seat Km, (Operating) Net Profit
- **Environment**: Fuel Use, Fuel Efficiency (kg fuel per 1000 seat km)
- **Consumers**: Passenger kilometres
- **Manufacturers**: Fleet size

4.1.4 The results are presented for two groups of spatial aggregation:

- At a Global level; and
- For routes to/from and within the United States, denoted U.S. only routes in the tables and figures.

4.1.5 Table 4.1 provides a summary of the input assumptions used for each of the three core scenarios tested. The FAA Analysis Baseline provides a benchmark for the alternative scenarios and the model is constructed to ensure that the inputs and outputs from all of the scenarios modelled from this common Baseline are internally consistent. This consistency is important

13 The model stores data at the level of country pair and stage length.

and is achieved by the model applying changes in inputs through time relative to Baseline to generate the alternative scenarios on a responsive basis. For example, if a higher fuel price is to be applied in an alternative scenario then the input specification requires that the alternative fuel price assumption and its timeline profile are provided to the model. The model then produces the alternative forecast as an adjustment relative to the underlying Baseline, thereby ensuring consistency of all of the other assumptions.

4.1.6 The analysis has only included passenger aircraft operations and demand.

Table 4.1 Core Test Scenario Summary

Core Scenario	Air Transport Growth	New Aircraft Fuel Use Technology	Airspace Operational Efficiency	Fuel Price Change
FAA Analysis Baseline	Short-term demand adjusted to reflect economic downturn	Low Trend-based new aircraft improvement (average 1% per annum)	No Additional Delays compared to Datum	None/ EIA Low
FAA Analysis Baseline with Alternative **Scenario A**	*Short-term demand adjusted to reflect economic downturn*	Optimistic trend new aircraft improvement (average 1.5% per annum)	High for U.S., with a 5 year lag before equivalent global improvement	*None/ EIA Low*
FAA Analysis Baseline with Alternative **Scenario B**	*Short-term demand adjusted to reflect economic downturn*	Optimistic trend new aircraft improvement (average 1.5% per annum)	High for U.S., with a 5 year lag before equivalent global improvement	High-plus phased over 5 years

The common assumptions for each alternative scenario relative to the Baseline case are shown in italics.

4.2 FAA Analysis Baseline

4.2.1 As we have described in Chapter 3, the FAA Analysis Baseline projection was generated from a combination of U.S. FAA short term projections and the FESG forecasts of demand and supply for 2016, 2026 and 2036, by route group and seat class, which were applied to the Datum representation.

4.2.2 The Baseline projection assumes no real changes in any of the **unit** cost components through time: thus, fuel price, labour costs, landing fees, route charges, volume related costs and maintenance costs all remain the same as the Datum values. The profit margin per passenger that was achieved in the Datum is also maintained through the Baseline projections. Aircraft in the Baseline are retired according to the retirement curves calibrated by FESG, based on historic data. As indicated above, replacement aircraft for the Baseline projections must come from a set of new replacement aircraft which are assumed to improve on average according to a low technology trend improvement in fuel burn of 1% per annum.

4.2.3 A snapshot of the relative changes in the model outputs at forecast years of 2016, 2026 and 2036 and the projection to 2050 is presented in Figure 4.1 and Figure 4.2. A further series of graphs illustrating the trend lines for the change in key metrics in the FAA Analysis Baseline projections are contained in separate documentation. In summary, the key trends in demand, supply, costs and fuel use in the FAA Analysis Baseline projection are:

- Growth in Passenger kilometres is larger than for seat kilometres – implying higher load factors (consistent with the underlying FESG scenario assumptions). Globally FAA Analysis Baseline assumptions would result in an increase in passenger kilometres of nearly 500% over the 2006 level, and over 250% for U.S. travel.
- Forecasts of Aircraft Operations grow faster than fleet – due to increased aircraft utilisation (again consistent with the underlying FESG scenario assumptions). Globally the Baseline increase in aircraft operations is projected to increase by 300% between 2006 ands 2050 and double for the U.S. over the same period.
- Total airline operating costs grow more slowly than passenger kilometres, partly driven by fuel efficiencies but also the changes in aircraft sizes and associated crew to passenger ratio efficiencies.
- There is a default assumption of a constant margin on each unit of demand (and capacity) which results in the forecast potential net profit being expected to increase at a rate that is similar to that of the growth in seat kilometres and passenger kilometres.

4.2.4 In terms of the fuel use forecast, the key driver is the fuel efficiency (RTK/Fuel Used) which increases by about 40% globally by 2036, (37% in the U.S.)[14]. This is brought about by the impact of today's aircraft penetrating through the fleet over a 30-year period, increases in load factors and changes in aircraft size type and distance travelled leading to fuel use efficiencies. At 2050 the fuel efficiency for the overall fleet is expected to increase by approximately 60% compared to 2006.

14 Fuel efficiency is also noted as the reciprocal of the measure used here (ie Fuel/RTK). In these terms the fuel used per RTK, by 2036 this is projected to fall by 29% at a global level and by 27% for the U.S.

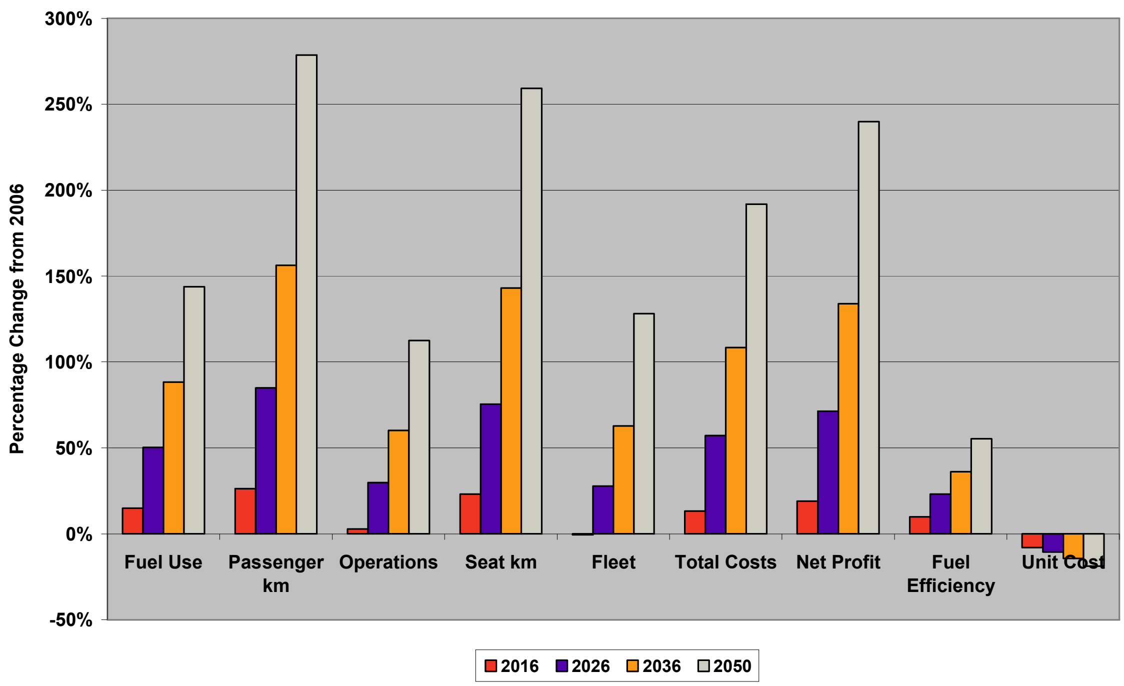


Figure 4.1 U.S. Projected Baseline Trends in Air Transport Demand, Supply, Costs, Revenues and Net Profit

Absolute

Indicator	Units	2006	2016	2026	2036	2050
Fuel Use	billion kg pa	68	79	103	129	167
Passenger km	billion pax-km pa	1692	2138	3129	4336	6407
Operations	million flights pa	10	10	13	16	21
Seat km	billion seat-km pa	2141	2635	3758	5204	7690
Fleet	number of aircraft	8263	8219	10566	13445	18854
Total Costs	billion 2006 US $	161	182	252	335	469
Net Profit	billion 2006 US $	1.6	1.9	2.8	3.8	5.5
Fuel Efficiency	kg per 1000 passenger km	40.4	36.8	32.8	29.7	26.0
Unit Cost	2006 US $ per seat km	0.075	0.069	0.067	0.064	0.061

% Change from 2006

Indicator	Units	2006	2016	2026	2036	2050
Fuel Use		-	15%	50%	88%	144%
Passenger km		-	26%	85%	156%	279%
Operations		-	3%	30%	60%	112%
Seat km		-	23%	76%	143%	259%
Fleet		-	-1%	28%	63%	128%
Total Costs		-	13%	57%	108%	192%
Net Profit		-	19%	71%	134%	240%
Fuel Efficiency		-	10%	23%	36%	55%
Unit Cost		-	-8%	-10%	-14%	-19%

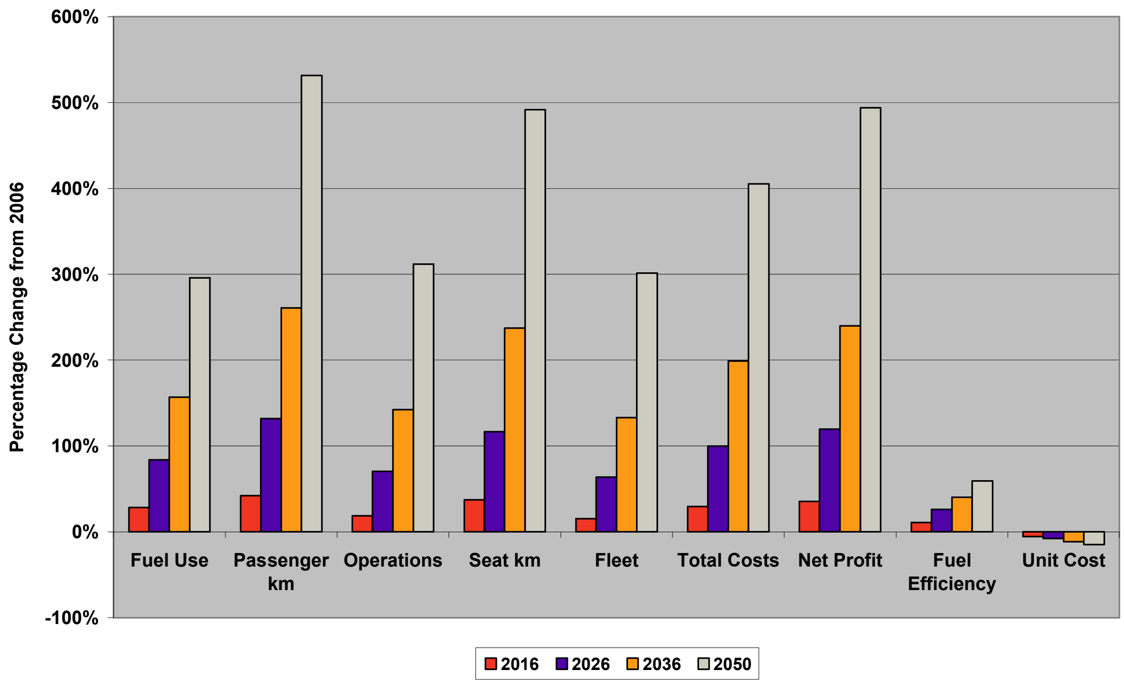


Figure 4.2 Global Projected Baseline Trends in Air Transport Demand, Supply, Costs, Revenues and Net Profit

Absolute

Indicator	Units	2006	2016	2026	2036	2050
Fuel Use	billion kg pa	174	224	321	448	690
Passenger km	billion pax-km pa	4140	5884	9610	14943	26141
Operations	million flights pa	25	30	43	61	103
Seat km	billion seat-km pa	5492	7542	11901	18531	32497
Fleet	number of aircraft	18773	21644	30722	43771	75380
Total Costs	billion 2006 US $	426	552	852	1274	2156
Net Profit	billion 2006 US $	4.3	5.8	9.5	14.6	25.6
Fuel Efficiency	kg per 1000 passenger km	42.1	38.0	33.4	30.0	26.4
Unit Cost	2006 US $ per seat km	0.08	0.07	0.07	0.07	0.07

% Change from 2006

Indicator	Units	2006	2016	2026	2036	2050
Fuel Use		-	28%	84%	157%	296%
Passenger km		-	42%	132%	261%	531%
Operations		-	19%	70%	142%	312%
Seat km		-	37%	117%	237%	492%
Fleet		-	15%	64%	133%	302%
Total Costs		-	29%	100%	199%	406%
Net Profit		-	35%	120%	240%	494%
Fuel Efficiency		-	11%	26%	40%	59%
Unit Cost		-	-6%	-8%	-11%	-15%

4.3 Comparing the FAA Analysis Baseline with Alternative Scenarios

4.3.1 We have considered additional scenarios to explore the range of potential fuel use outcomes up to 2050, relative to 2006. In particular, we sought to understand the impact of further improvements in aircraft and operating efficiency technology and then the potential outcomes that would arise if we assumed increases in effective fuel prices. The further technology impacts are illustrated by incorporating both the optimistic new technology aircraft available as future new aircraft and introducing global air traffic management airspace operational efficiencies. The impact of higher fuel prices is tested through running APMT-Economics with the EIA High-plus scenario containing additional market based GHG measures that are assumed to potentially reach an equivalent of over USD 200 per barrel by 2050.

4.3.2 Figure 4.3 and Figure 4.4 show the affects of the FAA Analysis Baseline and the two alternative scenarios at 2036 relative to 2006 for a number of key metrics, globally and for U.S. operations respectively.

4.3.3 In summary:

- With Alternative **Scenario A**: Further technology improvements, through the airspace operational improvements and the optimistic new aircraft technology assumptions, are forecast to result in some additional reductions in unit costs relative to the FAA Analysis Baseline (-9% globally at 2036) that would result in a small relative increase in aviation activity (3% increase in passenger km globally). Significantly, the technology improvements result in an 18% increase in global and U.S fuel efficiency, such that fuel use is forecast to be 12% lower than the FAA Analysis Baseline.
- With Alternative **Scenario B**: The introduction of higher fuel prices to the scenario (representing, in part, market based measures) results in a forecast increase in unit cost from 2006; and, that leads to a reduction in passengers in response to increased fares. Relative to the FAA Analysis Baseline, the unit cost increase is approximately 20% (and which would be 30% except for the mitigating effects of the optimistic technology improvements that are included in the scenario). Thus, the outturn forecast of passenger kilometres is lower by 11% at 2036; and, fuel burn growth is 26% lower than the FAA Analysis Baseline in 2036. There is a small improvement in fuel efficiency in comparison to the same scenario with the Baseline fuel price, where the model predicts that airlines will adjust their aircraft purchases in striving to lower their costs in response to the increased fuel price.

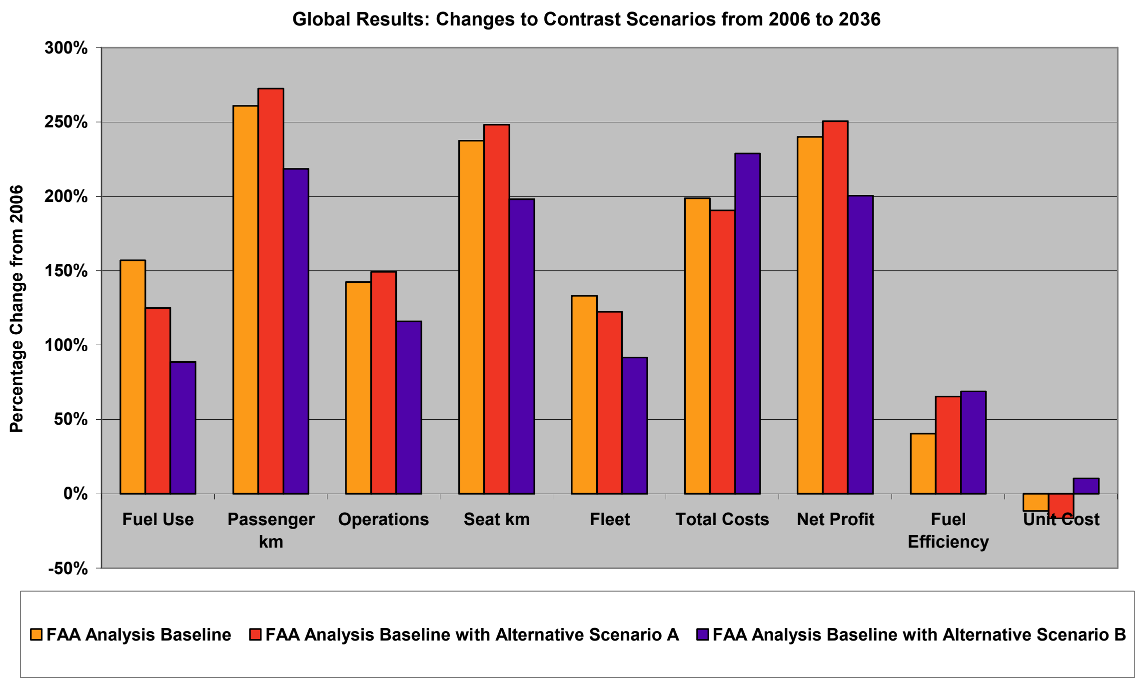


Figure 4.3 Comparison of Scenario Outputs at 2036 Relative to 2006 - Global

			2036		
Indicator	**Units**	**2006**	**FAA Analysis Baseline**	**FAA Analysis Baseline with Alternative Scenario A**	**FAA Analysis Baseline with Alternative Scenario B**
Fuel Use	billion kg pa	174	448	392	329
Passenger km	billion pax-km pa	4140	14943	15418	13184
Operations	million flights pa	25	61	63	54
Seat km	billion seat-km pa	5492	18531	19119	16371
Fleet	number of aircraft	18773	43771	41739	35973
Total Costs	billion 2006 US $	426	1274	1239	1402
Net Profit	billion 2006 US $	4.3	14.6	15.1	12.9
Fuel Efficiency	kg per 1000 passenger km	42.1	30.0	25.4	24.9
Unit Cost	2006 US $ per seat km	0.078	0.072	0.065	0.086

% Change from 2006

			2036		
Indicator	**Units**	**2006**	**FAA Analysis Baseline**	**FAA Analysis Baseline with Alternative Scenario A**	**FAA Analysis Baseline with Alternative Scenario B**
Fuel Use		-	157%	125%	89%
Passenger km		-	261%	272%	218%
Operations		-	142%	149%	116%
Seat km		-	237%	248%	198%
Fleet		-	133%	122%	92%
Total Costs		-	199%	191%	229%
Net Profit		-	240%	251%	201%
Fuel Efficiency		-	40%	66%	69%
Unit Cost		-	-7%	-17%	10%

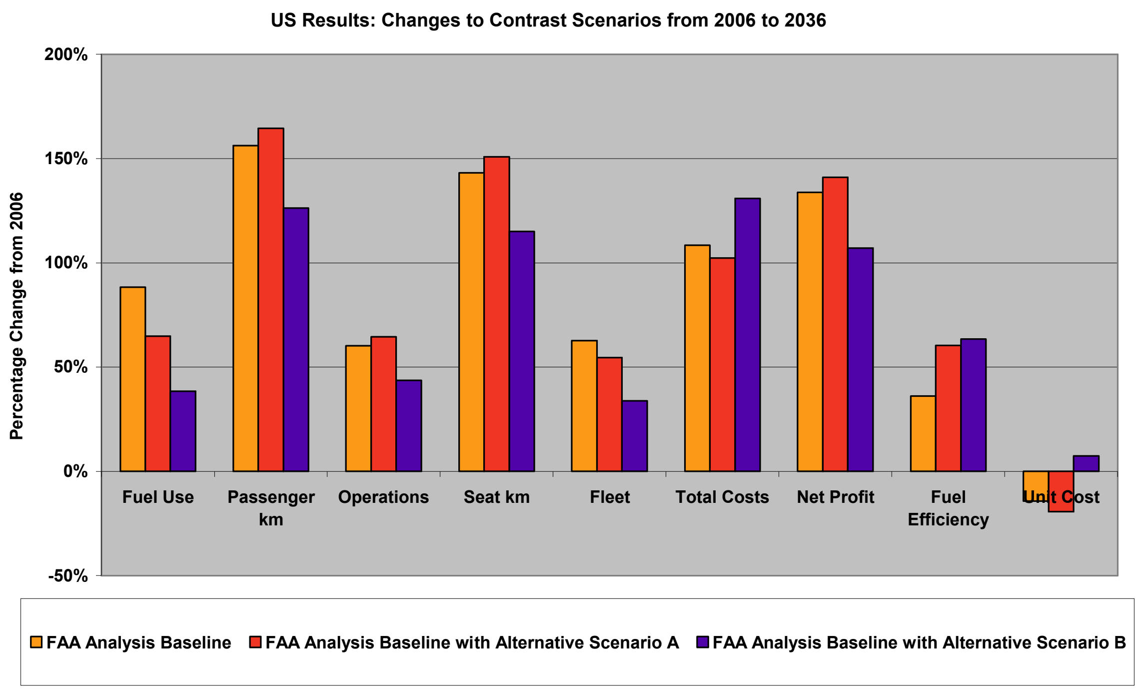


Figure 4.4 Comparison of Scenario Outputs at 2036 Relative to 2006 – U.S.

Absolute

Indicator	Units	2006	2036: FAA Analysis Baseline	2036: FAA Analysis Baseline with Alternative Scenario A	2036: FAA Analysis Baseline with Alternative Scenario B
Fuel Use	billion kg pa	68	129	113	95
Passenger km	billion pax-km pa	1692	4336	4475	3829
Operations	million flights pa	10	16	17	14
Seat km	billion seat-km pa	2141	5204	5371	4602
Fleet	number of aircraft	8263	13445	12768	11054
Total Costs	billion 2006 US $	161	335	325	371
Net Profit	billion 2006 US $	1.6	3.8	3.9	3.4
Fuel Efficiency	kg per 1000 passenger km	40.4	29.7	25.2	24.7
Unit Cost	2006 US $ per seat km	0.075	0.067	0.061	0.081

% Change from 2006

Indicator	Units	2006	2036: FAA Analysis Baseline	2036: FAA Analysis Baseline with Alternative Scenario A	2036: FAA Analysis Baseline with Alternative Scenario B
Fuel Use		-	88%	65%	38%
Passenger km		-	156%	164%	126%
Operations		-	60%	64%	44%
Seat km		-	143%	151%	115%
Fleet		-	63%	55%	34%
Total Costs		-	108%	102%	131%
Net Profit		-	134%	141%	107%
Fuel Efficiency		-	36%	60%	63%
Unit Cost		-	-11%	-19%	7%

4.4 Summary of Passenger Demand and Fuel Use Impacts Across Scenarios

4.4.1 Figure 4.5 presents the forecast percentage changes in global aviation activity, through passenger kilometres, for each of the five scenarios. Figure 4.6 presents the equivalent for U.S. operations. The range of growth in global passenger kilometres from 2006 to 2050 is between 460% and 550% and for the U.S. is between 235% and 290% over the same period. However, there is also a range of fuel efficiency gains in the fleet forecast to be operating over this period resulting in the average fuel use per passenger kilometre reducing from between 35 and 50%.

4.4.2 The resulting changes in the growth in fuel use for each of the five scenarios are shown in Figure 4.7 for global operations and Figure 4.8 for U.S. operations. The range of growth forecast from 2006 to 2050 is between 170% and 300% globally and 70% and 145% for U.S. operations.

Table 4.2 Annual global aviation fuel burn for the FAA Analysis scenarios, million tonnes of fuel

	US Operations			Global Operations		
	FAA Analysis Baseline	FAA Analysis Baseline with Alternative Scenario A	FAA Analysis Baseline with Alternative Scenario B	FAA Analysis Baseline	FAA Analysis Baseline with Alternative Scenario A	FAA Analysis Baseline with Alternative Scenario B
2006	68	68	68	174	174	174
2012	71	71	69	193	193	188
2016	79	77	73	224	221	207
2020	90	87	76	267	262	225
2025	101	96	82	312	297	253
2026	103	95	81	321	303	257
2036	129	113	95	448	392	329
2050	167	137	115	690	565	473

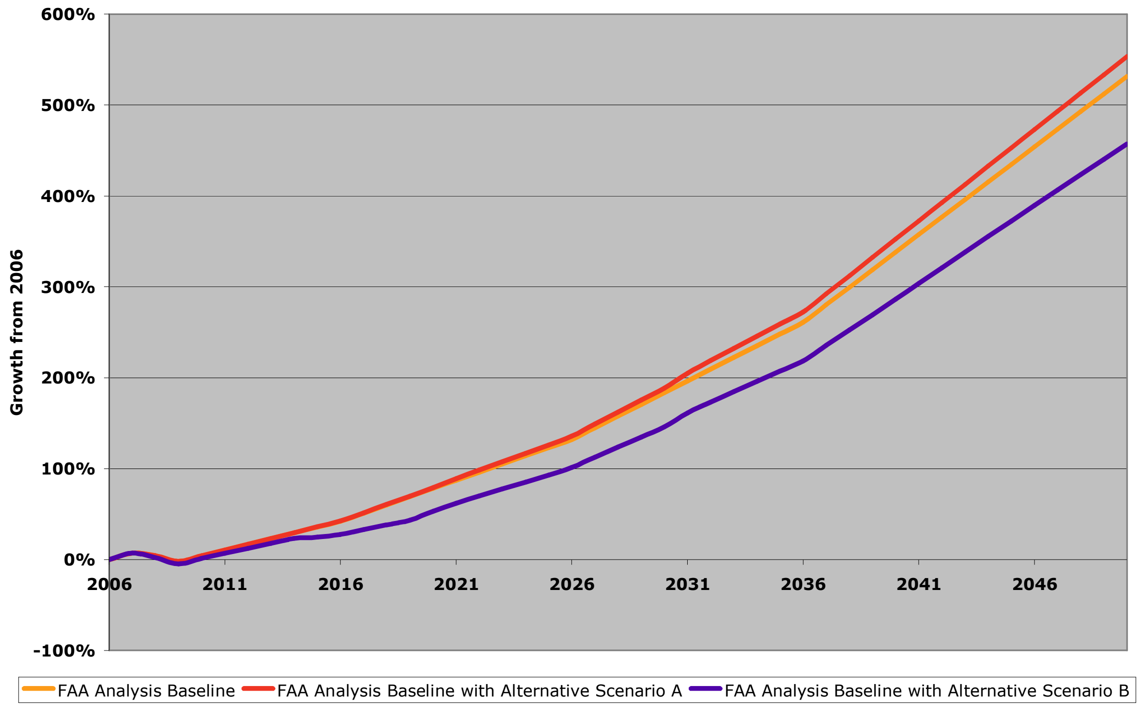


Figure 4.5 <u>Global</u> Projected Growth in Passenger km Across Scenarios

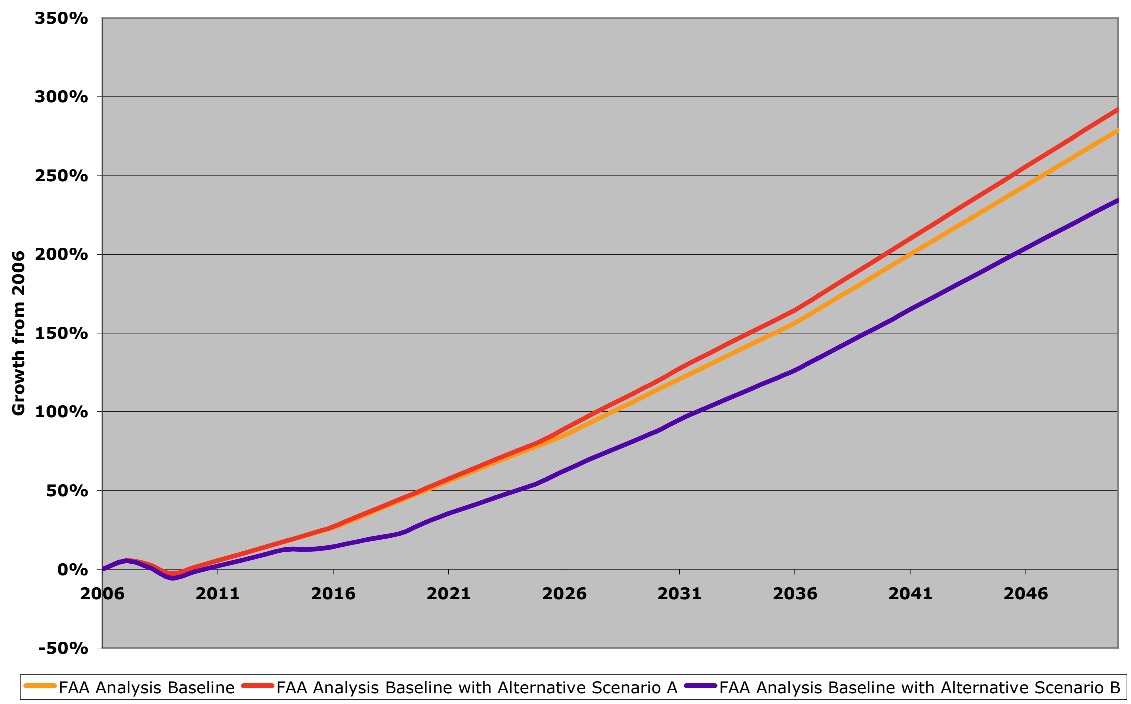


Figure 4.6 <u>U.S.</u> Projected Growth in Passenger km Across Scenarios

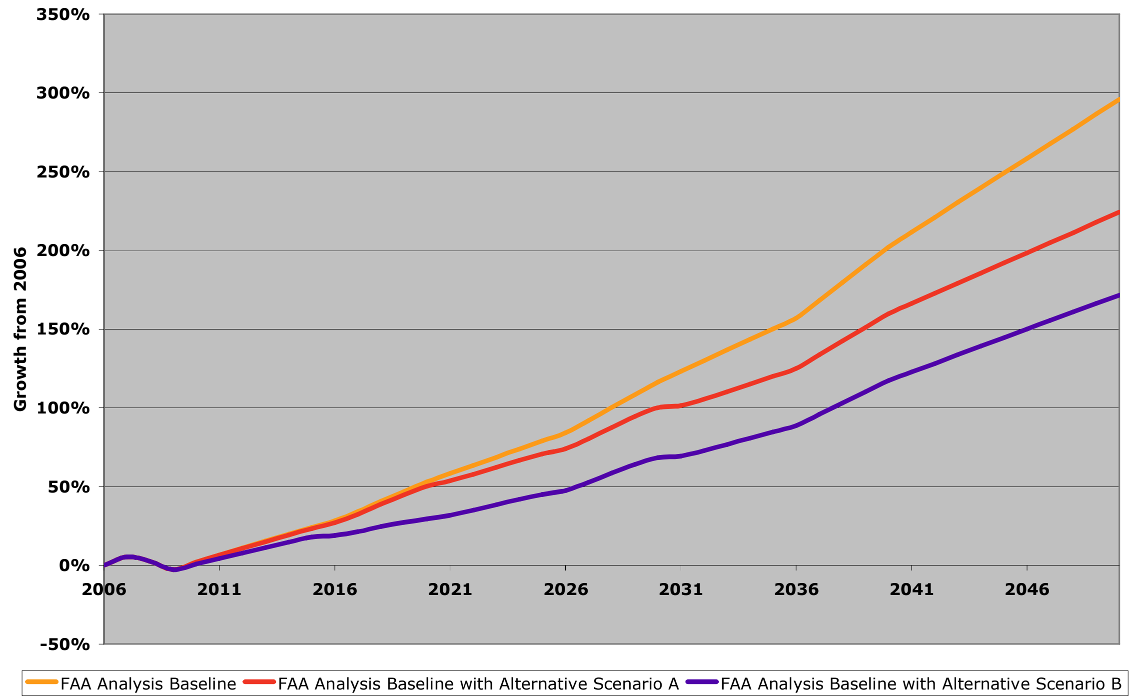


Figure 4.7 Global Projected Growth in Fuel Across Scenarios

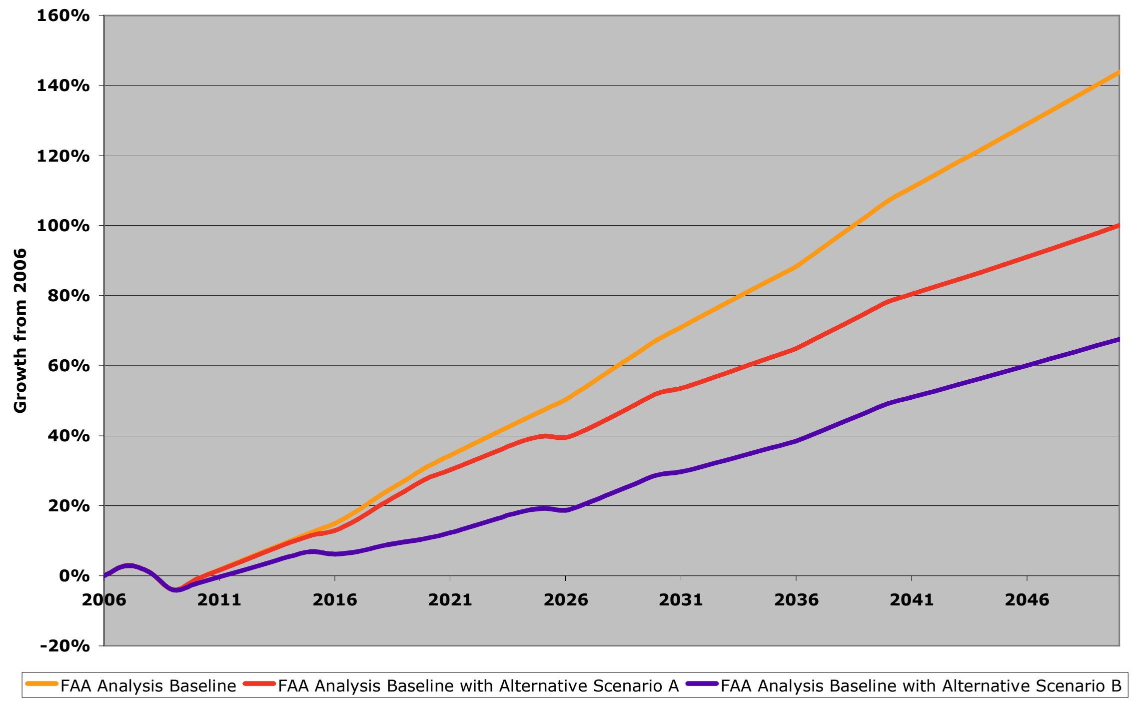


Figure 4.8 U.S. Projected Growth in Fuel Across Scenarios

Glossary

Term	Definition
Datum	The base year of the APMT-Economics analysis. The Datum year for the GIACC analysis is 2006.
Baseline	The projection of relevant factors affecting air transport demand and supply.
Policy	The policy assesses the impact of air transport related environmental policy measures on a given baseline projection.
Damped	General economic growth reduced as a consequence of dependence on rising oil prices. Reduced ability to pass on costs, slower growth in demand and higher costs leading to reduced profitability and investment in new technology
Strong	General economic growth unaffected as relatively independent of oil prices. Increasing oil prices leads to a shift to less oil dependent goods and services. Technical improvements to reduce the impact of increasing fuel costs. Operational improvements in the U.S. only.
Strong-Plus	As 'Strong' but operational improvements are introduced globally 5 years after implementation in the U.S..
Change in Consumer Surplus	The cost to aviation industry consumers resulting from a change in fares and consequently demand as a result of an alternative scenario to the Baseline. $\frac{1}{2}(D_B + D_P)(F_B - F_P)$ where D_B = Baseline Demand, D_P = Policy Demand, F_B = Baseline Fare, F_P = Policy Fare
Net Profit	The absolute profit to the aviation industry (total revenues – total costs)
Country-pair	The aggregation of airport-pair operations to a country level. Treated as bi-directional i.e. United States to United Kingdom and United Kingdom to United States are aggregated together.
Schedule	The aggregation of operations to a combination of country-pair and stage length
Fuel Efficiency	Fuel used per passenger km
Operational Efficiency	Refers to improvements in the air transport navigation systems that result in reduced flight times.

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Appendix B: Carbon Neutral Aviation Growth through Alternative Fuels

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. Executive summary

1.1 Introduction

Alternative jet fuel that is produced and created from renewable sources may have reduced life cycle greenhouse gas emissions relative to conventional, petroleum-based jet fuel. Researchers sponsored by the U.S. undertook a well-to-wake, life cycle analysis of some potential feedstock-fuel pathways that could be used as alternative jet fuels. The analysis included all of the GHG emissions that result from the creation of the alternative fuel—recovery, processing, and transport—as well as those resulting from its combustion.

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.

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

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, and can potentially overwhelm the gains from CO2 absorption.

1.2 Feedstock-to-Fuel Pathways Considered

The analysis considered multiple feedstock-to-fuel pathways. These included conventional jet fuel created from conventional petroleum resources as well as oil sands and oil shale resources. It also included Synthetic Paraffinic Kerosene (SPK) fuels created from Fischer-Tropsch (F-T) synthesis and hydroprocessing of renewable oils to create hydroprocessed renewable jet (HRJ) fuels.

F-T fuels can be created from natural gas (GTL), coal, (CTL), biomass (BTL) as well as a combination of coal and biomass (CBTL). Corn stover was used in the analysis of BTL and CBTL in this Appendix. HRJ fuels can be created from jatropha, soybeans, palm, and algae. Other feedstock options also exist (e.g., camelina and halophytes), but these have not yet been considered in the ongoing research effort that is summarized in this Appendix.

GTL and CTL fuels have large production potential, but they also have higher emissions than conventional jet fuel. With Carbon Capture and Sequestration (CCS), GHG emissions could be comparable to jet fuel, but CCS technology is not fully mature. BTL fuels have low GHG emissions but limited fuel production potential due to the large quantities of biomass required for their production. CBTL with the use of CCS could represent a means of combining the production potential of CTL with the low GHG emissions of BTL to yield a fuel with improved GHG emissions, relative to conventional jet fuel. However, Fischer-Tropsch facilities are capital intensive.

The use of excess palm and soy oils for HRJ production (excess meaning they are 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 is predicted to have large GHG emissions resulting from land-use changes of expanding production to meaningful quantities.

HRJ production from algae and jatropha holds promise for reducing aviation's GHG emissions. These feedstocks can be grown on marginal or wasteland that is not being used for agricultural purposes. Jatropha production is mature, but the limited oil production per acre for jatropha means that it cannot meet future jet fuel demand on its own. Jatropha HRJ may be a regional solution to reducing emissions from transportation, including that from aviation. Algae production is not technologically mature, but it has the potential for large oil production per acre.

Algal HRJ, jatropha HRJ, and CBTL all provide aviation with a potential means of GHG reduction. This field is rapidly developing, and the U.S. will continue to examine evolving options and provide results to the international community.

1.3 Carbon-Neutral Growth through Biofuels

The analysis also sought to examine the relationship between fuel usage, life cycle GHG emissions, and production potential. To begin the analysis, a number of potential fuel consumption scenarios for conventional jet fuel use were considered. These scenarios considered U.S. and global commercial aviation from 2006 to 2050.

Table 1 indicates the life-cycle GHG emissions that would be required from the jet fuel mix (conventional and alternatives) to achieve carbon-neutral growth through 2050 for a baseline year of 2006. The emissions are given as a fraction of those from conventional jet fuel on the basis of a unit of energy delivered to the tank; in this case, the conventional jet fuel is based on average US jet fuel in 2005. Three fuel use projections are presented. The upper and lower of these provide bounds on fuel use. A projection that lies between the bounds represents a nominal usage scenario. More information on the projections can be found in this Appendix.

Table 1: Life cycle GHG emissions required for carbon neutral aviation growth in 2050. Values are given as a percentage of conventional jet fuel life cycle GHG emissions.

Fuel Usage Scenario (US / Global)	Low Usage (D5 / G6)	Nominal Usage (D3 / G3)	High Usage (D1 / G1)
United States	62.8%	43.3%	29.6%
Global	25.7%	21.2%	13.1%

Notes:
1. Emissions target is 2006 emissions level in 2050.
2. 2006 level US emissions from aviation are equal to those from 1990. The lowest emissions in that period occurred in 2001 where emissions were 11.2% below 2006.

For example, in order to achieve carbon-neutral growth in 2050 under the "Low Usage (D5)" United States fuel use projection, the future jet fuel mix would need to be less than 62.8 percent of current GHG emissions (on a per unit energy basis). Additional discussion is presented in this Appendix.

1.4 Biofuel Land-Use Requirements

The nominal fuel use projections for the US and the globe were combined with calculations of fuel yield per hectare for the various feedstock-to-fuel pathways to estimate the amount of land that would be required to create sufficient biomass for a 50-50 blend of biofuel with conventional jet fuel and to replace jet fuel entirely with biofuel. The resulting landmasses are presented in Figures 1 and 2, for the US and the globe, respectively.

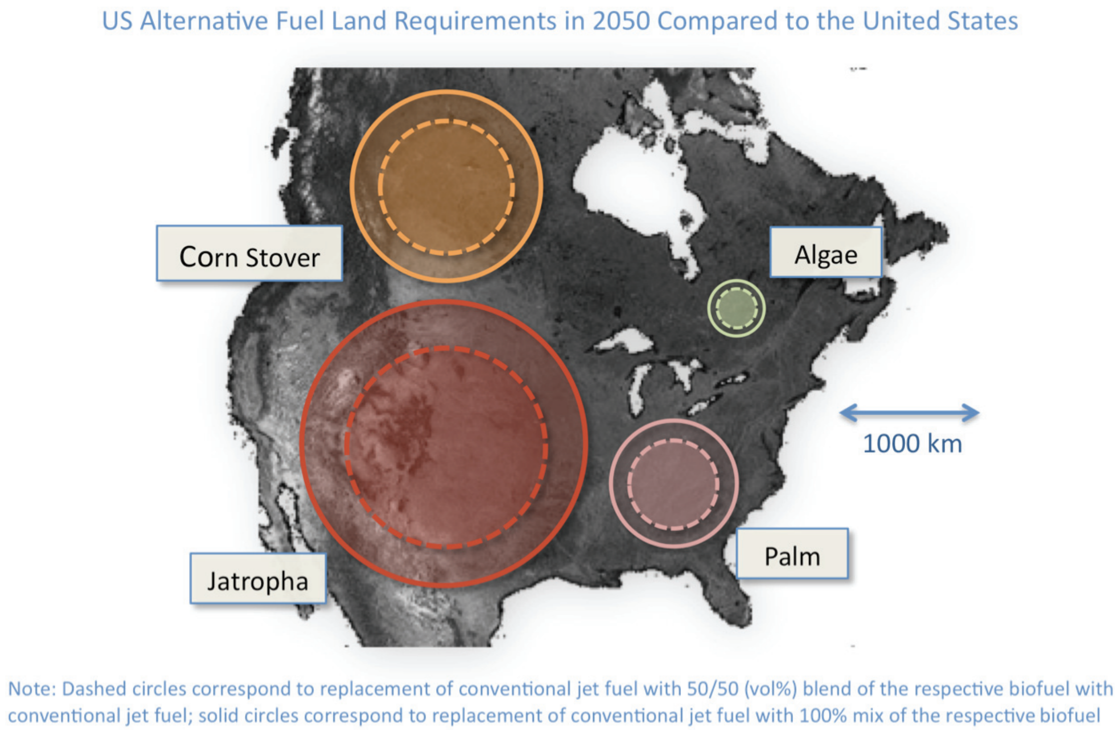

Figure 1: Land area requirements for different biofuels to replace US domestic conventional jet fuel use in 2050.

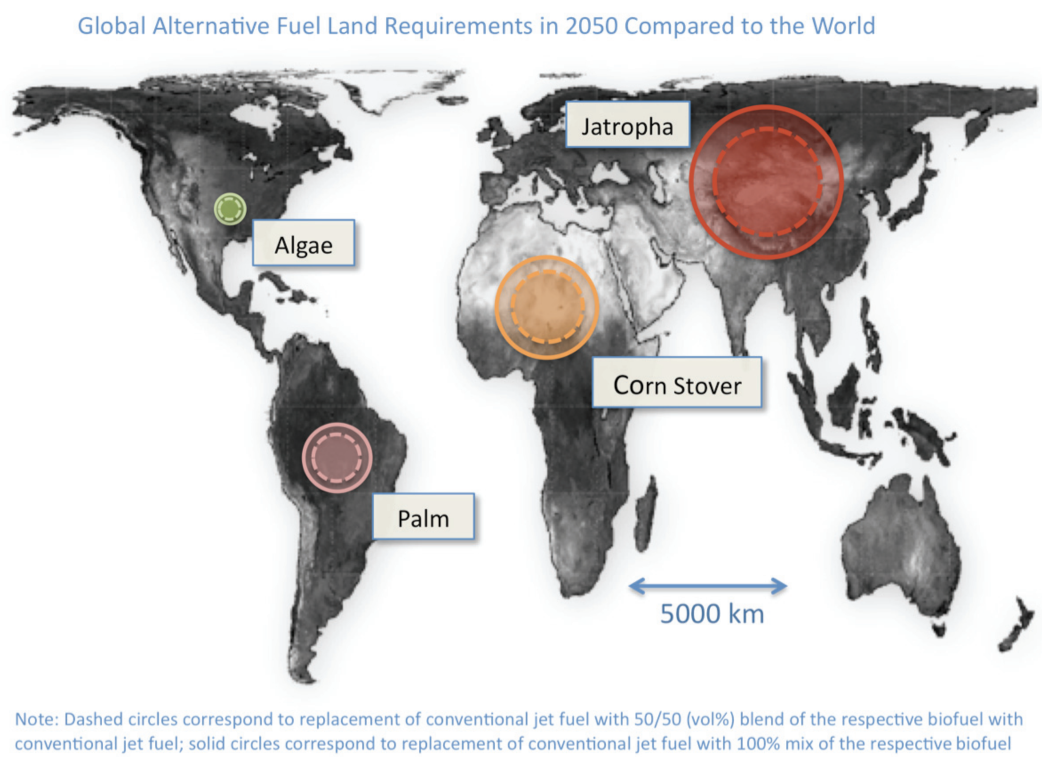

Figure 2: Land area requirements for different biofuels to replace global conventional jet fuel use in 2050.

Placement of the circles in no way indicates a preference or need for a specific region or climate. The smaller of the concentric circles represents the land requirement for the 50-50 blend while the larger circle represents the replacement of jet fuel with biofuel. Soybean HRJ was not included on these charts because it would not fit; the land area would be 1.6 times that of jatropha HRJ.

The palm oil requirement to replace half of US jet fuel with palm HRJ would be over three times current worldwide production. Palm production requires fertile land in tropical regions, thus its use as a biofuel will likely lead to land use changes with large GHG emissions. For these reasons, palm HRJ is not a practical alternative to jet fuel.

Jatropha HRJ would require unacceptably large land usage to replace an appreciable quantity of jet fuel. However, jatropha can be grown on marginal land without irrigation with less GHG emissions than conventional petroleum, so there may be reasons for its use as an alternative jet fuel.

The use of CBTL could lead to a one-fourth reduction in GHG emissions from aviation and considerable production of reduced GHG diesel fuel (the volume of diesel fuel is roughly twice the volume of jet fuel produced). Many feedstocks could be used for CBTL production such as agricultural residues like corn stover, forestry waste, or dedicated energy crops like grasses. However, these feedstocks could also be used for cogeneration of heat and power where their use may lead to greater societal benefit.

The most promising feedstock-to-fuel pathway thus far examined by the research team is algal HRJ. For the US nominal fuel use prediction, the use of 100% algal HRJ could lead to a 50% reduction in GHG emissions, relative to a business as usual scenario of continued use of conventional petroleum. This 2050 GHG emissions level would be 16% above the 2006 level. A land area comparable to 9% of US cropland may be sufficient to replace US projected fuel use in 2050. A land area slightly larger than France could supply sufficient algal oil to power global aviation in 2050. However, work remains in the commercial development of algae fuels.

1.5 Conclusion

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 (~10%) to large (~50%) reductions in emissions that contribute to global climate change.

A key factor in evaluating the benefits of feedstocks for alternative fuels includes the GHG emissions impacts of land used to produce them. The 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.

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, algal feedstocks may be able to produce sufficient jet fuel to replace jet fuel in 2050 for U.S. aviation on a landmass comparable to 9% of U.S. cropland with a 50% reduction in GHG emissions compared to a business as usual scenario. This combined with operational and technological advances, should be sufficient to reduce 2050 US aviation emissions below those of today.

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.

There remain substantial challenges in research and development, commercialization, environmental assessment, and fuel qualification. We are continuing to 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.

2. 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, GHG emissions are assessed and reported on the basis of per-unit energy consumed by the aircraft (per mega joule). 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-CO_2 or non-CO_2 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)

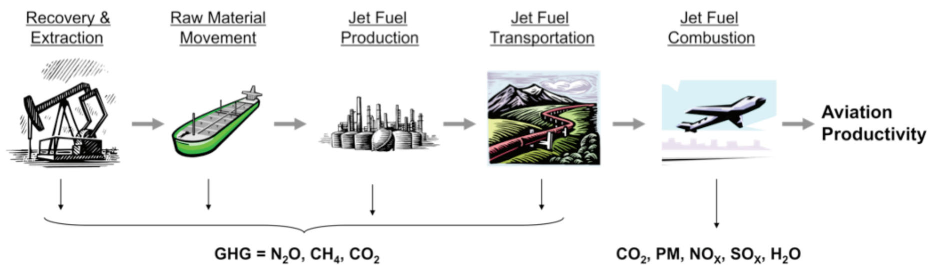

Figure B.1: Steps involved in the well-to-wake life-cycle analysis of jet fuel.

Fossil feedstocks such as crude oil, coal or natural gas are created from geologically sequestered carbon sources, and the carbon is released as CO_2 when the fuel products are burned. Such combustion CO_2 has to be taken into account in the life-cycle analysis (see Figure B.1). Biomass feedstocks absorb CO_2 from the atmosphere when they grow and the CO_2 emitted during fuel combustion is equal to that absorbed during biomass cultivation. Hence, many biofuels have net zero combustion CO_2 in the life-cycle analysis (see Figure B.2).

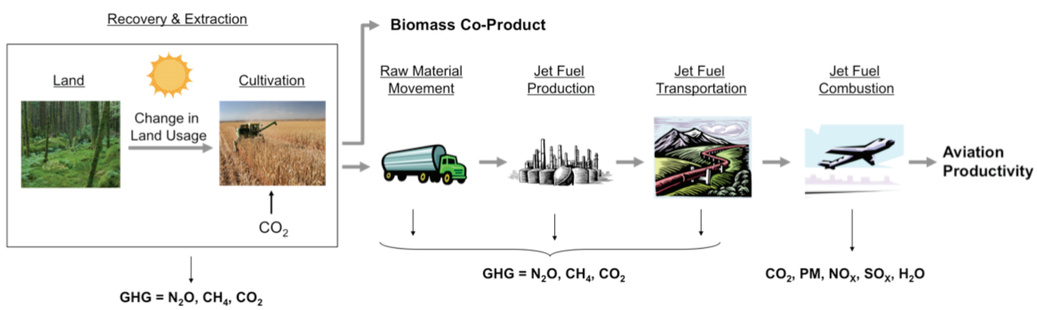

Figure B.2: Steps involved in the well-to-wake life-cycle analysis of bio-based alternative jet fuels.

Biomass feedstocks also have the potential for CO_2 emissions or CO_2 sequestration from changes in land use (see first step of Figure B.2). The CO_2 emissions or sequestration are due to changes in the biomass, soil and organic waste 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 of 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 the direct feeding of 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, fossil based electricity generation 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 need not 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 pre-requisite.

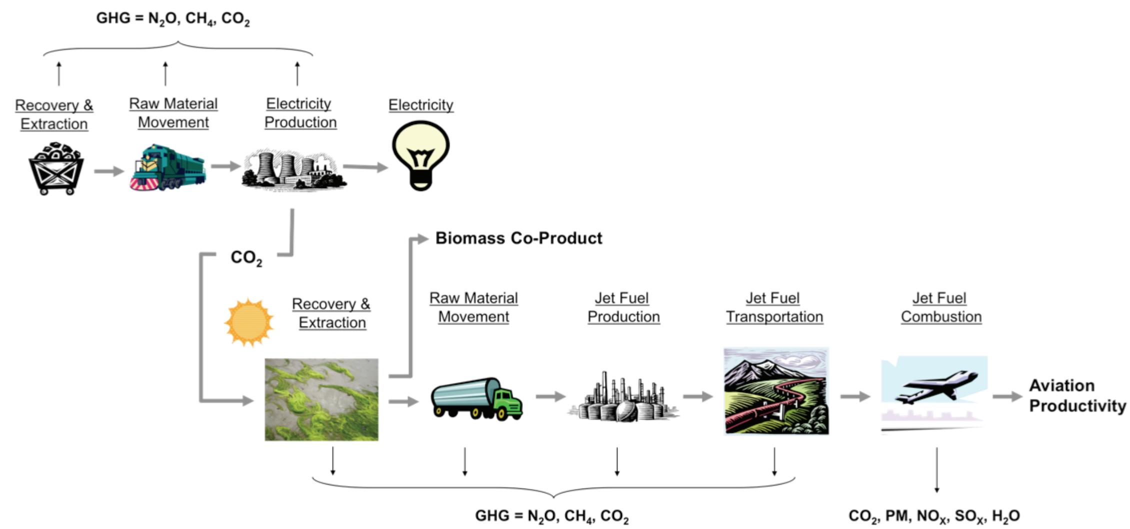

Figure B.3: Steps involved in the well-to-wake life-cycle analysis of bio-based fuels from algae.

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.

3. 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) framework (version 1.8b) 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 more recent data could be obtained. 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), respectively[1] (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 alternative jet fuels were not available, diesel fuel was used as a surrogate for jet fuel due to similarities in chemical composition.

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 CO_2 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.

4. 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 HRJ 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.

Table B.1 Fuel Pathways Investigated

Source	Feedstock	Recovery	Processing	Final product
Petroleum	Conventional crude[1]	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
	Jatropha Oil	Cultivation and extraction of jatropha oils	Hydroprocessing	HRJ Fuel

[1] 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.

5. 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, algae and jatropha, 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, algal and jatropha HRJ pathways are presented in a subsequent section.

5.1 Petroleum-Based Jet Fuel

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 $85gCO_2e/MJ_{Jet\ Fuel}$ and the refined value from NETL is $87.5gCO_2e/MJ_{Jet\ Fuel}$.

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 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.

5.2 Land Use Change Emissions from HRJ derived from Palm Oil and Soy Oil

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

5.3 F-T Fuels

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.

5.4 Hydroprocessing Jet Fuel and Diesel Fuel

In the biofuel pathways examined by Wong (2008), F-T diesel fuel was used as a surrogate for F-T jet fuel and Hydroprocessed Renewable Diesel fuel (HRD, also known as NexBTL, green diesel, or renewable diesel by various producers) was used as a surrogate for HRJ fuel. In the case of fuels created by the Fisher-Tropsch process, this is a valid assumptions as the fuels are literally synthesized from smaller molecules and only a different catalyst is needed to make F-T jet fuel instead of F-T diesel fuel. It should be noted for this case that although F-T jet fuel can be made without added burdens, it is not possible to have a product slate of 100% F-T jet fuel (25% is taken as a maximum value in these studies with a sensitivity shown later in the report).

In the case of HRJ, the "diesel as a surrogate for jet" assumption is only appropriate for crude estimates. The UOP process (UOP, 2005), described by the following chemical reaction, was the basis for the creation of HRD in Wong's analysis.

$$C_nH_{2n+1}COOH + 3H_2 \rightarrow C_{n+1}H_{2n+4} + 2H_2O$$

This equation can be re-written in a mass balance form for easier comparison to experimental data.

$$1.12 \text{ lb } Oil + 0.024 \text{ lb } Hydrogen \rightarrow 1.00 \text{ lb } HRD + 0.14 \text{ lb } Water$$

The feedstock, key products and process energy needed per pound of HRD are summarized in the Table B.3.

Table B.3: Experimental and theoretical requirements for the creation of renewable diesel

Feedstock (lb)	**Experimental**			**Theoretical**
	Low	**Baseline**	**High**	
Oil	100	100	100	100
H_2 (51586 Btu/lb)	1.5	2.72	3.8	2.14
Key Products (lb)				
HRD (18908 Btu/lb)	83.0	84.19	86	89.28
Propane Mix Gas (18568 Btu/lb)	2.0	4.75	5	0.00
Process Energy (Btu)				
Electricity	5785	6942	8099	--
Natural Gas	8950	8950	8950	--

Notes:
(1) Assume that steam is produced from natural gas at 80% efficiency
(2) Energy contents are taken from GREET, 2008
(3) Sources: (Kalnes, 2009); Appendix 2 of Huo et al., 2008

Further refinement is required for the creation of HRJ. The strategy to estimate the process requirements of HRJ is to use the experimental data for the creation of HRD and subsequently estimate the additional requirements to convert the HRD into HRJ. For this analysis, HRD and HRJ are assumed to be symmetrical distributions of straight carbon chains centered on C_{12} and C_{18} respectively. As shown schematically in Figure B.4, the cracking from diesel fuel to jet fuel is assumed to occur via the addition of gaseous hydrogen.

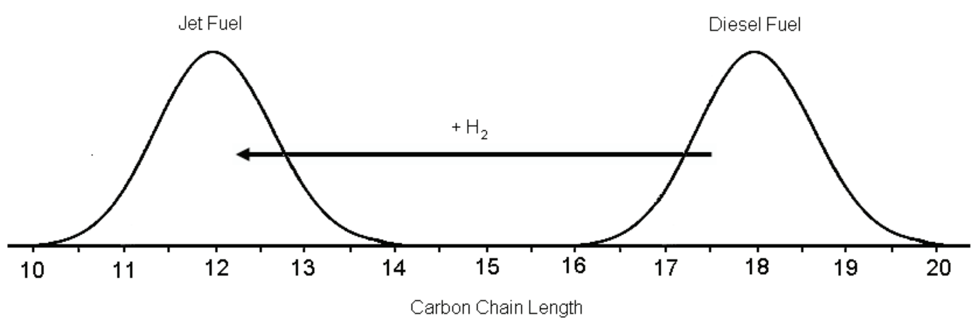

Figure B.4: Schematic showing the change in hydrocarbon composition between HRD and HRJ fuels that results from additional hydroprocessing.

The mechanism by which hydrocarbon chains crack is through smaller molecules, (e.g., pentane (C_5H_{12}) and hexane (C_6H_{14})) breaking off the end. The dominant effect that takes place is the reduction of C_{18} to C_{13} by cracking pentane and C_{12} by cracking hexane (Kalnes, 2009). There are other reactions taking place where molecules from the distribution about C_{18} crack to those from the distribution about C_{12}. To account fully for this effect would entail including the statistical nature by which chemical reactions are more likely to take place. In keeping with the level of detail required of this analysis, we assume that if the two distributions have the same shape about their mean, the aforementioned effects will cancel out.

Making use of these arguments simplifies the analysis to two chemical reactions, which convert diesel fuel to jet fuel:

$$C_{18}H_{38} + H_2 \rightarrow C_{13}H_{28} + C_5H_{12}$$
$$C_{18}H_{38} + H_2 \rightarrow C_{12}H_{26} + C_6H_{14}$$
$$2C_{18}H_{38} + 2H_2 \rightarrow C_{12}H_{26} + C_{13}H_{28} + C_5H_{12} + C_6H_{14}$$

Written out in mass balance form and normalized for one lb of HRD, the overall equation governing the formation of HRJ from renewable oil can be expressed as:

1.00 lb *HRD* + 0.0079 lb *Hydrogen* → 0.697 lb *HRJ* + 0.311 lb *Naphtha*

Naphtha in this case is a combination of 46 percent C_5H_{12} and 54 percent C_6H_{14} by mass. Using these ratios of HRD to HRJ, the process energies from Table B.3 can be modified to reflect the energy requirements to create HRJ as shown in Table B.4. Based on discussions with experts at UOP (Kalnes, 2009), it is assumed that total process energies (natural gas and electricity) will increase by 10-30 percent on a per-pound of renewable feedstock when including the hydrocracking required for the formation of HRJ. Total hydrogen consumption is the sum of the needs to first make HRD and then to crack it down to HRJ.

Table B.4: Energy requirements for the creation of HRJ

Feedstock (lb)	**Experimental**		
	Low	**Baseline**	**High**
Oil	100	100	100
H_2 (51586 Btu/lb)	2.15	3.38	4.48
Key Products (lb)			
HRJ (18950 Btu/lb)	57.8	58.7	59.9
Naphtha (19215 Btu/lb)	25.8	26.2	26.8
Propane Mix Gas (18568 Btu/lb)	2.0	4.8	5.0
Process Energy (Btu)			
Electricity	6364	8330	10529
Natural Gas	9845	10740	11635

The hydroprocessing step of converting renewable oil into HRD results in emissions of 8.7gCO_2/MJ. After making the changes discussed above to the model, the emissions from hydroprocessing renewable oil into HRJ are 10.3gCO_2/MJ. This revision to the HRJ pathway has been incorporated into the analysis methodology of Wong (2008) with the overall life cycle GHG emissions presented later in this appendix.

6. Life Cycle GHG Emissions of F-T 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 alone appears to be a poor choice. 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 current F-T plant designs 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. Configurations without CCS are not 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 primarily 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 syngas streams being mixed together afterwards. This work examines co-gasification as the parallel configuration is a superposition of CTL and BTL, both of which have 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 of diameter 1mm or less. Currently, the most energy efficient method of milling the biomass is torrefaction, 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 commonly cited value.

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. CTL plant 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_{CO2} 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.

6.1 Allocation Methodology

An F-T facility can produce a wide product slate. For example, the study carried out by NETL on F-T diesel from CBTL assumes an output of 70% diesel and 30% naphtha (NREL, 2009). In this study, F-T jet fuel is the product of interest but it is commonly accepted that it will not consist of more than roughly a quarter of the total plant output. Since other F-T fuels are made as a result of producing F-T jet fuel, there is an issue of allocation with regards to the processing and all other upstream emissions. Even when configured to make jet fuel, diesel fuel will be the primary output of the F-T facility. For this reason, it is sensible to allocate emissions among the fuel products, (i.e., jet fuel, diesel fuel, and naphtha), on the basis of their respective energy content. This prevents a product that is responsible for a quarter, or less, of the output of the facility receiving ‘credit’ for all the emissions benefits coming from the full product slate. Instead of allocating based on energy content of the products, NETL (2009) used a displacement (system expansion) scheme to account for the benefit of making a reduced carbon, biomass-based F-T naphtha in addition to the F-T diesel. Since F-T diesel is the primary product, this choice was justified.

As shown in Figure B.5, the displacement method encounters problems when the quantity of by-products made per unit of primary product leads to credits given per unit of primary product that dominate the other life cycle steps. When the yield of jet fuel is 25%, there are 3 liters of other F-T fuels being made for every 1 liter of jet fuel. When the yield of jet fuel is only 5%, there are 19 liters of other F-T fuels made for every 1 liter of jet fuel. This is an asymptotic result for small yields of jet fuel because the life cycle emissions that are reported by the life cycle analyst are the WTW jet fuel emissions minus the credits from other fuels. As the yield of jet fuel is reduced closer to zero, the fuel will appear to the life cycle analyst as having emissions that approach negative infinity.

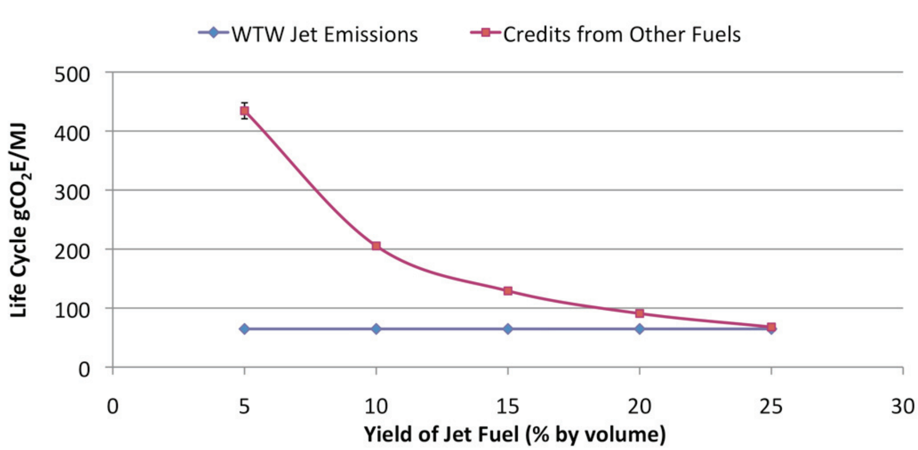

Figure B.5: The effects of product slate composition on life cycle emissions of F-T jet fuel

The diverging effect resulting from use of the displacement method is unavoidable because F-T jet fuel cannot be made to represent more than roughly a quarter of the final products. In order to maintain consistent results, which cannot be skewed by subjective choices of the analyst/operator, energy allocation is used. The results using this method come with the caveat for each unit of jet fuel produced, there are also substantial volumes of other fuels produced, such as diesel and naphtha, that could also carry environmental benefits. The specific product slate considered in this analysis was 25% F-T jet fuel, 55% F-T diesel and 20% F-T naphtha.

6.2 Results

As shown in Figures B.1 through B.3, the life cycle of a fuel can be broken down into steps. Figure B.6 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 CO_2 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.

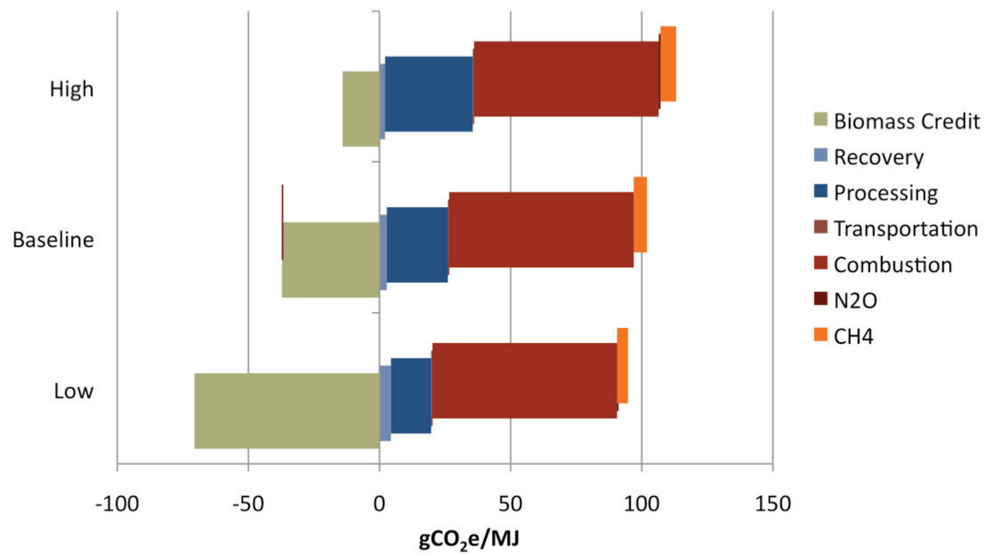

Figure B.6: Breakout of life cycle emissions of CBTL by processing step for the low, baseline, and high emissions scenarios.

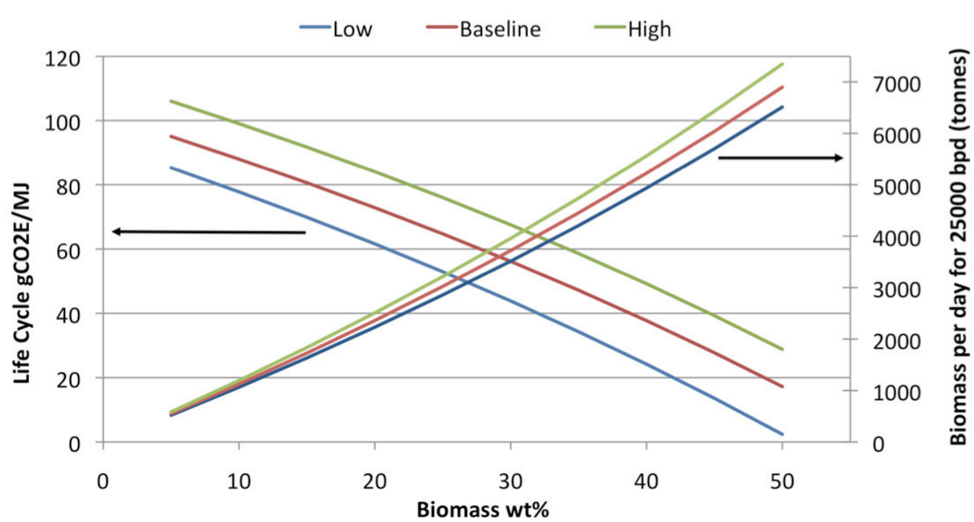

Figure B.7 Dependence of cumulative life cycle emissions and biomass requirements for varied biomass utilization within CBTL.

Figure B.7 presents the implication of varying biomass weight over a range of 0% to 50% (Figure B.6 examined three discrete values within this range). Life cycle GHG emissions can be reduced to a fraction of conventional jet fuel with considerable biomass usage. For example, a CBTL jet fuel that is created from 50% biomass could have life cycle GHG emissions that are only 20% of conventional jet fuel; however, roughly 264 railroad cars of biomass would be needed every day to create sufficient CBTL jet fuel to fuel Boston Logan airport.[2] This large amount of biomass highlights the importance of considering GHG reductions for a high biomass wt% in conjunction with biomass feeding requirements; it also points to a reduced biomass percentages being more realistic. Future work will consider the economics of CBTL fuels.

7. Life Cycle GHG Emissions 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 HRJ. The ASP focused most of its 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. Macroalgae are the classical long strands that grow on the bottom of ponds and lakes, (a.k.a. seaweed). While some work has been performed using macro-algae as a fuel source, it is not considered here; hereafter, algae will refer to microalgae.

7.1 General Information

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 growth in vertical geometries thereby reducing land requirements; 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 examined further as a part of this continuing research effort.

The two defining characteristics for algae as a biofuel are the growth rate (generally given in g/m^2/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 gained from their literature review of open ponds. During peak periods of growth, 50g/m^2/day could be achieved but a yearly average of 20 g/m^2/day appears to be more 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 g/m^2/day and 40% lipids by weight was adopted for the low emissions case, 25 g/m^2/day and 25% lipids by weight was adopted for the baseline case and 20 g/m^2/day at 15% lipids by weight was adopted for the high emissions case.

The extraction of oil from algae and its processing into HRJ also results in the creation of marketable co-products (see Figure B.8). This is similar to the creation of HRJ from 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, naphtha and mix propane gas were allocated based on their energy.

[2] 7,000 tonnes of biomass would be needed per day to provide 25,000 barrels per day of jet fuel (this is roughly the consumption of Boston Logan Airport). A typical railroad car can carry 26.5 tonnes of biomass (Mahmudi, 2006).

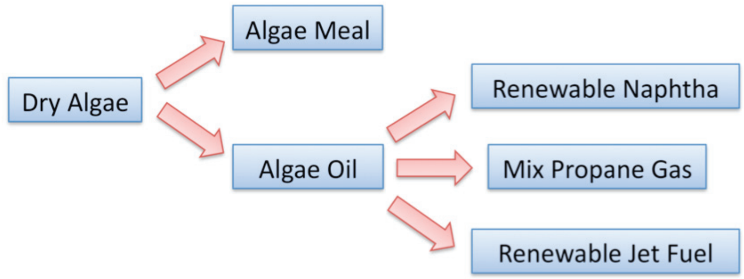

Figure B.8: Co-products that can be created from dried algae. It should be noted that this pathway is the same for palm oil, soybean oil, and many other renewable oil sources. For the allocation methodology used in this analysis, the algae meal is treated as an animal feedstock; however, it could also be used for energy generation.

7.2 System Expansion (Displacement) for Electricity Emissions

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. As is schematically shown in Figure B.9, system expansion (displacement method) is used instead of energy allocation of 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 that is producing equivalent electricity to that within the original system boundary. The expanded system has HRJ and the biomass co-product leaving the system boundary, but there is net zero electricity exiting the expanded system. Thus, the expanded system can be dealt with in a similar manner to the palm and soybean HRJ pathways.

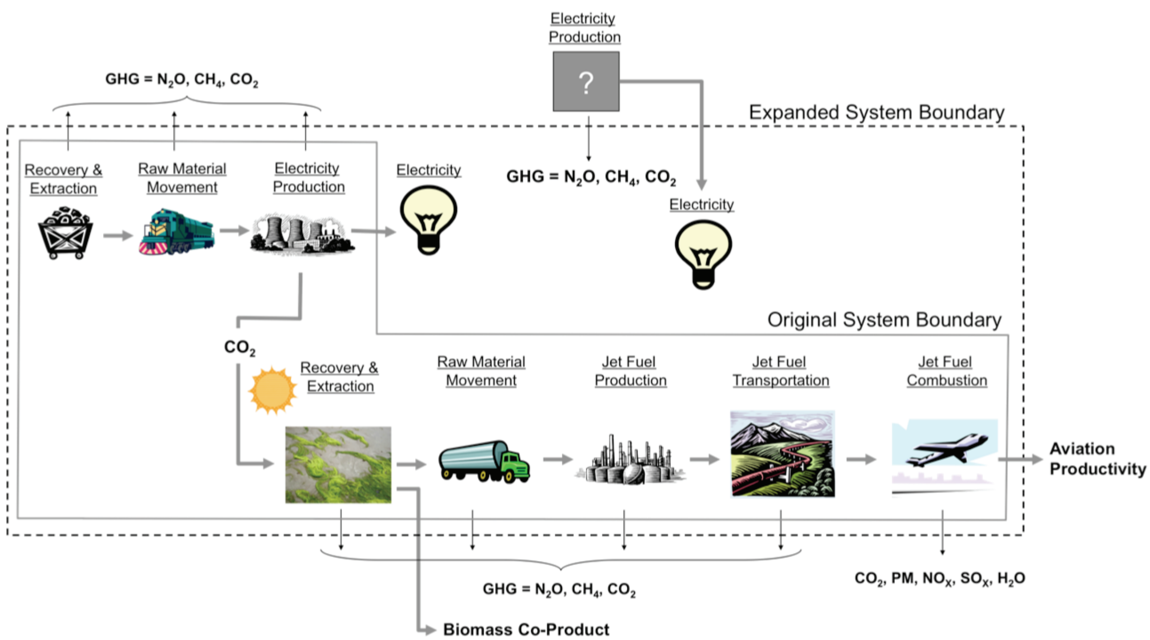

Figure B.9: System boundary expansion of the algal HRJ fuel pathway.

The life cycle GHG emissions from the electricity that is used to supply CO_2 for algal growth and the type of electricity that is being displaced both impact the life cycle emissions of the algal fuel. This is due to the variation that could exist in the emissions per kilowatt-hour being generated, (e.g., a utility boiler has higher emissions than an integrated gasification combined cycle which in turn has higher emissions than a nuclear power plant). The options in Table B.5 outline the effects on the life cycle emissions that these choices can have. When 'dirty' electricity is used to create CO_2 to feed algal growth, but 'clean' electricity is included in the expanded system 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 create CO_2 to feed the algae but 'dirty' electricity is included in the expanded system then the CO_2 emissions credit is greater than the CO_2 used to grow the algae; this results in a fuel that appears to be 'clean.' In this analysis, the electricity used to provide the CO_2 is assumed to be the same as that in the expanded system. For this configuration, the CO_2 emissions credit is approximately equal to the biofuel combustion emissions, which is the assumption used for biofuels that have not been 'fed' CO_2 for enhanced growth.

Table B.5: Impact of electricity choice on the biomass credit given to algal HRJ.

Type of Electricity Coupled to Algae Growth	**Type of Electricity in the Expanded System Boundary**	**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 $CO_2 >> 0$)

7.3 Dewatering

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. After harvesting, the algae must be first dewatered and then dried. It was found that the applicability of algae as a biofuel with environmental benefits is highly dependent on the extent of dewatering and the method of drying. This is shown schematically in Figure B.10.

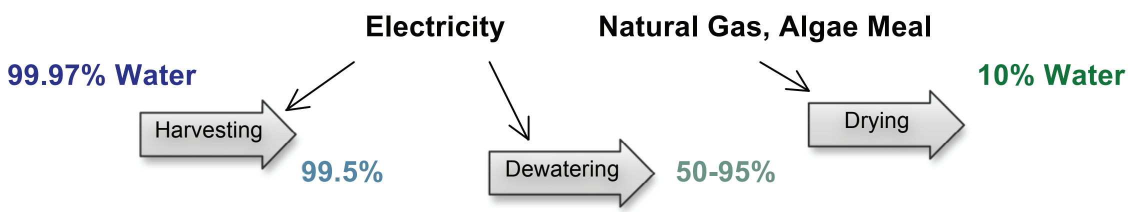

Figure B.10: Flow chart of dewatering and drying of algae

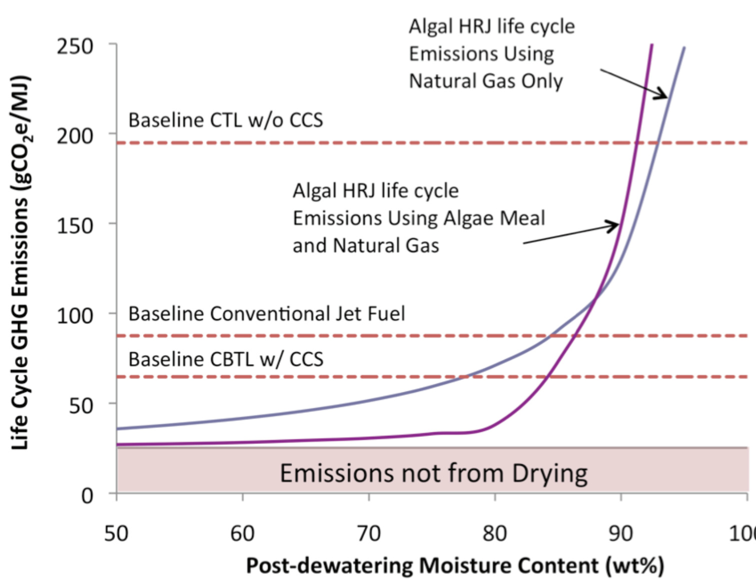

Figure B.11: An examination of moisture content after dewatering and drying method on life cycle GHG emissions from algal HRJ fuel. A constant dewatering energy was assumed that was based on 90% moisture content; however, in reality more energy would be required for dewatering to levels below 90%.

Generally, dewatering is performed by mechanical or gravitational force while drying relies on generating sufficient energy to evaporate the remaining water. As the latent heat of water is high and a combustible fuel must be used to generate this energy, increased dewatering, and hence less drying, has considerable impact on reducing the life cycle GHG emissions of the pathway. Natural gas and algae meal were considered as options for creating this energy. Common types of dewatering procedures are flocculation or sedimentation (solids content doesn't exceed 3%), filtering with a vacuum or press (solids content ranges from 5-37%) or centrifugation (solids content ranges from 1-15%) (Molina Grima et. al., 2002). These values are based on historical studies and are likely pessimistic for a simulation year of 2015 given the recent surge in research within the field. Each method has its own energy requirements and must be considered within the context of reliability and scalability. The high impacts of the level of dewatering and the fuel type used for drying are demonstrated with the results shown in Figure B.11. As the moisture content of the algae after dewatering is decreased, there is a sharp reduction in the life cycle emissions of the fuel. This results from less fuel being burned for drying and occurs regardless of the fuel type.

Although the shapes of the two curves in Figure B.11 show the same general trend, the consequences differ. When natural gas is used to fuel the process, the emissions up to and including oil extraction are allocated between the oil and the meal based on market valuation. For an algae strain that is comprised of 25% oil by mass, there is sufficient energy in the algae meal to dry other algae from a post-dewatering moisture content of roughly 80%. If the algae were dewatered to a moisture content below ~80%, then the emissions are allocated based on the relative market values of the oil and the meal that is left over after drying is completed. If the post-dewatering moisture content were above ~80%, then the algae meal would need to be supplemented by natural gas to supply the energy needed for drying. The point where the life cycle emissions begin to rise rapidly when using meal as the fuel for drying (80% post-dewatering moisture content) is due to supplementing the meal with natural gas.

The decision of whether to use the algae meal or natural gas as the fuel for drying must be made in the context of the economic, technological and energy input limitations of dewatering. It is commonly accepted that a moisture content of 90% after dewatering is achievable (SERI, 1989). The data forming the basis for the cultivation inputs of growing algae does not differentiate between the uses of input electricity and does not specify the final moisture content after dewatering; however, it is known that a centrifugation dewatering method is employed. Based on a review of the technology survey conducted by Molina Grima et. al. (2002) and the conclusions by the SERI (1989), it was assumed that the algae was dewatered to 90% moisture content using a centrifuge consuming 0.8kWh/m^3 of throughput containing 0.8% algae. Furthermore, it was concluded that using a press filter mechanism could allow for an 80% post-dewatering moisture content with good reliability consuming 0.88kWh/m^3 of throughput containing 0.5% algae. It is the opinion of the authors that post-dewatering moisture content under 70% is economically unrealistic using current technology due to the necessary power consumption. Given these restrictions on dewatering, both the high and low emissions cases use a post-dewatering moisture content of 90% via centrifugation with the high case using natural gas as the fuel for drying and the low emissions case using solar energy. Solar drying is considered to be an optimistic option but is not out of the realm of possibility with some reports estimating an area required for drying that is 12% of that required for growing (SERI, 1984). The baseline case assumes dewatering to 80% moisture content with a press filter and subsequently uses the algae meal (supplemented by natural gas if there is not enough energy in the meal on a sustainable basis) as the fuel for drying.

7.4 S***ummary***

In a similar manner to Figure B.6, Figure B.12 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 most notable differences between the cases lie in the recovery step and the WTT CH_4. The recovery step includes emissions from dewatering and drying. The dominating contribution of this procedure was described in the previous section and is the reason for the variation in these results. The WTT CH4 also comes as a result of the drying process. Only the high emissions case suffers from substantial methane emissions because of the large quantities of natural gas needed for drying. Methane is emitted in the recovery and processing of the natural gas before it is burned for the drying of algae.

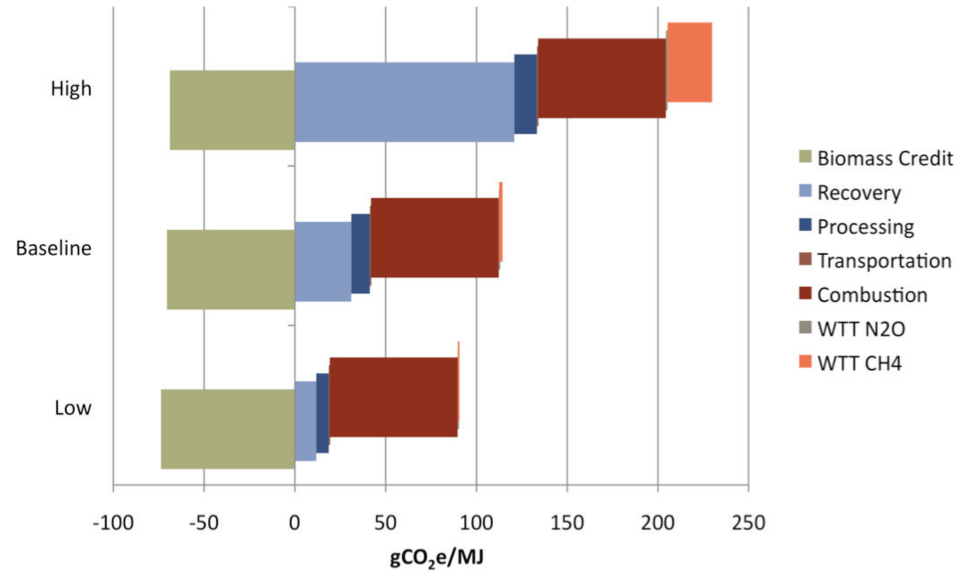

Figure B.12: Breakout of life cycle emissions of algal HRJ by processing step for the low, baseline, and high emissions scenarios.

8. Life Cycle GHG Emissions of HRJ from Jatropha Oil

The jatropha plant is a small tree or large shrub, up to 5-7 meters tall, which can grow without irrigation in a broad spectrum of rainfall regimes. Under normal conditions, the jatropha plant flowers only once a year during the rainy season; however, in permanently humid regions or under irrigated conditions it can be made to flower almost all year round (Achten et. al., 2008). Although it is considered a wild plant, there is considerable hype surrounding the potential for the production of biofuels from the fruit that grows on the tree (Achten et. al., 2008). The fruit is composed of an outer capsule containing two or three seeds. Each seed has a shell and a kernel, which contains oil. Although jatropha plants are generally considered to have higher oil yields than many other oil yielding crops, the husk and the seed shells result in more co-product per unit mass of jatropha oil than both algae and palm fresh fruit bunches.

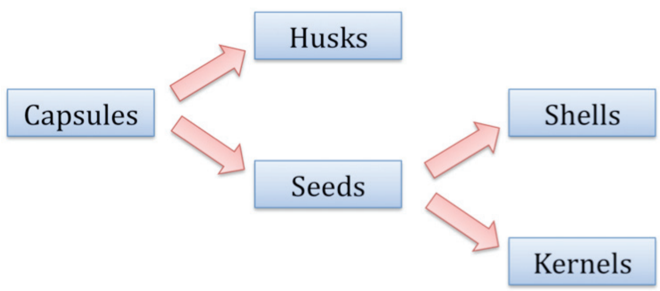

Figure B.13: Parts of the Jatropha fruit: husks, seeds, shells and kernels

Jatropha plants are well adapted to semi-arid conditions, although more humid environments are shown to result in higher crop yields. The plant can tolerate high temperature extremes but it does not tolerate frost, which causes immediate damage. Upon examination of 28 growth sites worldwide, it was found that a correlation of 0.22 exists between the quantity of precipitation and seed yield. This means that although more precipitation is moderately connected to higher seeds yields, there are many cases where excellent yields have been realized in dry conditions and poor yields realized in wet conditions. Based on a survey of recent literature it was concluded that a yield of 2500kg/ha/yr of dry seeds is a reasonable estimate for the average land type while 5000kg/ha/yr could be realized under optimal management practices; 1000kg/ha/yr appears to be a reasonable lower bound (Achten et. al., 2008, Reinhardt et. al., 2008). Note that yields are quoted in terms of seed weight and not capsule weight. For every kilogram of seeds, there is an additional 0.6kg of husks (the walls of the capsules containing the seeds) that must also be processed. The oil content of jatropha seeds is relatively constant with most samples ranging between 34% and 37% by weight (Reinhardt et. al., 2008). The nominal case in this study uses 35%, with 37% and 34% making the upper and lower bounds, respectively.

Extracting oil from the jatropha fruit has a large influence on the life cycle emissions. Before beginning, a dehusker is required to remove the husks and obtain the seeds. In small-scale production facilities, the seeds would then be crushed in a screw press to extract the oil. This method can only obtain up to 80% of the oil so larger production facilities mill the seeds into small particles and use a N-hexane chemical solvent to obtain up to 99% of the oils (Achten et. al., 2008). The deterministic factor in this life cycle is how the by-products are used (husks, shells, meal). It is not necessary to remove the shells from the kernels before the solvent treatment, but it turns out to be more energy efficient to do so. The additional burden of processing the shells through the chemical solvent with the kernels is more than the burden of removing the shells beforehand. If the shells are removed prior to milling, the shells are obtained independently of the meal and the oil. If the shells are not removed, the seeds are split into a de-oiled cake and the oil itself. Regardless of whether the shells are removed, the resultant product is toxic to both animals and humans; however, detoxification would be possible if there were a market to drive the technology. Figure B.14 shows how many of the by-products created during oil extraction can be used for a variety of purposes and how the types of by-products change depending on the processing technique.

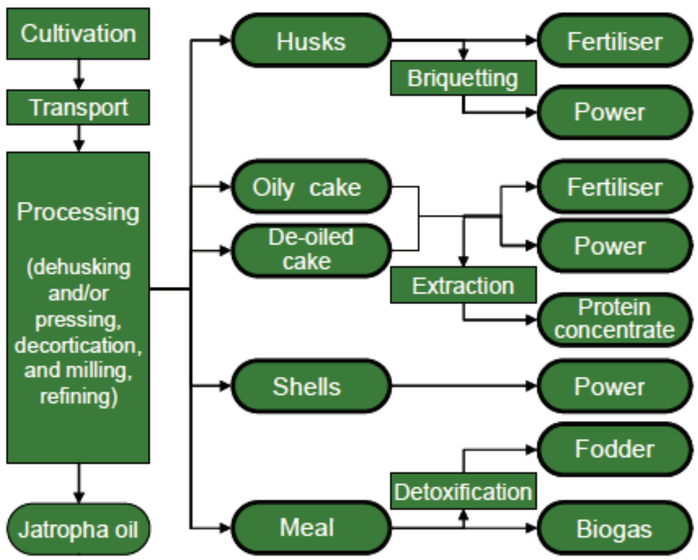

Figure B.14: Utilization of by-products from Jatropha cultivation and oil extraction (image adapted from Reinhardt et. al., 2008)

Table B.6: Co-product creation and allocation scenarios from the oil extraction process for Jatropha capsules. The corresponding life cycle emissions for each scenario are shown in Figure B.15.

Scenario 1	Husks and de-oiled cake are burned for electricity; the emissions are allocated via energy content.
Scenario 2	Husks and de-oiled cake are used as fertilizer; the emissions are examined via the displacement method.
Scenario 3	Shells are removed and the husks and shells are burned for electricity; the emissions are examined via displacement (system expansion) method with US grid electricity being displaced. The meal is detoxified and sold for animal feed.
Scenario 4	Husks and de-oiled cake are burned for electricity and the emissions are examined via displacement (system expansion) method with US grid electricity being displaced.

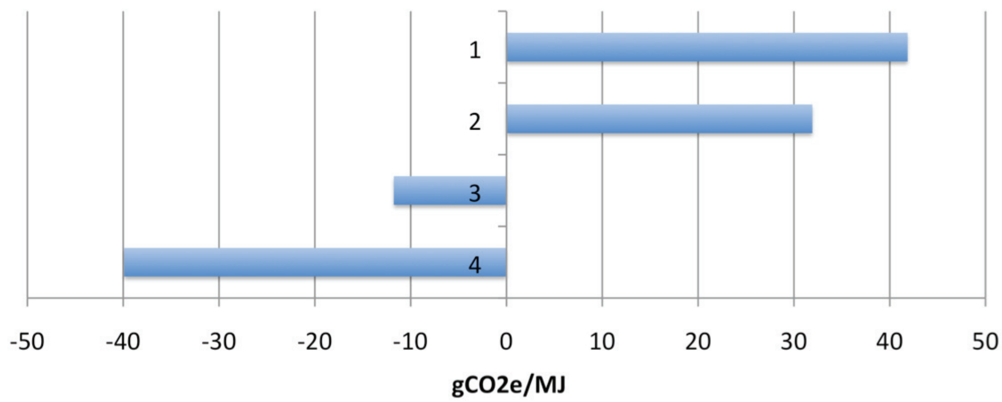

Figure B.15: Sensitivity of life cycle emissions of HRJ from Jatropha to by-product utilization and allocation scheme.

To understand the influence of co-product type and usage on the life cycle emissions of the fuel, the scenarios outlined in Table B.6 were examined. These scenarios examined how the life cycle emissions of HRJ from jatropha change depending on the use of co-products for animal feed, fertilizer or electricity production. The electricity production was further broken down to examine displacement of US average grid electricity as well as energy allocation of emissions. The life cycle emissions that would result from each of these scenarios are summarized in Figure B.15.

After considering the relative merits of each, Scenario 1 was chosen. Using the products for power generation seems a more logical choice for the resource because the displacement of fertilizer on large scales with a product that is toxic to humans was deemed undesirable due to the potential for ground water contamination. Energy allocation was chosen over displacement due to the large quantities of co-product that would be generated per unit of oil production. As shown in Figure B.15, the displacement of fossil based electricity results in the unrealistic result of negative life cycle emissions for the fuel.

In a similar manner to Figures B.6 and A.12, Figure B.16 shows both positive and negative (i.e., biomass usage) contributions from each life cycle step for the production of HRJ from Jatropha with the summation of positive and negative contributions being the cumulative total. The most noticeable difference in life cycle emissions of HRJ from jatropha in comparison to other renewable oil plants is the emissions from nitrous oxide. The N_2O comes from nitrogen fertilizer than is needed to grow the plant.

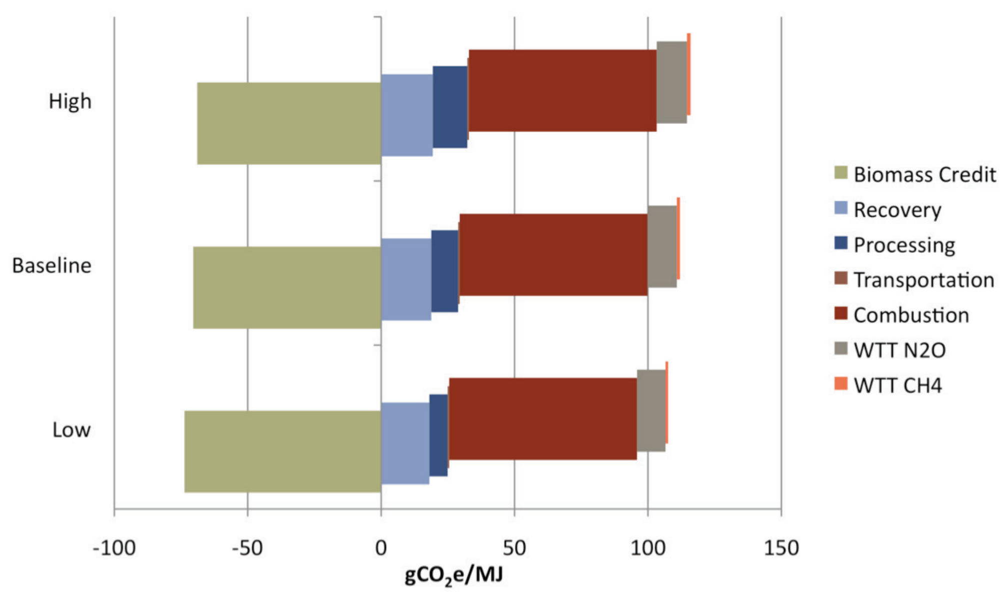

Figure B.16: Breakout of life cycle emissions of Jatropha HRJ by processing step for the low, baseline, and high emissions scenarios.

9. Summary of Life Cycle GHG Emissions and Fuel Production Potential from Biomass

The results from the CBTL, algal HRJ and jatropha 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.17. The presentation of these emissions is the same as Figures B.6, A.12 and A.16. 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 CO_2 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.

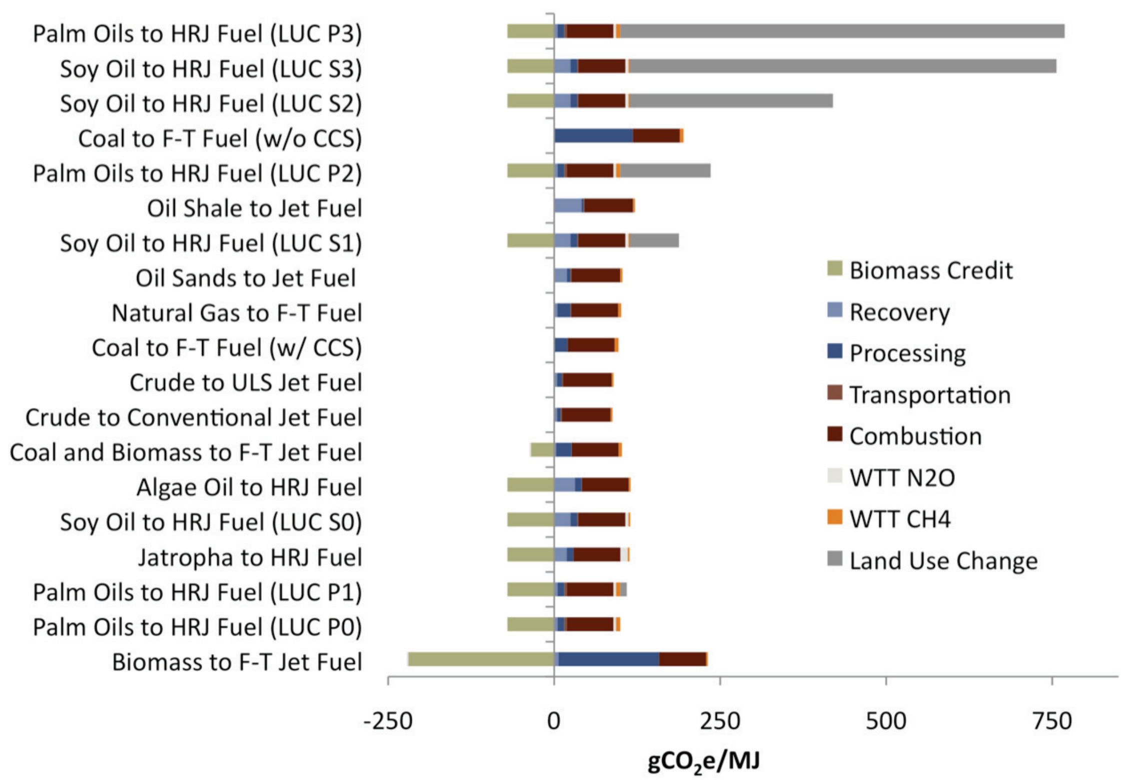

Figure B.17: Comparison of the life cycle GHG emissions from a wide range of alternative fuel pathways. The cumulative GHG emissions are given by the summation of the positive and negative contributions. This is not an all-encompassing list of alternative jet fuel options; it merely represents those examined by the authors as part of their ongoing research. **Note:** CCS denotes Carbon Capture and Storage. Land Use Change (LUC) scenarios were defined in Table B.2.

Figure B.18 gives the cumulative totals for each of the pathways presented in Figure B.17 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 but have the potential to have GHG emissions that are higher than conventional jet fuel. The estimates of life cycle GHG emissions from jatropha based HRJ have a much narrower range than either CBTL or algae and have an upper bound that is only 54% of the GHG emissions from conventional jet fuel. For this reason, it is essential not to simply assume that biofuels are beneficial for the environment without knowing the specifics of how the fuel is produced.

The focus of this work is to establish life cycle GHG emissions inventories for a variety of 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.7 summarizes the fuel production potentials for all of the biofuel pathways presented in Figures B.17 and A.18. The range in yields of fuel per kilogram of jatropha/algae/palm/soy arises partially from the variation in oil fraction. Jatropha seeds yield the most oil per kilogram (35%) followed by algae (25%), then palm kernels (22%) and finally soybeans (18%). Recall that there can be considerable variability in biomass oil yields, (e.g., in some of their briefings 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 jet fuel results is that only 25% of the fuel output from the F-T 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). All 976 liters of fuel produced carry an environmental benefit; therefore, accounting for the total CO_2 mitigated per liter of jet fuel produced involves looking at all the fuels produced. 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 a relatively small quantity of jet fuel (which has a relatively high energy density). Although the same feedstock could be 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 (Wong, 2008). Corn stover was the focus of this work because of its relative availability in large quantities.

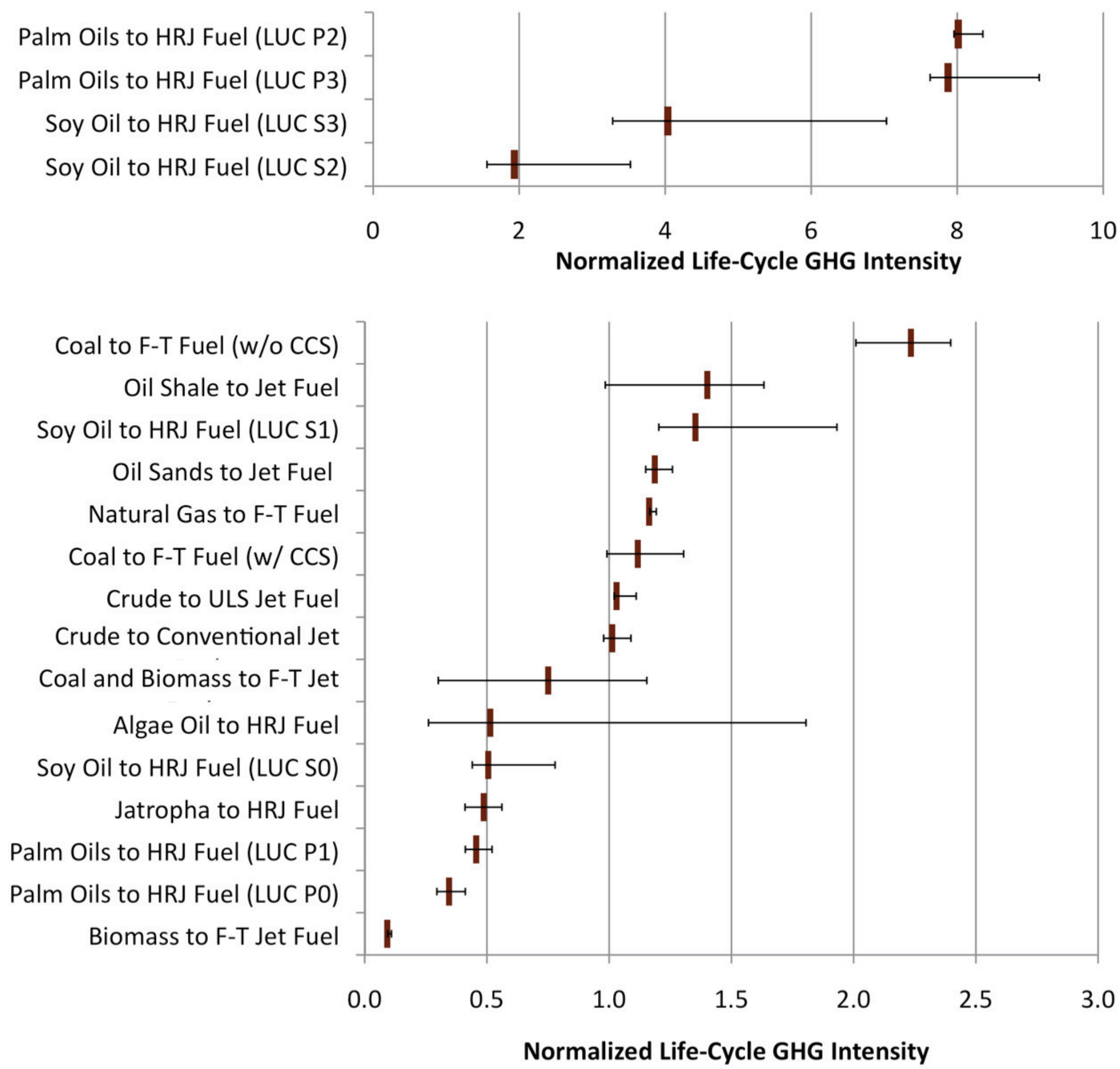

Figure B.18 Normalized life cycle GHG intensity for the alternative jet fuel pathways under consideration. Uncertainty bars represent the low emissions, baseline, and high emissions scenarios. Please note the different scales for the top and bottom portions of the figure. This is not an all-encompassing list of alternative jet fuel options; it merely represents those examined by the authors as part of their ongoing research. **Note**: CCS denotes Carbon Capture and Storage and Land Use Change (LUC) scenarios are defined in Table B.2.

The life cycle GHG emissions from Figures B.17 and A.18 and the production potentials that are summarized in Table B.7 can be combined to select fuel pathways that hold the most potential for reducing aviation's GHG emissions. This combination is needed to reduce aviation's GHG emissions because 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 oil 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.

Table B.7: Fuel production potential for various alternative jet fuels that could be derived from biomass. This is not an all-encompassing list of alternative jet fuel options; it merely represents those examined by the authors as part of their ongoing research.

Process	Biomass Type	Biomass Requirements ($kg_{Biomass}/MJ_{Jet\ Fuel}$)	Biomass Yield ($kg_{Biomass}$/ha/year)	Jet Fuel Yields ($L_{Jet\ Fuel}$/ha/year)	Other Fuel Yields[3] ($L_{diesel\ equivalent}$/ha/year)
BTL via Fisher Tropsch[1]	Corn Stover	0.542	4434	244	682
CBTL via Fisher Tropsch[1]	Corn Stover	0.090	4434	1464	4094
UOP via Hydroprocessing[2]	Jatropha	0.115	2500	649	275
UOP via Hydroprocessing[2]	Soybeans	0.220	2993	406	172
UOP via Hydroprocessing[2]	Palm FFB	0.174	19228	3301	1400
UOP via Hydroprocessing[2]	Algae	0.161	91250	16919	7176

Notes:
(1) F-T calculations assume a product slate of 25% jet fuel, 55% diesel and 20% naphtha by volume; May be lower.
(2) Hydro-renewable jet fuels produce renewable naphtha and mix propane gas as by products. Only renewable naphtha is counted as a liquid fuel but production of mix propane gas is minimal by comparison.
(3) Diesel equivalent is total energy of all liquid fuel byproducts represented as a volume of conventional diesel

10. Reducing Aviation Carbon Emissions 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 HRJ. In this section, various fuel pathways are considered along with conventional jet fuel to better understand the fuel usage and landmass that would be required for carbon neutral aviation growth. Work is ongoing to identify other pathways that could yield GHG emissions reductions.

10.1 Historical and Projected Fuel Usage and Life Cycle Emissions

For this section of the report, future life cycle emissions projections were created based on fuel use projections for both the US and the world. The US fuel use projections were based on an economic tool developed by MVA (MVA, 2009). The Modeling and Databases Task Force (MODTF) as part of the ICAO CAEP/8 Work Program was responsible for the global fuel use projections. In all cases, the life cycle emissions are based on conventional jet fuel with life cycle GHG emissions of 87.5 gCO2e/MJ.

There were five US fuel use scenarios developed by MVA in support of this analysis. A summary of those scenarios, detailing the input assumptions is as follows:

<u>Scenario D1 (*FESG Baseline: Baseline Fuel Price*)</u>: The Baseline projection was generated from FESG forecasts of demand and supply for 2016, 2026 and 2036, by route group and seat class, which were applied to the 2006 operations from the Common Operations Database (COD). The 'Frozen' NextGen technology assumptions were used to represent improvements in aircraft performance in the future with no improvement in aircraft specific fuel use. The Baseline projections also have no real changes in the cost components assumed through time: fuel price, labour costs, landing fees, route charges, volume related costs and maintenance costs all remain the same. Aircraft in the Baseline are retired according to the retirement curves calibrated by FESG, based on historic data.

Scenario D2 (*FESG Baseline: Baseline Fuel Price, Low Trend Technology*): The Low Trend Technology Baseline is based on Scenario D1, but uses a 'Low Trend' technology assumption to represent improvements in aircraft performance in the future with an average 1% per annum improvement in the specific fuel use of new aircraft.

Scenario D3 (*Reduced Trend APO Baseline: Baseline Fuel Price, Low Trend Technology*): Given the current and recent market conditions for aviation, FAA-APO produced a US passenger demand forecast in November 2008 showing a significant impact on short-term passenger growth. This forecast was used to adjust the FESG forecasts on a global basis, to reflect the APO profile to 2012. For the remaining years, the FESG demand growth curves were essentially shifted by around 5 years. The remaining assumptions were those used in Scenario D2.

Scenario D4 (*Strong Plus: Baseline Fuel Price*): The Strong Plus, Baseline fuel price scenario was based on Scenario D3, but uses a 'Very High Trend' technology assumption to represent improvements in aircraft performance in the future with an average 1.5% per annum improvement in new aircraft specific fuel use. Operational efficiency improvements, based on the NextGen High Density analysis have also been assumed, with improvements in the US realized 5 years prior to the global improvement.

Scenario D5 (*Strong Plus: High Plus Fuel Price*): The Strong Plus, High Plus fuel price scenario was based on Scenario D4 but with a forecast increase in fuel price through time. The US Energy Information Administration (EIA) International Energy Outlook for 2008 'High' price scenario was used as the basis for the fuel price scenario. An additional market based GHG measure, phased in over 5 years from a notional starting year of 2015 was added to the 'High' price scenario to generate the High Plus fuel price.

Scenarios D1 and D5 were chosen to represent the upper and lower bounds respectively of US fuel use in this analysis. Scenario D3 was chosen for use in the estimate of land requirements and carbon mitigation opportunities of the biofuel feedstocks. It was chosen because it falls between the two extremes. In further discussions, Scenario D3 is referred to as the 'US baseline' while scenario D1 is called the 'US high' and scenario D5 is called the 'US low'.

Emissions from each of the fuel use projections using the current mix of jet fuel within the United States are shown in Figure B.19. It is essential to stress that these emissions projections are based on a life cycle analysis that was conducted for the average US crude in 2005 and hence may not be an accurate estimates of future emissions.

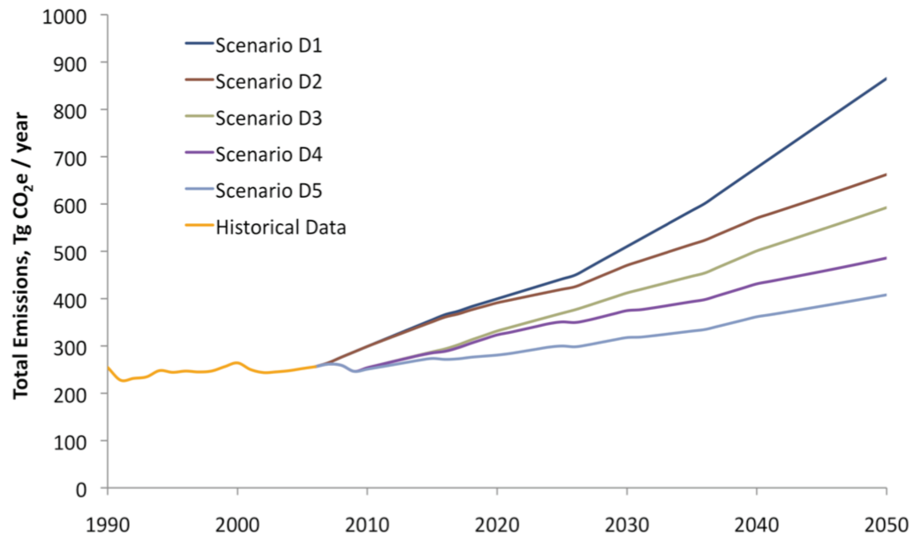

Figure B.19: Emissions from the projected fuel use cases developed by MVA for this analysis. The upper and lower extrema are taken as boundaries while the D3 projection has been chosen to demonstrate the carbon mitigation potential if the fuels and the corresponding land requirements. Historical data 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.

There were six global fuel use scenarios developed for the preliminary report of CAEP/8 environmental goals/trends in global aviation fuel burn presented at GIACC-3. A summary of those scenarios, detailing the input assumptions in terms of exogenous operational and technological improvements, is as follows:

Scenario G1 (*Do Nothing*): This scenario assumes no improvements in aircraft technology beyond those available today and no improvements from communication, navigational and air traffic management (CNS/ATM) investment or from planned initiatives, e.g., those planned in NextGen and SESAR.

Scenario G2 (*CAEP7 Baseline*): This scenario includes the CNS/ATM improvements necessary to maintain current ATM efficiency levels, but does not include any technology improvements beyond those available today.

Scenario G3 (*Low Aircraft Technology and Moderate Operational Improvement*): In addition to including the improvements associated with the migration to the latest CNS/ATM initiatives, e.g., those planned in NextGen and SESAR (Scenario G2), this scenario includes fuel burn improvements of 0.95 percent per annum for all aircraft entering the fleet after 2006 and prior to 2015, and 0.57 percent per annum for all aircraft entering the fleet beginning in 2015 out to 2036. It also includes additional fleet-wide moderate operational improvements of 0.5, 1.4 and 2.3 percent in 2016, 2026 and 2036, respectively.

Scenario G4 (*Moderate Aircraft Technology and Operational Improvement*): In addition to including the improvements associated with the migration to the latest CNS/ATM initiatives, e.g., those planned in NextGen and SESAR (Scenario G2), this scenario includes fuel burn improvements of 0.96 percent per annum for all aircraft entering the fleet after 2006 out to 2036, and additional fleet-wide moderate operational improvements of 0.5, 1.4 and 2.3 percent by 2016, 2026 and 2036, respectively.

Scenario G5 (*Advanced Technology and Operational Improvement*): In addition to including the improvements associated with the migration to the latest CNS/ATM initiatives, e.g., those planned in NextGen and SESAR (Scenario G2), this scenario includes fuel burn improvements of 1.16 percent per annum for all aircraft entering the fleet after 2006 out to 2036, and additional fleet-wide advanced operational improvements of 1.0, 1.6 and 3.0 percent by 2016, 2026 and 2036, respectively.

Scenario G6 (*Optimistic Technology and Operational Improvement*): In addition to including the improvements associated with the migration to the latest CNS/ATM initiatives, e.g., those planned in NextGen and SESAR (Scenario 2), this sensitivity study includes an optimistic fuel burn improvement of 1.5 percent per annum for all aircraft entering the fleet after 2006 out to 2036, and additional fleet-wide optimistic operational improvements of 3.0, 6.0 and 6.0 percent by 2016, 2026 and 2036, respectively. This sensitivity study goes beyond the improvements based on industry-based recommendations.

Scenarios G1 and G6 were chosen to represent the upper and lower bounds respectively of global fuel use in this analysis. As was the case with the US analysis, a baseline case, scenario G3, was chosen for use in the estimate of land requirements and carbon mitigation opportunities of the biofuel feedstocks. Scenario G3 was chosen as the baseline both because it lies in the middle of the range and because the assumed level of technological and operational improvements corresponds most closely to those of the US baseline scenario.

Emissions from each of the fuel use projections using the current mix of jet fuel within the United States are shown in Figure B.20. It is essential to stress that these emissions projections are based on a life cycle analysis that was conducted for the average US crude and hence are not an accurate estimates of the global average. An example of where this assumption is not valid is South Africa where the production of F-T jet fuel from coal by Sasol is used for operations from Johannesburg. In further discussions, Scenario G3 is referred to as the 'global baseline' while scenario G1 is called the 'global high' and scenario G6 is called the 'global low'.

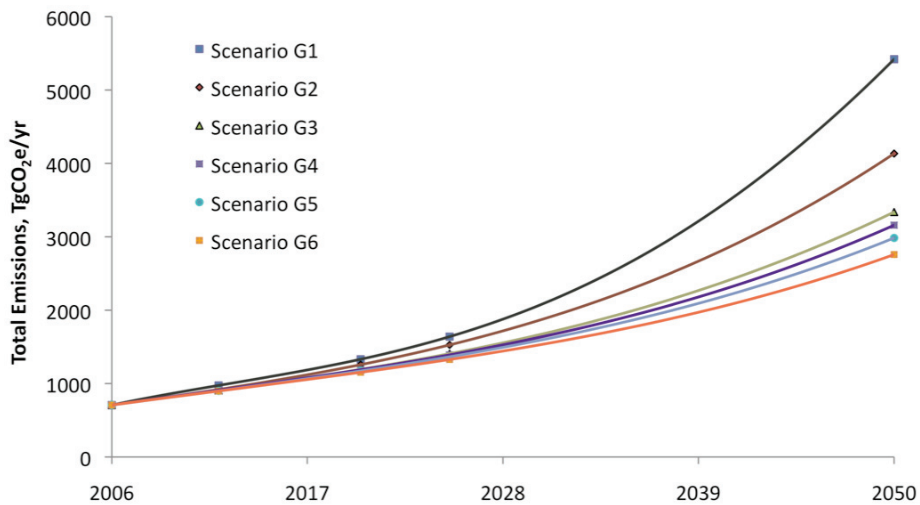

Figure B.20: Emissions from the projected fuel use cases developed for GIACC-4. The upper and lower extrema are taken as boundaries while Scenario 3 has been chosen to demonstrate the carbon mitigation potential if the fuels and the corresponding land requirements. The baseline jet fuel life cycle GHG emissions were used to estimate the total life cycle emissions.

10.2 Carbon Neutrality Life Cycle Goals

The prospect of carbon neutral growth for the aviation industry was considered for a target emissions level equal to that from 2006 (also known as 2006 level emissions) and then again for a target emissions level 10% below those from 2006. The US fuel use projections came from the US baseline scenario and the global fuel use projections came from the global baseline scenario. For the 2006 emissions target to be met in the year 2050, the life cycle GHG emissions from the average fuel being used in the US can be no higher than 43.3% of conventional US jet fuel. The same calculation on the global scale determined that the threshold life cycle GHG emissions from the average fuel being used globally is 20.3% of conventional US jet fuel. These values are not only dependent on the chosen baseline year but also on the fuel usage scenario adopted. Tables B.8 and B.9 show how the threshold of carbon neutrality changes depending on the target emissions level and fuel use scenario. 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 US jet fuel (87.5gCO_2e/MJ).

Based on the life cycle results, algal HRJ, soy HRJ (with LUC Scenario S0), palm HRJ (with LUC Scenarios P0 or P1), and jatropha HRJ all have the potential to meet the emissions target under the US low fuel use scenario (Scenario D5). However, the palm and soy HRJ pathways would incur unacceptable land use change emissions prior to reaching a production level sufficient to meet national jet fuel demand. Only the low emissions version of CBTL has the potential to meet this emissions target under any of the fuel use scenarios. The 2006 emissions target under the US baseline fuel projections is too stringent for the baseline GHG emissions of the fuels considered in this analysis; however, optimistic assumptions for the life cycle emissions and/or the projected fuel use allows for all of the biofuel pathways without land use changes to achieve the target.

Table B.8: Average life cycle GHG emissions required to achieve carbon neutral aviation growth for the US in 2050. Two different emissions targets and three different fuel use scenarios are considered. Emissions are given as a percentage of those for conventional US jet fuel. Fuel use scenario definitions are given previously in this section.

US Emissions Target	Fuel Use Scenario D5	Fuel Use Scenario D3	Fuel Use Scenario D1
Equal to 2006	62.8%	43.3%	29.6%
10% below 2006	56.6%	38.9%	26.7%
Note: 2006 level US emissions from aviation are equal to those from 1990. The lowest emissions in that period occurred in 2001 where emissions were 11.2% below 2006			

Table B.9: Average life cycle GHG emissions required to achieve carbon neutral aviation growth for the world in 2050. Two different emissions targets and three different fuel use scenarios are considered. Emissions are given as a percentage of those for conventional US jet fuel. Fuel use scenario definitions are given previously in this section.

Global Emissions Target	Fuel Use Scenario G6	Fuel Use Scenario G3	Fuel Use Scenario G1
Equal to 2006	25.7%	21.2%	13.1%
10% below 2006	23.1%	19.1%	11.8%
Note: Emissions targets for the world study were chosen in order to remain consistent with the US only study.			

None of the fuels considered, given the input assumptions of this study, have baseline life cycle emissions that are sufficiently low to meet the global emissions targets under any of the global fuel use projections. Global aviation is growing adequately fast that it appears that none of the fuels considered in this analysis are capable of providing GHG reductions leading to global carbon neutral aviation growth.

Although this analysis has shown the limited potential of biofuels as a complete environmental solution for the aviation industry, the subsequent section of this report quantifies the environmental benefits that could be gained through the widespread introduction of biofuels. It is essential not to disregard biofuels as a form of emissions mitigation simply because they cannot solve the problem alone; however, they are an essential component of a broader approach to achieving GHG reductions.

10.3 Potential Carbon Reduction and Land Requirements for United States Biofuel Use

Both HRJ and CBTL have the potential to reduce GHG emissions from aviation. To better understand their potential, a future was envisioned where biofuels have been adopted on a scale that is sufficient to displace conventional jet fuel. Two scales were considered. In the first, the biofuels are being used as a 50/50 (vol%) blend with conventional jet fuel. In the second, biofuels have replaced conventional jet fuel. These two hypothetical future scenarios examine single feedstock solutions; in other words, all of the biofuel comes from a single source. This is obviously not a real world solution, but it helps to frame the potential for various fuel pathways. Soy-based and palm-based HRJ feedstocks were examined in a limited way because their widespread use would inherently lead to land use changes that would have unacceptable increases in GHG emissions. The future scenarios are quantified both in terms of a fraction of the 2006 emissions and a fraction of the emissions that would have occurred given the use of conventional jet fuel. This business as usual, BAU, scenario uses the assumption that the life cycle GHG emissions of jet fuel are constant with time. In addition to examining the change in GHG emissions, the land requirements to yield the requisite biomass were estimated.

Table B.10 shows the change in GHG emissions for a range of biofuel options under the 50/50 blend scenario using the US baseline fuel use projection. Beyond the simple emissions savings, the last column shows the types and quantities of the other fuels that are made as a result of renewable jet fuel production. Notice that although CBTL does not offer the same emissions reductions as other fuel pathways, each kilogram of F-T jet production results in 15 times more production of other fuels that result in environmental benefits for other energy consuming sectors (such as diesel fuel in ground transportation). Table B.11 quantifies the potential emissions reductions for the case where all fuel needs are met through a 100% biofuel substitute (CBTL or HRJ). The same points of interest that were highlighted for the 50/50 (vol%) blend are also relevant here.

Table B.10: Emissions from aviation in 2050 given that all jet fuel demands are met with a 50/50 blend of biofuel with conventional jet fuel. Emissions are stated relative to those from 2006 as well as relative to those that would have occurred without the usage of any biofuels. Additional biofuels made in the process of making renewable jet fuel are also quantified.

Feedstock Type	Life Cycle Emissions ($TgCO_2e/yr$)	Fraction of 2006 Emissions Target in 2050	Fraction of BAU Emissions	Other Fuels Created with 2050 Production(1)
Algae	451.6	1.75	0.76	• 34 billion kg Naphtha • 6 billion kg MPG(3)
Coal and Biomass(2)	521.1	2.02	0.87	• 220 billion kg Diesel • 80 billion kg Naphtha
Jatropha	443.5	1.72	0.74	• 34 billion kg Naphtha • 6 billion kg MPG(3)

(1) 2050 production assumes that all US jet fuel demands in that year are met with 50/50 (vol %) blend of conventional jet fuel with HRJ from the respective feedstock
(2) F-T calculations are assume a product slate of 25% jet fuel, 55% diesel and 20% Naphtha
(3) Mix Propane Gas

Table B.11: Emissions from aviation in 2050 given that all jet fuel demands are met with a 100% biofuel substitute. Emissions are stated relative to those from 2006 as well as relative to those that would have occurred without the usage of any biofuels. Additional biofuels made in the process of making renewable jet fuel are also quantified.

Feedstock Type	Life Cycle Emissions ($TgCO_2e/yr$)	Fraction of 2006 Emissions Target in 2050	Fraction of BAU Emissions	Other Fuels Created with 2050 Production(1)
Algae	300.3	1.16	0.50	• 69 billion kg Naphtha • 13 billion kg MPG(3)
Coal and Biomass(2)	441.7	1.72	0.74	• 448 billion kg Diesel • 163 billion kg Naphtha
Jatropha	284.0	1.10	0.46	• 69 billion kg Naphtha • 13 billion kg MPG(3)

(1) 2050 production assumes that all US jet fuel demands in that year are met with 100% pure HRJ from the respective feedstock
(2) F-T calculations are assume a product slate of 25% jet fuel, 55% diesel and 20% Naphtha
(3) Mix Propane Gas

The most important point to take from Tables B.10 and B.11 are that biofuels made from algae and jatropha can be used to reduce emissions from the aviation industry by approximately 50% compared to business as usual case. Soybeans and palm HRJ fuels could also offer similar potential if land use changes were neglected, but this assumption is invalid at the production scales being considered here. CBTL could reduce emissions by 26% compared to the business as usual case and also result in the widespread production of F-T diesel to be used for ground transportation.

Given the fuel usage projections from Figure B.19 as well as the fuel yield per hectare of land from Table B.7, land area requirements were estimated such that sufficient biomass would be grown in the US for the 50/50 blend and 100% pure biofuel scenarios. These land areas only consider the arable land requirements; they do not include land that would be needed for infrastructure such as roads and production facilities nor do they include existing towns, cities, etc. Figure B.21 presents the requisite landmass relative to a map of the majority of North America. 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 solid outer circles correspond to the land area for the 100% pure biofuel case while the inner dashed circles correspond to the 50/50 blend of the biofuels with conventional jet fuel. The land masses correspond to exactly the same cases considered in Tables B.10 and B.11 and hence can be used in conjunction with the emissions reduction potential of each fuel to simultaneously understand multiple benefits and limitations surrounding each feedstock. Although it was not included in Table B.10 and B.11, the area required for palm HRJ was added to the map for comparison purposes. Soybean HRJ was not included on the map because it was too large; specifically, the landmass was 1.6 times larger than that required for jatropha HRJ.

In 2006, 1.33 million square km of land was used for crop production in the US (USDA, 2007). A land mass comparable to 4.4% of current cropland (59,000 km^2) would be sufficient to create a 50-50 blend of algal HRJ with conventional jet fuel while an area comparable 9.0% of current cropland (120,000 km^2) would be needed to create sufficient algae to replace all of the conventional jet fuel with algal HRJ.

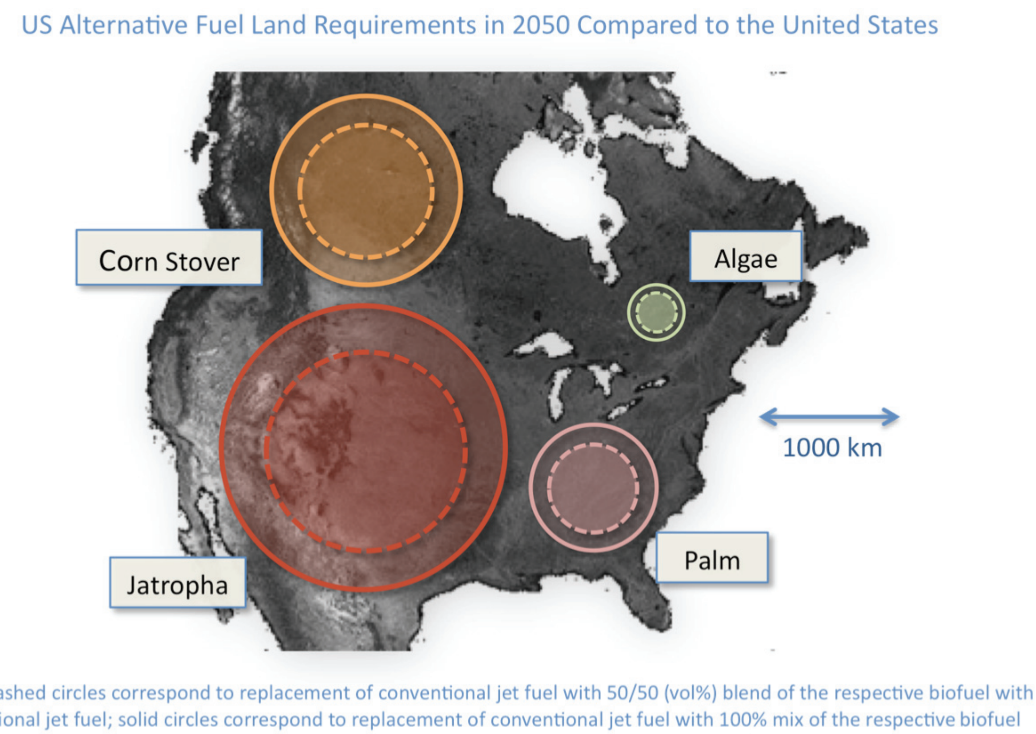

Figure B.21: Land area requirements for different biofuels given total replacement of US conventional jet fuel use with a 50/50 (vol%) blend of biofuel and conventional jet fuel (dashed circles) or with a 100% pure biofuel (solid circles).

Figure B.21 graphically demonstrates the challenges of land mass requirements, growth and maintenance logistics as well as infrastructure limitations faced by biofuels; Tables B.10 and B.11 quantify the environmental benefits that could be realized from each of the fuels, however, there is still a substantial aspect missing from the analysis. Each land requirement corresponds to the same level of biofuel production but each feedstock requires a different quantity of biomass to create the biofuel. Currently, there is no industrial scale production of CBTL fuels, no industrial scale production of algae and no industrial scale production of jatropha. Soybeans and palm production are well developed industries but even the 50/50 blend scenario requires 3.1 times current worldwide production of palm (Flexnews, 2008) and 3.4 times current global production (USDA, 2009) of soybeans to meet the projected US demand for jet fuel in 2050. In order to get these industries to the scale at which they can have a measureable environmental benefit, quick development and mobilization of technology must occur at large scales.

Assuming the feedstocks 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 biomass resources for ethanol may be more effective from perspectives of energy efficiency and CO_2 mitigation when used in heat and electricity rather than for transportation where the displaced petroleum would be used for transportation.

10.4 Land Requirements for Worldwide Biofuel Use

The analysis methodology used to estimate the land requirements required for biofuel production in the US was also extended to a global scale. The simple extension is done by scaling the land area for each feedstock by the ratio of projected 2050 fuel use from the global baseline to that from the US baseline. It is not appropriate to calculate a reduction in the global emissions through the introduction of biofuels because the life cycle values for each of the fuels from Figure B.18 are based on US input assumptions and parameters for 2015. Global estimates using this life cycle inventory would be flawed even if every other aspect of the analysis could be considered perfect.

Figure B.22 shows approximate land requirements for each feedstock type needed to meet global jet fuel demand in 2050 using a 50/50 blend of biofuel with conventional fuel or with a 100% pure biofuel. The areas are drawn on a Gall-Peters projection of the world. A standard map increasingly inflates areas according to their distance from the equator. The Gall-Peters projection distorts the image such that areas of equal size on the globe are also equally sized on the map. Such a projection is appropriate when drawing a two dimensional circle over certain regions. As was the case with the North American map of Figure B.21, 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.

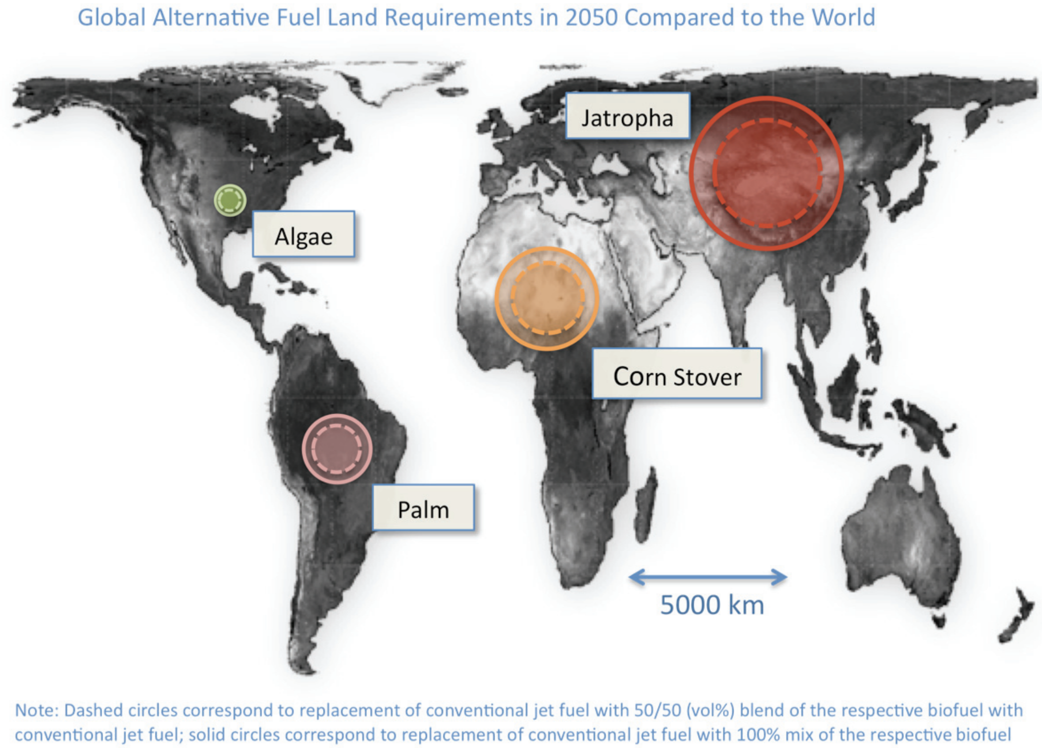

Figure B.22: Land area requirements for different biofuels given total replacement of global conventional jet fuel use with a 50/50 (vol%) blend of biofuel and conventional jet fuel (dashed circles) or with a 100% pure biofuel (solid circles).

The issues of large-scale implementation, which were discussed in conjunction with the US analysis, are exacerbated when taken to a global scale. It is inconceivable that an area the size of Russia would be devoted to the production of jatropha for HRJ. It is equally unlikely that palm production of the scale shown on Figure B.22 would be devoted to jet fuel. Both of these scenarios would lead to land use changes that would increase GHG emissions. However, it is not out of the realm of possibility that an area similar to France could be flooded for algae ponds for HRJ production - the algae area on Figure B.22 is slightly larger than the nation of France. However, this industry would require considerable economic investment and require an extended period of time to develop. Furthermore, the algal growth rates that are at the foundation of the analysis behind Figure B.22 are based on the use of an external source of CO_2 that fuels growth; thus, they depend on the continued use of fossil fuels by other industries such as electricity.

The results from Figures B.21 and B.22 reveal two important findings: no single feedstock or region will be able to bare the burden for the entire planet and large scale implementation of biofuels will come as a result of a superposition of different feedstocks. As such, it is critical to continue examining feedstocks that could be used to create transportation fuels, such as jet fuel, that: do not require arable land, require a minimum of fresh water, and are grown with large yields per hectare. There are other fuel pathways, such as halophyte-based HRJ, that could meet such criteria. This fuel production pathway, and others like it, is currently being considered as part of this ongoing research effort.

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