ANL/ESD/12-8

Life-Cycle Analysis of Alternative Aviation Fuels in GREET

Energy Systems Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Availability of This Report

This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

ANL/ESD/12-8

Life-Cycle Analysis of Alternative Aviation Fuels in GREET

by
A. Elgowainy,[1] J. Han,[1] M. Wang,[1] N. Carter,[2] R. Stratton,[2] J. Hileman,[3]
A. Malwitz,[4] and S. Balasubramanian[4]
[1]Energy Systems Division, Argonne National Laboratory
[2]Massachusetts Institute of Technology
[3]Massachusetts Institute of Technology; currently with the Federal Aviation Administration
[4]John A. Volpe National Transportation Systems Center

June 2012

CONTENTS

FIGURES

FIGURES (CONT.)

TABLES

TABLES (CONT.)

ACKNOWLEDGMENTS

This research effort by Argonne National Laboratory was supported by the Office of Biomass Program and the Vehicle Technology Program of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy under Contract Number DE-AC02-06CH11357. We are particularly grateful to Zia Haq of the Office of Biomass Program and Jake Wards of the Office of Vehicle Technology Program for their support of this study. We also wish to thank Ignasi Palou-Rivera, Jennifer Dunn, and Edward Frank of Argonne National Laboratory for contributing their knowledge and experience in petroleum refining and upgrading processes, biomass feedstock characterization, and algae process descriptions in support of this work. The authors are also grateful to Mary Fitzpatrick of Argonne National Laboratory for reviewing and editing this report.

The research effort for this study by the Massachusetts Institute of Technology was supported by the Office of Environment and Energy, U.S. Federal Aviation Administration (FAA), and Air Force Research Laboratory (AFRL), U.S. Department of Defense, and the Defense Logistics Agency Energy (DLA-Energy), U.S. Department of Defense, under the Partnership for AiR Transportation Noise and Emissions Research (PARTNER) Center of Excellence Cooperative Agreement Number 09-C-NE-MIT. The effort was managed by Warren Gillette (FAA), Bill Harrison and Tim Edwards (AFRL), and Daniel Baniszewski (DLA-Energy). The opinions, findings, conclusions, or recommendations expressed in this document are those of the authors and do not necessarily reflect the views of the FAA, AFRL, or DLA-Energy.

ACRONYMS AND ABBREVIATIONS

AAFEX-1	Alternative Aviation Fuels Experiment
AD	anaerobic digestion
AEDT	Aviation Environmental Design Tool
Argonne	Argonne National Laboratory
ASTM	American Society for Testing and Materials
BJ	business jet
BTL	biomass to liquid
CAPP	Canadian Association of Petroleum Producers
CCS	carbon capture and storage
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CTL	coal to liquid
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EnSys	EnSys Energy, Inc.
FAA	U.S. Federal Aviation Administration
FT	Fisher-Tropsch
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GTL	gas to liquid
HEFA	hydroprocessed esters and fatty acids
HRJ	hydroprocessed renewable jet
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
JP-8	jet propulsion fuel type 8
JP-5	jet propulsion fuel type 5
K_2O	potassium
KXL	Keystone XL (EnSys)
LCA	life-cycle analysis
LEA	lipid extracted algae

LQ	large quad
LQ-F	large quad —freight
LTA	large twin aisle
LTA-F	large twin aisle — freight
LTO	landing and takeoff
MIT	Massachusetts Institute of Technology
N	nitrogen
N_2O	nitrous oxide
NO_x	nitrogen oxides
P_2O_5	phosphorus
PADD	petroleum administration for defense districts
PFEI	payload fuel energy intensity
PM_{10}	particulate matter with diameters measuring 10 micrometers or less
PTW	pump-to-wheel
PTWa	pump-to-wake
RJ	regional jet
SA	single aisle
SA-F	single aisle — freight
SKA	synthetic kerosene aromatic
SO_x	sulfur oxides
SPK	synthetic paraffinic kerosene
STA	small twin aisle
STA-F	small twin aisle — freight
TMX	Transmountain
ULSJ	ultra-low sulfur jet
UOP	a division of Honeywell Inc. for fuel refining, processing, and petrochemical production
VOC	volatile organic compound
Volpe Center	John A. Volpe National Transportation Systems Center
WTP	well-to-pump
WTWa	well-to-wake

UNITS OF MEASURE

Btu	British thermal unit(s)
g	gram(s)
gal	gallon(s)
J	joule(s)
kg	kilogram(s)
kJ	kiloJoule(s)
km	kilometer(s)
kWh	kilowatt hour(s)
L	liter(s)
lb	pound(s)
m^3	cubic meter(s)
mbd	million barrel(s) per day
MJ	megajoule(s)
MMBtu	million Btu(s)
ppm	part(s) per million

LIFE-CYCLE ANALYSIS OF ALTERNATIVE AVIATION FUELS IN GREET

by

Amgad Elgowainy, Jeongwoo Han, Michael Wang, Nicholas Carter, Russell Stratton, James Hileman, Andrew Malwitz, and Sathya Balasubramanian

ABSTRACT

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, developed at Argonne National Laboratory, has been expanded to include well-to-wake (WTWa) analysis of aviation fuels and aircraft. This report documents the key WTWa stages and assumptions for fuels that represent alternatives to petroleum jet fuel. The aviation module in GREET consists of three spreadsheets that present detailed characterizations of well-to-pump and pump-to-wake parameters and WTWa results. By using the expanded GREET version (GREET1_2011), we estimate WTWa results for energy use (total, fossil, and petroleum energy) and greenhouse gas (GHG) emissions (carbon dioxide, methane, and nitrous oxide) for (1) each unit of energy (lower heating value) consumed by the aircraft or(2) each unit of distance traveled/ payload carried by the aircraft.

The fuel pathways considered in this analysis include petroleum-based jet fuel from conventional and unconventional sources (i.e., oil sands); Fisher-Tropsch (FT) jet fuel from natural gas, coal, and biomass; bio-jet fuel from fast pyrolysis of cellulosic biomass; and bio-jet fuel from vegetable and algal oils, which falls under the American Society for Testing and Materials category of hydroprocessed esters and fatty acids. For aircraft operation, we considered six passenger aircraft classes and four freight aircraft classes in this analysis.

Our analysis revealed that, depending on the feedstock source, the fuel conversion technology, and the allocation or displacement credit methodology applied to co-products, alternative bio-jet fuel pathways have the potential to reduce life-cycle GHG emissions by 55–85 percent compared with conventional (petroleum-based) jet fuel. Although producing FT jet fuel from fossil feedstock sources — such as natural gas and coal — could greatly reduce dependence on crude oil, production from such sources (especially coal) produces greater WTWa GHG emissions compared with petroleum jet fuel production unless carbon management practices, such as carbon capture and storage, are used.

This page intentionally left blank.

EXECUTIVE SUMMARY

ES.1 STUDY DESCRIPTION

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model was expanded to include aviation fuel production pathways and aircraft operations, allowing researchers to examine the environmental sustainability of various alternative aviation fuels. This report documents the expansion of the model to evaluate the life-cycle energy use and greenhouse gas (GHG) emissions associated with the production of jet fuel alternatives for various types and classes of aircraft.

Life-cycle analysis (LCA) includes all stages in a product's life — from the extraction of raw materials through the materials' processing, manufacture, distribution, use, and disposal or recycling. For this analysis, we account for all the stages in the life cycle of aviation fuels, including feedstock recovery and transportation, fuel production and transportation, and fuel consumption in an aircraft. The exploration and recovery activities from the well to fuel production and the subsequent transportation to the pump constitute the well-to-pump (WTP) stage. The combustion of fuel during aircraft operation constitutes the pump-to-wake (PTWa) stage. These two stages combined comprise the well-to-wake (WTWa) fuel cycle.

ES.2 BACKGROUND

Worldwide air traffic is expected to grow significantly over the coming decades. Boeing (2011) predicts an annual global average growth rate of 5.1 percent for passengers and 5.6 percent for cargo through 2030. The aviation industry is exploring ways to help ensure sustainable growth of air traffic, including methods to reduce fuel consumption and GHG emissions. In collaboration with the Massachusetts Institute of Technology (MIT), Argonne recently expanded the GREET model to include new pathways for alternative aviation fuels production and aircraft characterization.

ES.3 METHODOLOGY

The WTWa results are presented in terms of energy use and GHG emissions

- For each unit of energy (lower heating value) consumed by the aircraft (e.g., Joules or grams per MJ of consumed fuel);
- For each great-circle distance[1] traveled by each passenger for passenger aircrafts (e.g., Joules or grams per passenger-km); and

[1] Great-circle distance is the shortest distance between any two points on the surface of a sphere, measured along a path on the surface of the sphere.

- For each great-circle distance traveled per kg of good for freight aircrafts (e.g., joules or grams per kg-km).

The energy use is broken down by type in the WTWa cycle; energy types include fossil, petroleum, natural gas, coal, and renewable. Our GHG emissions calculation combines carbon dioxide, methane, and nitrous oxide with their global warming potentials (1, 25, and 298, respectively, based on a 100-year time window).

The jet fuel production pathways in GREET include the following:

- Petroleum-based jet fuel from conventional and unconventional sources (conventional oil and oil sands);

- Fisher-Tropsch (FT) jet fuel from coal, biomass, and conventional and renewable natural gas;

- Hydroprocessed renewable jet (HRJ) fuels (also known as hydroprocessed esters and fatty acids [HEFA]) from soy oil, palm oil, rapeseed oil, jatropha oil, camelina oil, and algae oil; and

- Renewable jet fuel from hydrotreated pyrolysis oil.

For aircraft operation (PTWa), we included in GREET six classes of passenger aircraft (single aisle, small twin aisle, large twin aisle, large quad, regional jet, and business jet), and four classes of freight aircraft (single aisle, small twin aisle, large twin aisle, and large quad). Each aircraft class was characterized by its average payload, average trip great-circle distance, total flight payload fuel energy intensity, emissions during cruise, and fuel consumption and emissions during a landing and takeoff (LTO) cycle. The LTO and cruise fuel use and emissions for alternative jet fuels were normalized relative to the baseline petroleum jet fuel's energy use and emissions. We distribute the LTO energy use and emissions over the entire flight by spreading their numerical values over the flight payload and great-circle distance.

ES.4 DATA SOURCES AND ASSUMPTIONS

Table ES-1 lists the sources for the data and assumptions used in the study.

ES.5 GREET ENHANCEMENTS

The aviation module in GREET consists of three spreadsheets that present detailed characterization of WTP and PTWa pathways and parameters, as well as WTWa results. The jet fuel production processes from the various feedstock sources are incorporated in a single spreadsheet (JetFuel_WTP). The upstream processes — such as petroleum recovery and transportation for petroleum jet fuel, coal mining or natural gas recovery and processing for FT

TABLE ES-1 Sources for Data and Assumptions Used in WTWa Study of Aviation Fuels

Data/Assumption	Source
Estimates of process fuels used in petroleum refineries	Energy Information Administration's (EIA's) annual survey of the five Petroleum Administration for Defense Districts (EIA 2011a,b)
Method to allocate the refineries' energy use and emissions among the fuel products	Argonne technical memorandum (Palou-Rivera et al. 2011).
Energy, fertilizer and pesticide use for various cellulosic biomass feedstock options	Several Argonne studies (Han et al. 2011; Dunn et al. 2011)
FT production from coal and cellulosic biomass	Argonne study (Xie et al. 2011)
Production assumptions for soybeans oil	Argonne study (Huo et al. 2008)
Production assumptions for palm, jatropha, and rapeseed oil	MIT study (Stratton et al. 2010)
Production assumptions for algal oil	Argonne study (Frank et al. 2011)
Production assumptions for camelina oil	Shonnard et al. (2010)
Energy use and emissions associated with HRJ fuel production from plant oils	MIT study (Pearlson 2011)
Energy use and emissions associated with jet fuel production via fast pyrolysis of cellulosic biomass	Argonne study (Han et al. 2011).
Energy use and emissions associated with aircraft operation	Department of Transportation, John A. Volpe National Transportation Systems Center (Volpe Center) (Malwitz 2011)

jet fuel, and bio-oil production from plant or algal feedstocks — are in their original respective spreadsheets within GREET (i.e., in the petroleum, coal, natural gas, and bio-oil spreadsheets, respectively, for these feedstock sources). The different aircraft classes, their operational characteristics, and the properties of the conventional and alternative jet fuels are incorporated in another spreadsheet (JetFuel_PTWa). The WTWa energy use and emissions results for various jet fuels and blends are listed in a third spreadsheet (JetFuel_WTWa) for the different aircraft types and classes, on the basis of various LCA functional units (i.e., per MJ of fuel use, per kg-km, and per passenger-km). Argonne is developing a user manual for the aviation module in GREET; the manual will be posted on the GREET Web site (http://greet.es.anl.gov) upon completion.

This page intentionally left blank.

1 INTRODUCTION

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, developed by Argonne National Laboratory (Argonne), was expanded to include aviation fuel production pathways and aircraft operations, allowing researchers to examine the environmental sustainability of various alternative aviation fuels. This report documents the expansion of the model to evaluate the life-cycle energy use and greenhouse gas (GHG) emissions associated with the production of jet fuel alternatives used to propel various types and classes of aircraft.

Life-cycle analysis (LCA) includes all the stages of a product's life — from the extraction of raw materials through the materials' processing, manufacture, distribution, use, and disposal or recycling. For this analysis, we account for all the stages in the life cycle of aviation fuels, including feedstock recovery and transportation, fuel production and transportation, and fuel consumption by aircraft. The exploration and recovery activities from the well to fuel production, and the subsequent transportation to the pump, constitute the well-to-pump (WTP) stage. The combustion of fuel during aircraft operation constitutes the pump-to-wake (PTWa) stage. The combination of these two stages comprise the well-to-wake (WTWa) fuel cycle. Figures 1 and 2 show the WTWa stages for the conventional jet fuel and the bio-based alternative jet fuel pathways in GREET, respectively.

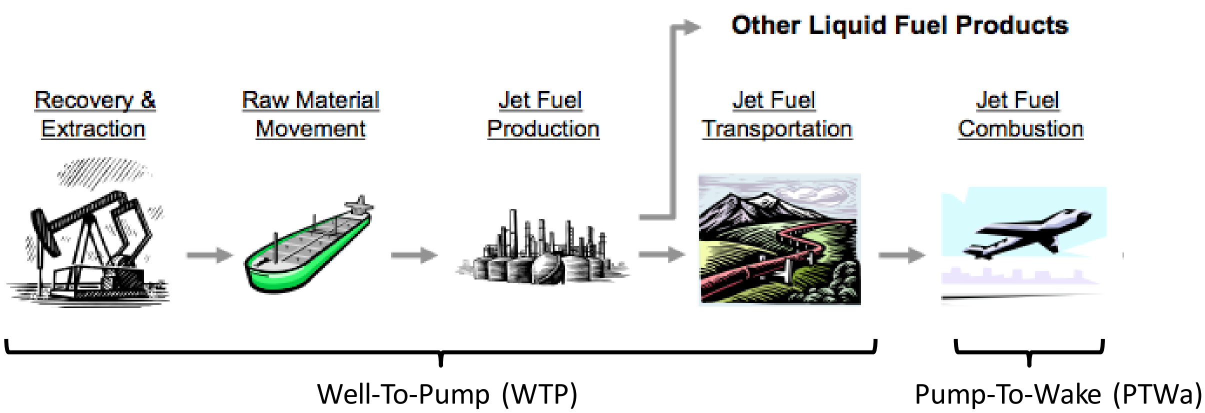


FIGURE 1 WTWa Pathway for Conventional Jet Fuel

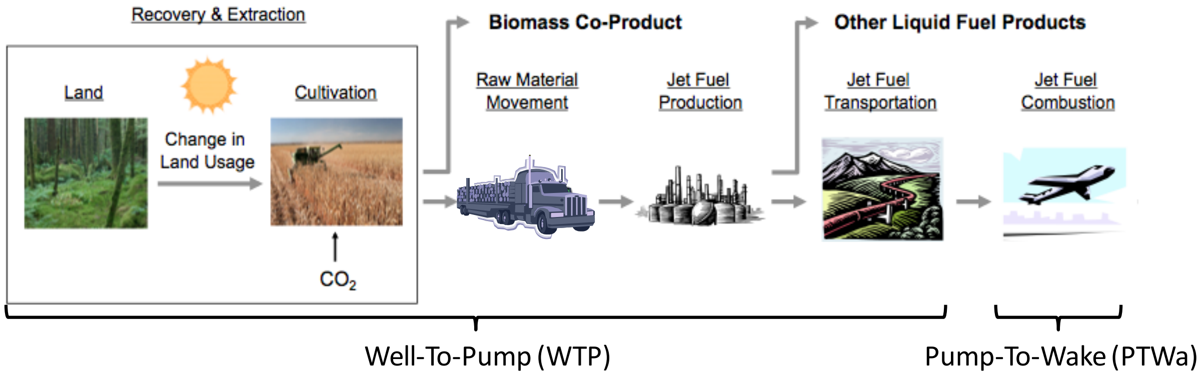


FIGURE 2 WTWa Pathway for Bio-Based Alternative Jet Fuel

1.1 BACKGROUND

The aviation industry carries approximately 2.3 billion passengers and 38 million metric tons of freight annually, while contributing 8 percent of the global gross domestic products and 2 percent of the global carbon dioxide (CO_2) emissions (Concil 2006; International Air Transport Association [IATA] 2011). Global emissions of CO_2 from the aviation sector reached 660 million metric tons in 2010 (IATA 2011).

Worldwide air traffic is expected to grow annually by an average of 5.1 percent for passengers and 5.6 percent for cargo by 2030 (Boeing 2011). The U.S. Federal Aviation Administration (FAA) forecasts that one billion passengers will be flown on U.S. commercial carriers in 2021, up from 720 million passengers in 2010. FAA also projected an average annual growth rate of 3.7 percent over the next 5 years, followed by 2.5 percent per year through 2031(FAA 2011a).

The aviation industry is exploring the economical, societal, and environmental factors related to the sustainable growth of air traffic (IATA 2011). The industry seeks to reduce fuel consumption and GHG emissions as the two major drivers for such sustainable growth. To help meet these goals, the IATA has set targets to improve fuel efficiency at an annual average rate of 2 percent through 2050, achieve neutral carbon growth starting in 2020, and reduce net CO_2 emissions by 50 percent in 2050 compared with 2005 emissions (IATA 2011; International Civil Aviation Organization [ICAO] 2010). Improvements in key design and operational parameters are needed to meet these targets. Such improvements include designing more efficient aircraft, developing shorter routing options, optimizing flight management and planning, using auxiliary power units, managing aircraft weight, and using biofuels (IATA 2011).

The European Union Emissions Trading Scheme, launched in 2005, requires large installations to monitor and report their CO_2 emissions. Under the trading scheme, each installation receives an initial allowance of emissions and is given the opportunity to purchase or sell emission credits, depending on its reported emissions relative the initial allowance. Starting in 2012, aviation emissions will be included in the European Union Emissions Trading Scheme. However, the trading scheme is being challenged in the European Court of Justice by airlines in a number of countries, including the United States (IATA 2011).

The 2011 United Nations Framework Convention on Climate Change, held in Durban, South Africa, established a global treaty to limit carbon emissions that would be legally binding for all countries. The terms of the treaty will be prepared by 2015 and take effect in 2020. However, considering the projected growth in the aviation sector, the sector's carbon emissions will likely increase; in response, airlines will need to reduce their fuel use, increase their use of biofuels, and/or purchase emissions allowances. Experts predict that the gains in efficiency from technological advances and operational optimization will not offset the emissions generated by the expected growth in air traffic. The "mitigation gap" between air transport emissions growth (after incorporating efficiency improvements) and the goal of a 50 percent reduction in net CO_2 emissions by 2050 (compared with 2005) must be closed using other strategies (ICAO 2010).

Drop-in biofuels are one of the primary candidates to close the GHG emissions mitigation gap in response to the projected growth in air travel. Sustainable biofuels produced from biomass or plant oils have the potential to reduce life-cycle GHG emissions in the aviation sector. IATA has set a target of using 10 percent alternative fuels in aircraft by 2017 (IATA 2007). FAA has set a target of having 1 billion gallons of alternative fuels in aviation use by 2018 (FAA 2011b). The U.S. Air Force has set a goal to acquire 50 percent of domestic aviation fuel from alternative fuel blends by 2016; these blends must be cost competitive with and "greener" than fuels produced from conventional petroleum (U.S. Air Force 2010). The U.S. Navy has also set a goal that by 2020, half of its total energy consumption afloat will come from alternative sources (U.S. Navy 2010). In July 2011, the American Society for Testing and Materials (ASTM) certified the blending of up to 50 percent hydroprocessed esters and fatty acids (HEFA) fuel with conventional jet fuels as drop-in fuels to power aircraft engines (ASTM 2011). This follows a similar certification in 2009 that enables the blending of up to 50 percent Fisher-Tropsch (FT) fuel with conventional jet fuels. Efforts are ongoing to certify additional fuel pathways.

1.2 STUDY DESCRIPTION

In this study, we evaluate the potential GHG emissions reductions and petroleum savings offered by various bio-jet fuels compared with petroleum jet fuel using the GREET model. The model was developed by Argonne, with the support of several programs in the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy. The model was originally developed to examine the life-cycle energy use and emissions associated with a wide range of light-duty vehicle technologies and the feedstocks used to produce alternative fuels (Wang 1996).

The fuel pathways considered in this analysis include petroleum-based jet fuel from conventional and unconventional sources (i.e., oil sands); FT jet fuel from natural gas, coal, and biomass; bio-jet fuels from fast pyrolysis of cellulosic biomass; and hydroprocessed renewable jet fuel from vegetable and algal oils.

1.3 REPORT ORGANIZATION

Section 2 of this report provides an explanation of the methodology, data sources, and assumptions used to characterize the fuel production (WTP) pathways for the conventional and alternative jet fuels. Section 3 describes the methodology used to characterize the fuel consumption and emissions of the alternative jet fuels during cruise and during landing and takeoff (LTO) operations (PTWa) for the different aircraft categories. In Section 4, we introduce the aviation module implementation in GREET. Section 5 presents and discusses the WTWa results for the alternative jet fuel types and sources and different aircraft systems. Section 6 provides our conclusions, and Sections 7 and 8 provide acknowledgments and list the references used in preparing the report.

2 JET FUEL PRODUCTION (WTP) PATHWAYS

In this report, we examine jet fuels produced from a variety of feedstock sources, including conventional crude and oil sands, conventional natural gas and shale gas, renewable natural gas, coal, cellulosic biomass, and plants and algal oils. We arrange these feedstock/fuel pathways in four main categories: petroleum jet fuel from conventional crude and oil sands; renewable jet fuel from fast pyrolysis of biomass; FT jet fuel from natural gas, coal, and biomass; and hydroprocessed HEFA jet fuel (also known as hydroprocessed renewable jet [HRJ]) from the bio-oil found in soybeans, palm, rapeseed, jatropha, camelina, and algae. The FT jet and HEFA jet must meet the requirements of ASTM D7566 and can be blended up to 50 percent with conventional jet fuel (ASTM 2011). The resulting jet fuel properties do not vary considerably with either the feedstock properties or the conversion process characteristics. While FT and HEFA jet fuels are composed of paraffins and can be grouped as synthetic paraffinic kerosene (SPK) fuels because their molecules boil in the range of jet fuel, pyrolysis-based jet fuel is primarily composed of aromatic compounds and can be grouped as a synthetic kerosene aromatic (SKA) fuel, which is compositionally different from SPK fuels. Furthermore, pyrolysis-based fuels have not yet been certified for use in jet engines. Because the ASTM D1655 standard for jet fuel limits aromatic content to 25 percent (ASTM 2007), SKA fuel is not likely to be blended with conventional jet fuel because jet fuel already has roughly a 20-percent aromatic content; instead, SKA fuel may be certified in a blend with SPK fuels to increase aromatic content, thus potentially enabling a 100-percent bio-derived jet fuel that does not need to be blended with conventional jet fuel.

2.1 JET FUEL PRODUCTION FROM PETROLEUM OIL

2.1.1 Life Cycle

The life cycle of petroleum jet fuel begins with petroleum recovery in oil fields and ends with jet fuel combustion in the aircraft. The key stages in the WTWa pathway of petroleum jet fuel are (1) petroleum recovery in oil fields, (2) petroleum refining to produce jet fuel, and (3) jet fuel use in the aircraft. Besides recovery and production-related activities, all transportation-related activities involved in moving goods from one location to another (e.g., crude oil from oil fields to petroleum refineries and jet fuel from refineries to refueling sites) are included. Infrastructure-related activities (e.g., construction of drilling rigs and petroleum refineries) are not included in this study. Figure 3 shows the LCA system boundary and key stages and activities associated with the petroleum jet pathway.

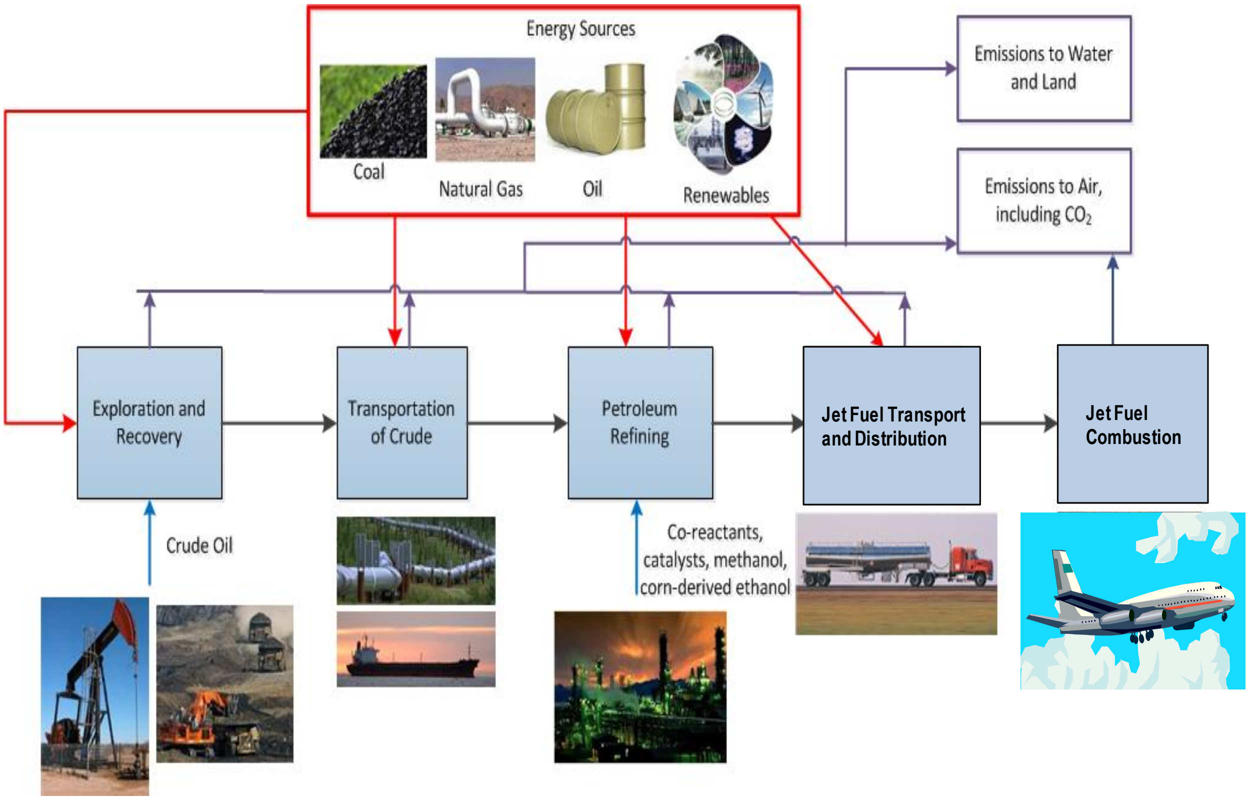


FIGURE 3 Key Stages and Activities of Petroleum Jet Fuel Pathway

The petroleum recovery stage includes activities beginning with removing oil from underground to treating it in the oil fields. Associated gas is a byproduct of conventional crude oil recovery; the gas contains significant amounts of methane (CH_4), a potent GHG with a global warming potential 25 times that of CO_2 (assuming a 100-year global warming potential). While the energy efficiency calculated for petroleum recovery does not account for the energy in the flared and vented gas because it is not an intended energy source, the emissions associated with gas flaring and venting are taken into account in GREET life-cycle modeling.

2.1.2 GHG Emissions in Oil Fields

In this study, we charge GHG emissions produced in the country of origin during crude recovery to the percentage of crude imported from that country into the U.S. market. The emissions associated with crude recovery, as well as those from tailing ponds in oil sands operations, are documented in a recent Argonne study (Burnham et al. 2012). The associated gas is flared and vented at average rates of 3.37 and 1.49 standard m^3, respectively, per barrel of crude processed in U.S. refineries. These flaring and venting rates result in 2.92 kg of CO_2-equivalent emissions per million Btu (mmBtu) of crude oil (Burnham et al. 2012).

2.1.3 Petroleum and Oil Sands Production

Petroleum recovery efficiency was estimated at 98 percent (Wallace et al. 2001).The energy efficiencies of extraction and upgrading of bitumen from oil sands via surface mining and in-situ production are estimated at 84.3 percent and 80.3 percent, respectively (Larsen et al. 2005). The Canadian Association of Petroleum Producers (CAPP) estimated that half of the produced bitumen from oil sands is currently produced by surface mining (CAPP 2011). This share is projected to continue through 2025, assuming production from current and in construction operations. However, the share of in situ production is projected to grow to 62 percent of total oil sands production by 2025 if the market demand for oil sands products grows substantially. Considerable fossil energy use (mainly for hydrogen production) is required for recovery, upgrading, and refining of oil sands — resulting in significant GHG emissions. Thus, the share of oil sands products contained in total crude oil supplied to U.S. refineries must be estimated.

The oil sands products (in the form of synthetic crude and blended bitumen) supplied to U.S. refineries (i.e., in five petroleum administration for defense districts [PADDs]) averaged 933,000 barrels per day in 2010 according the Canadian National Energy Board (2010). An additional 530,000 barrels per day of conventional heavy crude mix was also supplied to U.S. refineries in 2010 (synthetic crude oil and blended bitumen from Western Canadian Select[2] sales accounts for approximately half of the mix). Thus, the total supply of oil sands blends to the U.S. market averaged approximately 1.2 million barrels per day (mbd) in 2010. This total is consistent with the 1.18 mbd of Western Canadian oil sands supplied to U.S. markets in 2010, as estimated by EnSys Energy, Inc. (EnSys) in its assessment of the Keystone XL (KXL)[3] for DOE's Office of Policy and International Affairs (EnSys 2010). According to Energy Information Administration (EIA) petroleum supply annual data, the total amount of crude oil supplied to U.S. refineries was 14.724 mbd in 2010 (EIA 2011b). Thus, the share of oil sands products in the total crude supply to U.S. refineries is estimated at 8.1 percent in 2010.

On the basis of current and in-construction operations in oil sands fields, CAPP estimates that the total supply of Western Canadian oil sands and upgraders to markets will increase from 1.822 mbd in 2010 to 2.609 mbd in 2015, peak at 2.783 mbd in 2019, then decline to 2.740 mbd by 2025 (CAPP 2011). A growth scenario by CAPP (which assumes approval of new pipeline projects, expanded export capacity to Canada's west coast, and strong market demand for oil sands products in Asia) results in much higher and sustained growth in the supply of Western Canadian oil sands and upgraders to market: 2.650, 3.679 and 4.591 mbd in 2015, 2020, and 2025, respectively.

The share of Canadian oil sands supplies to the U.S. market is also expected to grow, but at an uncertain pace because of the uncertainty surrounding the construction of the KXL. Despite EIA's projected decrease in U.S. oil imports through 2035 (resulting from increased domestic

---

[2] Western Canadian Select — produced in Western Canada — is made up of existing Canadian heavy conventional and bitumen crude oils blended with sweet synthetic and condensate diluents.

[3] Keystone XL is a proposed pipeline system to transport oil sands products from Western Canada to U.S. refineries; the pipeline primarily targets refineries in Illinois (PADD II) and the Cushing oil distribution hub in Oklahoma that connects to refineries in the Gulf Coast (PADD III).

production of oil and biofuels, as well as increased fuel economy standards), U.S. imports of oil sands products are expected to grow to balance the declining supply of oil from Alaska, California, Mexico, and Venezuela (EIA 2011c).

EnSys examined seven different market demand and pipeline expansion scenarios (EnSys 2010). Using the global and U.S. petroleum supply and demand projections in the “reference case” of EIA’s *2011 Annual Energy Outlook*, EnSys evaluated a low-supply scenario for total Canadian oil sands refined in the United States. This scenario assumes that the KXL is not constructed, a Transmountain (TMX) pipeline is expanded to the British Columbia coast, and that a significant amount of oil sands are exported to Asia. The EnSys high-supply scenario (i.e., to the United States) assumes construction of the KXL but not of the TMX. In its mid-supply scenario, EnSys assumes construction of the KXL and TMX; see Table 1 (EnSys 2010).

Table 1 lists EnSys estimates of oil sands supplies to U.S. refineries for these three scenarios for the period between 2010 and 2030. Table 2 lists EIA’s *2011 Annual Energy Outlook* “reference case” projections of total inputs to distillation units in U.S. refineries. Because the total inputs to distillation units include crude oil plus other inputs, we estimate the non-crude portion of the total input by subtracting the crude oil input from the total inputs, both of which are available for 2010.

TABLE 1 EnSys Projections of Canadian Oil Sands Supplies to U.S. Refineries (mbd) Using EIA’s 2011 *Annual Energy Outlook* “Reference Case” Projections (EnSys 2010)

	Year				
Scenario	2010	2015	2020	2025	2030
Low-supply (no KXL, TMX, and high Asia demand)	1.18	1.97	2.05	2.45	2.62
Mid-supply (KXL and TMX)	1.18	1.98	2.29	2.99	3.27
High-supply (KXL and no TMX)	1.18	2.04	2.63	3.39	3.66

TABLE 2 Crude Oil to U.S. Refineries (mbd) Using EIA's 2011 *Annual Energy Outlook* "Reference Case" Projections (EIA 2011c)

	Year				
Inputs	2010	2015	2020	2025	2030
Total inputs to distillation units	15.31	15.32	15.17	14.88	14.76
Crude oil inputs to distillation units in 2010	14.72				
Estimate of crude oil inputs to distillation units[a]	14.72	14.73	14.58	14.29	14.17
Projected share of oil sands products in crude oil input to refineries (using oil sands mid supply scenario projections from Table 1)	8%	13.4%	15.7%	20.9%	23%

[a] Calculated as the total inputs to distillation units minus the difference between total inputs and crude inputs in 2010.

Argonne used data from two EIA annual reports — the *2011 Refinery Capacity Report* and *2010 Petroleum Supply Report* — to obtain and allocate U.S. process fuel use among individual refinery products (Palou-Rivera 2011). Argonne estimated a refining efficiency of 91.1 percent for conventional jet fuel and 89.6 percent for ultra-low sulfur jet fuel (11 ppm sulfur ratio by mass). The energy use and emissions associated with each transportation mode for conventional crude and oil sands products to U.S. refineries, and the transportation and distribution of refined products to refueling stations, are estimated by Wallace et al. (2001).

2.2 ALTERNATIVE PRODUCTION PATHWAYS FOR JET FUEL PRODUCTION

Reducing petroleum use and GHG emissions are vital to the sustainable growth of the aviation industry. The use of synthetic fuels, including biofuels, to replace or blend with conventional jet fuels, represents one of the opportunities examined by the aviation industry to achieve petroleum and GHG emissions reductions. The nature and properties of jet fuel produced from the feedstock sources depends on the conversion process. While the gasification of coal and/or biomass produces syngas that is polymerized into SPK via the FT process, the fast pyrolysis of biomass produces oil that can primarily be upgraded to SKA, which is also similar to a component of petroleum-based jet fuel — but one that is limited within the ASTM fuel specification. Conversion of triglycerides in plant and algal oils via a hydrogenation process produces jet fuel (HEFA) similar to the fuel produced by the FT process. In the following sections, the pathways for SPK production via FT of syngas and hydroprocessing of plant oils are presented separately from the pyro-jet production pathways.

2.2.1 SPK Production Pathways

2.2.1.1 FT Jet Fuel

FT jet fuel can be produced from a variety of feedstock sources, including natural gas, coal, biomass, and co-feeding of coal and biomass (Figure 4). Syngas produced from these feedstocks is converted via the FT process. FT plants usually produce three groups of hydrocarbons: FT naphtha (C5–C9), FT middle distillates (C10–C20), and FT wax (>C20). In some FT plant designs, wax is further cracked into middle distillates. FT middle distillates (diesel and jet fuels) are premium fuels that contain virtually no sulfur; they have a high cetane number but poor cold-flow properties. FT naphtha could be used as a reformer feedstock for hydrogen production or as a gasoline blendstock. In our analysis, we allocated energy use between FT jet/diesel and FT naphtha according to the share of their energy content in the total liquid fuel products. This is consistent with the naphtha being used as a gasoline blendstock.

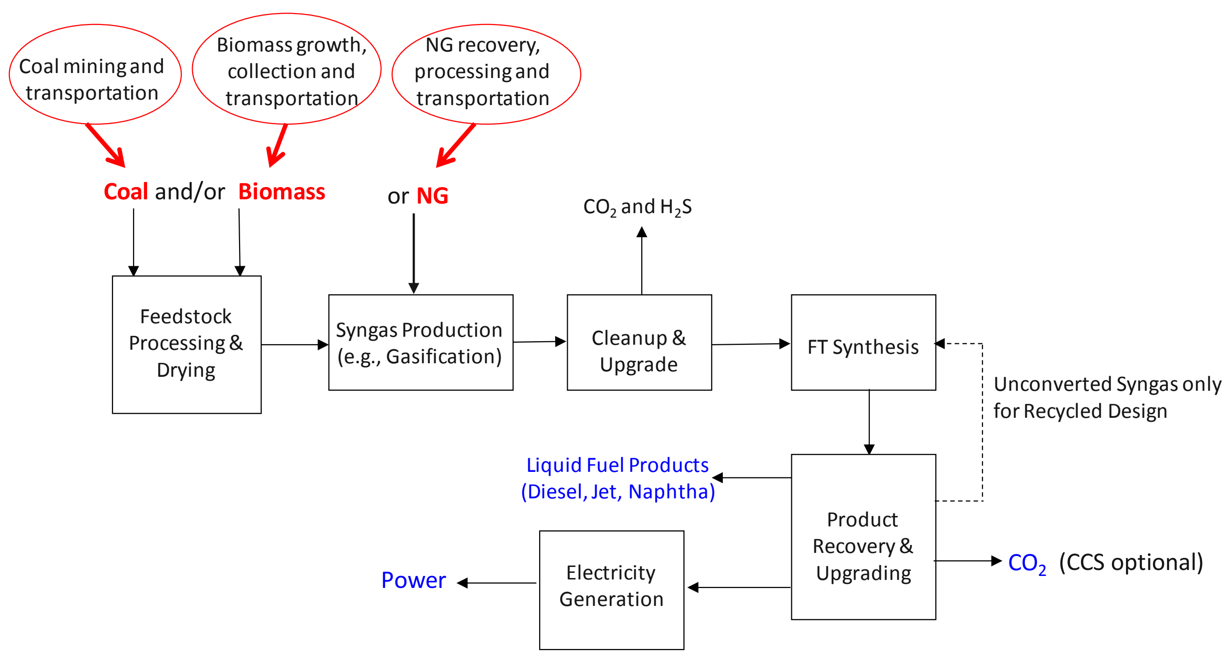


FIGURE 4 LCA System Boundary and Key Stages and Activities of FT Jet Pathway

Figure 5 shows the key stages and activities associated with FT jet fuel production via gasification of cellulosic biomass. The energy use and emissions associated with the farming and collection of biomass and the manufacturing of agricultural inputs are based on recent Argonne studies (Han et al. 2011; Dunn et al. 2011). Argonne examined the fuel-cycle energy use and GHG emissions for FT diesel produced from coal and cellulosic biomass (Xie et al. 2011), assessing the effects of co-feeding of biomass and coal in FT plants and the effects of carbon capture and storage (CCS) technology.

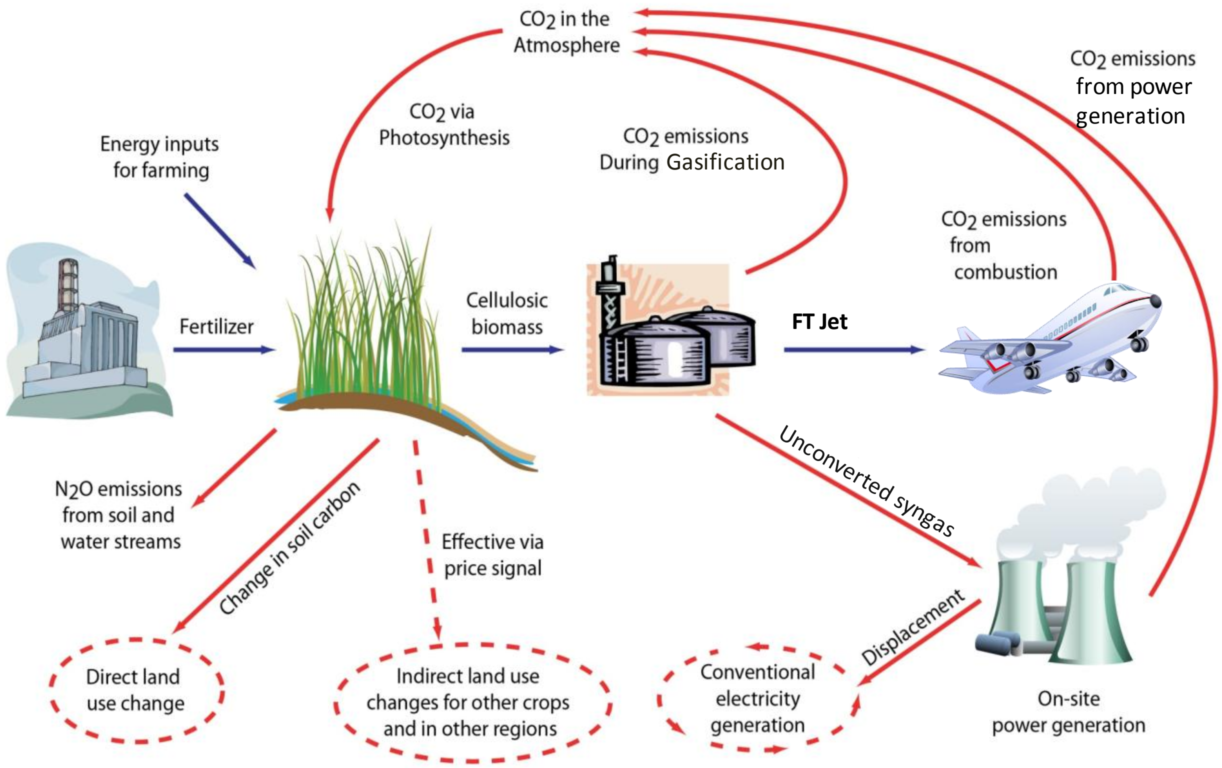


FIGURE 5 FT Jet Production from Cellulosic Biomass Showing Major Co-Products and Carbon Sources and Sinks in the Pathway (Switchgrass Shown as Example)

Coal and/or biomass are fed into a gasifier to produce syngas. The CO_2 in syngas may be vented or captured and sequestered. Unconverted syngas may be recycled for further synthesis of the FT fuels (Figure 4); electricity may be produced from the unconverted syngas. Less electricity can be produced from the "recycled" design while increasing liquid fuel yield, and vice versa for the once-through design. Potential electricity export is estimated at 15.8 and 162 kWh per mmBtu of FT products for the recycled design and the once-through design, respectively. Excess electricity may be exported to the electric grid. In such a case, the excess co-produced electricity is assumed to displace an equal amount of U.S. average grid emissions, resulting in GHG emissions credit. By default, GREET assumes no electricity export. Argonne estimated an energy efficiency of 50 percent for the conversion of coal and/or biomass in FT plants when the plant energy use is allocated among all fuel products according to their energy contents and any exported electricity is credited by using the displacement method (Xie et al. 2011).

We assume a carbon capture efficiency of 90 percent (defined as the ratio of captured CO_2 to produced CO_2) and estimate 300 kWh/ton of carbon for the electric energy associated with the compression of CO_2. For the coal to liquid (CTL) pathway, Argonne estimated CH_4 emissions from coal mining (Burnham et al. 2012).

The discovery and exploration of shale gas plays in the United States could change the role of natural gas in the general energy sectors and, potentially, in the transportation sector. Natural gas is produced in the United States in abundance and has a much lower carbon intensity and cost compared with petroleum. Argonne estimated the energy use and emissions associated with natural gas recovery from conventional wells and shale gas plays (Burnham et al. 2012). Argonne also examined FT plant designs with natural gas as a feedstock, their production efficiencies, and yields of other co-products. Argonne estimated a conversion process efficiency of 63 percent to produce FT diesel (Wang and Huang 1999). To produce jet fuel instead of diesel, additional hydrocracking and a higher rate of syngas recycling are needed, resulting in a small increase in hydrogen and power requirements for the plant (Stratton et al. 2010). However, a moderate decrease in the CO_2 associated with jet fuel compared with diesel would result from changes in the allocation fractions. Thus, the additional energy requirements do not lead to substantial increases in CO_2 emissions from the facility. Consequently, the differences in GHG emissions between FT diesel and FT jet are ignored in this analysis for all of the FT jet fuel pathways (i.e., pathways using natural gas, coal, and biomass as feedstock sources).

2.2.1.2 HEFA Jet Fuel

This study examines the production of HEFA fuel (hydroprocessed esters and fatty acids, which is also known as HRJ) from the oil of soybeans, algae, palm, jatropha, rapeseed, and camelina. The processing involves hydrotreatment to deoxygenate the oil with subsequent hydrocracking to create a range of hydrocarbons that fill the distillation ranges of naphtha, jet, and diesel fuels (Hileman et al. 2009). The produced fuel has properties similar to those of FT fuels. As noted above, we assumed that these various feedstock sources produce bio-oils with similar properties. Thus, we first discuss the farming and oil extraction phase for each of these feedstock sources, followed by a discussion of the hydroprocessing of oil to produce HEFA fuels.

Soybeans

Soybean oil is a feedstock of interest because it is used extensively in the United States for biodiesel production. Argonne examined the life-cycle energy use and GHG emissions of soybean-derived biodiesel and renewable fuels (Huo et al. 2008). Figure 6 shows the key stages and activities associated with HRJ production from soybeans. The major co-products of the oil extraction and oil conversion processes are also shown. Default assumptions about soybean farming energy use, fertilizer use, and products' yields were recently updated using data from the literature. Farming energy use is estimated at 16,560 Btu/bushel (Pradhan et al. 2011). Fertilizer use per bushel of soybeans was estimated at 30.9 g of nitrogen (N), 113.4 g of phosphorus (P_2O_5), and 210 of potassium (K_2O); these values were adopted from the National Agricultural Statistics Service (2010). Emissions of nitrous oxide (N_2O) resulting from direct and indirect conversion of nitrogen in soil are estimated at 1.325 percent of the nitrogen in fertilizer and soybean biomass that is left in the field (Huo et al. 2008). Energy use for oil extraction is estimated at 3,590 Btu/ lb of oil; 5.4 lb of soybeans yield 1 lb of oil and 4.4 lb of soy meal (Omni Tech International 2010). Soy meal is used as a livestock feed and is assumed to displace soybeans in GREET modeling of its emissions and energy credits. The displacement ratio of soy meal to soybeans is determined by protein content, resulting in the replacement of 1.2 lb of soybeans by each lb of soy meal (Huo et al. 2008).

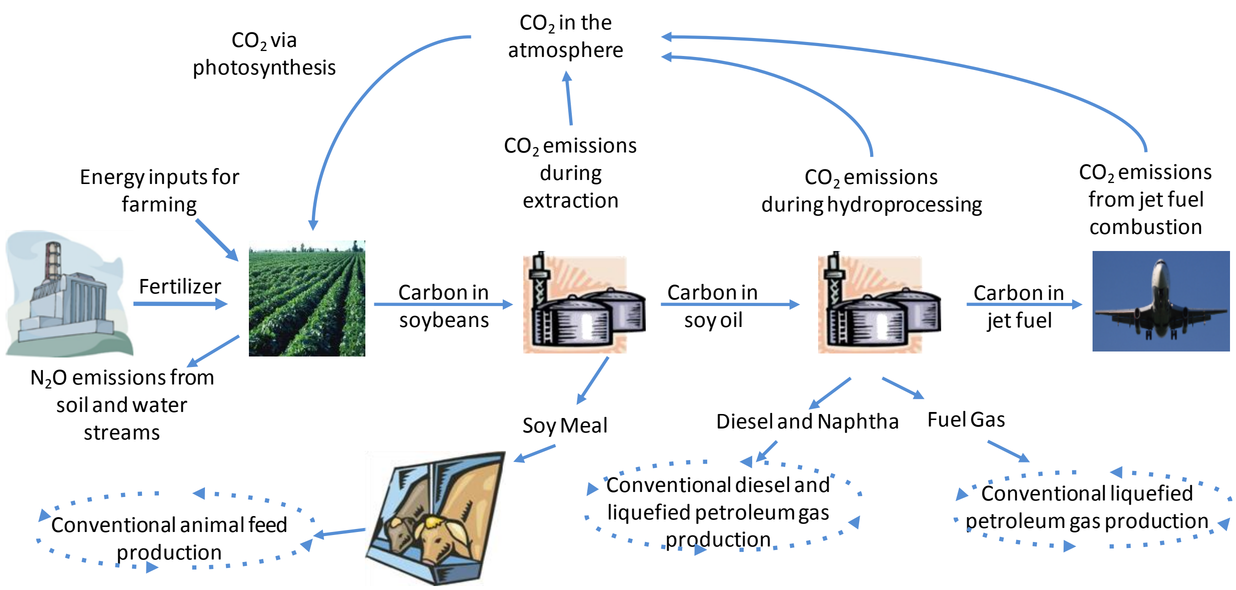


FIGURE 6 HRJ Production from Soybeans Showing Major Co-Products, Displaced Products, and Carbon Sources and Sinks in the Pathway

Algae

Argonne examined in detail the energy use and GHG emissions associated with the growth and dewatering of algae in open ponds and the subsequent extraction of oil from the algal biomass (Frank et al. 2011). Figure 7 shows the key stages and major co-products associated with HEFA production from algae. Emissions and energy consumption are allocated among the algal oil and the co-products on the basis of their energy values. The lipid extracted algae (LEA) can be used for CH_4 production using anaerobic digestion (AD) and/or for electric power generation. The residual digestate (solids remaining after AD) can be used for soil applications to displace fertilizers. Figure 8 shows the potential co-products that can be produced from the LEA. Each of the co-products has the potential to displace an equivalent amount of an existing market product and result in unique energy and emissions credits to LCA of the algae pathway. The impacts of different co-product treatment scenarios are discussed in detail in another Argonne study (Frank et al. 2012).

Argonne estimated that the energy used for algae growth and dewatering is 1,997 Btu/kg of algae and that 4.68 kg of algae are needed to produce 1 kg of oil (dry basis) and 3.68 kg LEA for methane production via AD. Argonne also estimated the energy use for oil extraction at 9,467 Btu/kg of oil and a methane yield from AD at 0.123 kg per kg of LEA with 2 percent loss during biogas production (Frank et al. 2012). However, the results are highly dependent on the facility configuration, especially in regard to water management and co-product selection, so facility-to-facility variations could be large (Vesudevan et al. 2012). Consequently, ongoing studies will work to reconcile differences between Argonne algae model inputs, assumptions, and methodologies with those of MIT.

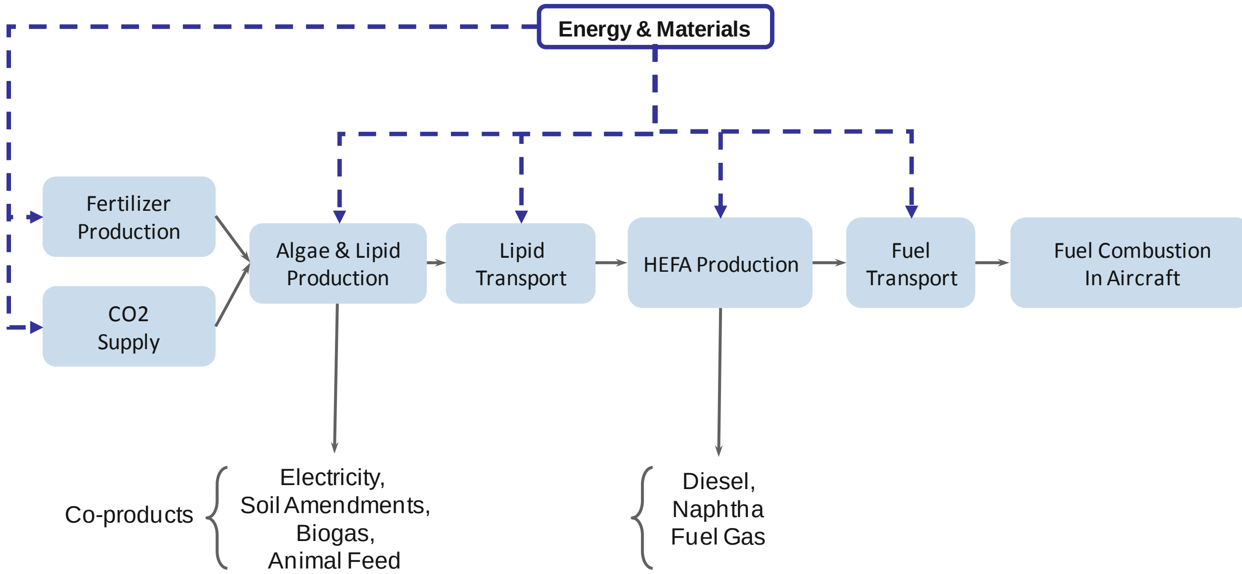


FIGURE 7 HRJ Production from Algae Showing Major Co-Products in the Pathway

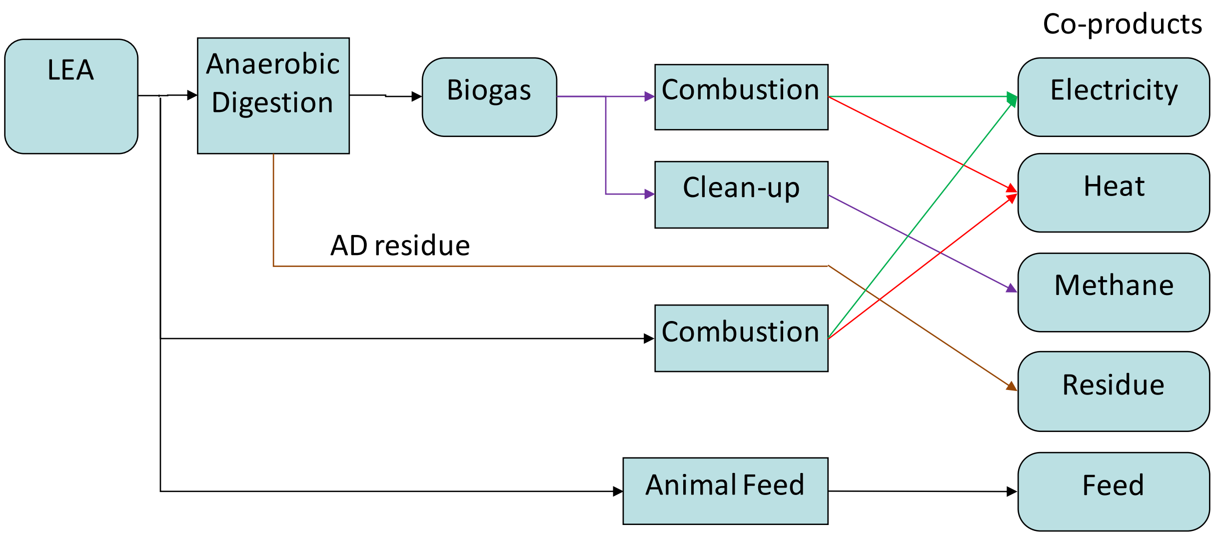


FIGURE 8 LEA Can Produce a Variety of Co-Products with Different Impacts on the LCA of the Algae Pathway

Palm, Jatropha, Rapeseed, and Camelina

Farming energy use, oil extraction, and oil and coproduct yield have been examined for palm, jatropha, rapeseed, and camelina (Stratton et al. 2010, 2011; Shonnard et al. 2010). Table 3 lists the farming energy and fertilizer use for various oily plants, as well as the energy use and yields of the bio-oil and the major coproducts. The parameters listed in Table 3 decide the life-cycle energy use and emissions associated with the production of the bio-oil and the credits awarded for the coproducts of the extraction process.

TABLE 3 Farming Energy and Fertilizer Use for Various Plants and Oil Extraction Energy Use and Yields

	Soybeans[a]	Palm[b]	Rapeseed[b]	Jatropha[b]	Camelina[c]
Farming					
Energy (Btu/dry lb)	317	72	416	599	438
Nitrogen (g/dry lb)	0.593	3.28	22.2	15.4	16.8
P_2O_5 (g/dry lb)	2.17	0.00	6.36	5.90	6.80
K_2O (g/dry lb)	4.02	0.00	5.76	17.0	4.54
Extraction					
Energy (Btu/lb oil)	3,590	200	1,316	852	842
Dry feed-to-oil ratio (lb/lb)	4.7	4.5	2.4	3.0	2.9
Co-products	Soy Meal	Palm Kernel Expeller	Rapeseed Meal	Electricity	Camelina Meal
Co-product amount per lb of oil	3.7 lb	0.115 lb	1.27 lb	0.88 kWh	1.78 lb

[a] Huo et al. 2008

[b] Stratton et al. 2010; 2011

[c] Shonnard et al. 2010.

The hydrotreatment process for the production of HEFA from renewable oils is based on the UOP[4] hydrodeoxygenation process (Huo et al. 2008). It is estimated that 1.39 lb of plant oil is required to produce 1 lb of HEFA together with 0.1 lb of propane fuel mix and 0.14 lb of naphtha, and that 6,291 Btu of energy is required for the conversion process (Pearlson 2011). The energy use and emissions associated with the conversion process are allocated among HEFA jet, diesel, and naphtha coproducts on the basis of their energy values in the product stream.

2.2.2 Pyrolysis-based Jet Fuel Production Pathways

The production of oil via fast pyrolysis and the subsequent upgrading and refining of that oil produce a mixture of liquid fuels that are compatible with the current transportation fuel distribution infrastructure and current engine technologies. With the right processing, some of the resulting liquid fuel might be classified as SPK; however, the majority would be aromatic compounds that are limited by the specifications for jet fuel. Within this analysis, no distinction is made between aromatic and paraffinic compounds. This is a subject requiring further analysis.

Fast pyrolysis is performed under a range of temperatures around 500°C and short residence times (few seconds) in the reactor to maximize the pyrolysis oil yield. The fast pyrolysis reaction results in rapid decomposition of the biomass under these thermal conditions in the absence of oxygen. The short residence time maximizes the yield of the condensable phase (oil). This

[4] A division of Honeywell Inc. for fuel refining, processing, and petrochemical production

process contrasts with the much slower gasification process, which provides a high yield of fuel gas that can be synthesized into liquid fuel (e.g., via the FT process). Figure 9 shows the key stages of liquid fuel production from cellulosic biomass using fast pyrolysis, three possible sources for hydrogen, and major coproducts.

The pyrolysis oil product is unstable due to high oxygen and water content. Phase separation and polymerization may occur if the oil is stored for an extended period of time. Thus, pyrolysis oil is stabilized by reducing its oxygen content via hydrotreatment. This process requires a considerable amount of hydrogen. Further hydroprocessing (upgrading) of the pyrolysis oil, possibly including a hydrocracking step, is necessary to produce liquid fuels such as gasoline, diesel, and jet fuels. When the upgrading process is integrated with the pyrolysis reactor in the same facility, the pyrolysis oil can be stabilized and upgraded concurrently. The final step of the upgrading process is the separation of the liquid product into different fuels with the desired boiling range. Additional hydrogen is needed for the hydrocracking process. Hydrogen may come from an external source (e.g., steam methane reforming of natural gas) or from an internal source (e.g., reforming co-produced fuel gas or a fraction of the pyrolysis oil). The amount and source of hydrogen significantly impact the GHG emissions associated with liquid fuel production via fast pyrolysis.

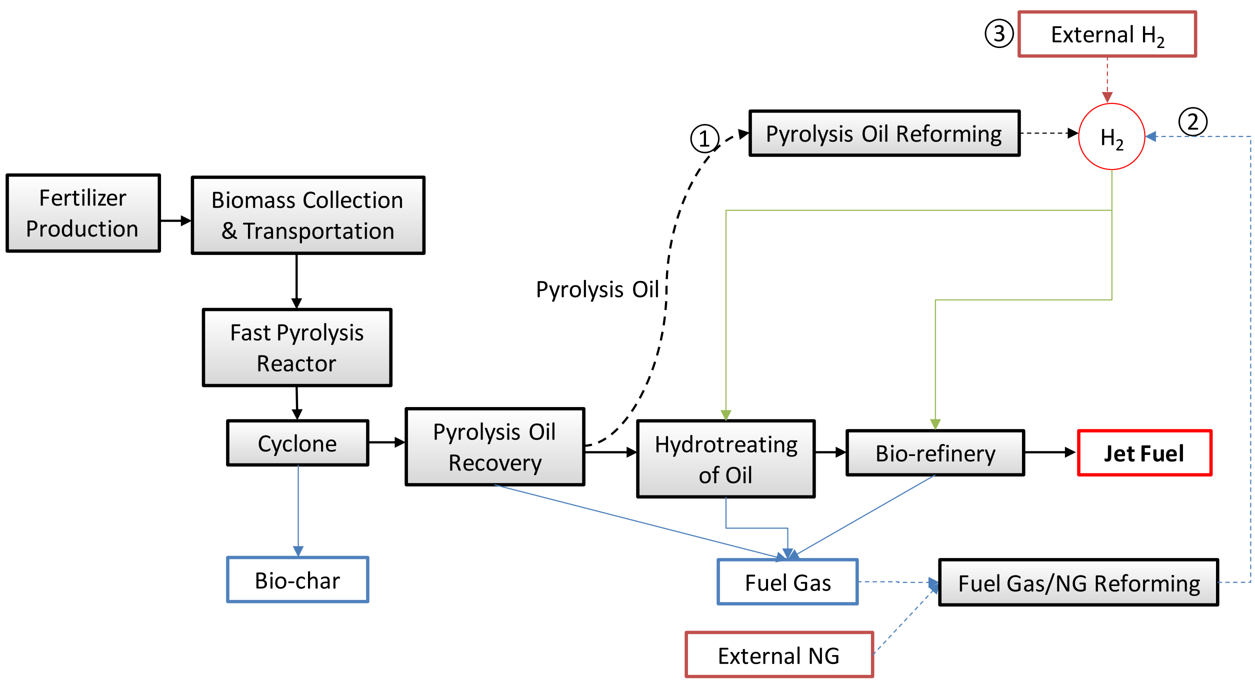


FIGURE 9 Liquid Fuel Production from Cellulosic Biomass via Fast Pyrolysis

The pyrolysis and subsequent upgrading processes can be self-sufficient with regard to heat and electricity requirements. The pyrolysis reaction produces other combustible co-products, such as fuel gas (a mixture of carbon monoxide and methane) and bio-char, both of which can be used to produce combined heat and power. These co-products can satisfy — and often exceed — the heat and power requirements of the biomass drying and grinding, as well as the bio-oil upgrading processes.

Argonne examined the life-cycle energy use and emissions of liquid fuel production via fast pyrolysis of cellulosic biomass using a wide variety of possible hydrogen sources, liquid fuel yields, and co-product application and treatment methods (Han et al. 2011). When hydrogen is produced from natural gas and bio-char is used to satisfy process energy needs, the liquid fuel yield is high (31 percent of biomass input by mass [dry basis]) but the reduction in GHG emissions is modest, at 45 percent relative to petroleum fuels. However, when hydrogen is produced internally via reforming of pyrolysis oil and bio-char is sequestered in soil applications, the liquid fuel yield is reduced (15 percent of biomass input by mass [dry basis]), but such a scenario offers a large reduction in GHG emissions (103 percent) relative to petroleum fuels. While the internal hydrogen production significantly reduces fossil fuel use and GHG emissions, it also reduces the potential for petroleum energy savings (per unit of biomass resources) because the fuel product yield declines dramatically. Sequestration of the large amount of bio-char co-product (e.g., in soil applications) provides a significant CO_2 credit. Similarly electricity generation from bio-char combustion provides a large energy credit. The life-cycle analysis by Argonne was based on mass and energy balance data from two design cases by National Renewable Energy Laboratory and Pacific Northwest National Laboratory (Wright et al. 2010; Jones et al. 2009).

Wright et al. examined the conversion of corn stover to liquid fuels via integrated fast pyrolysis/refining design. They estimated that 3.61 dry lb of biomass is needed to produce 1 lb of finished liquid fuel. The conversion process required 4,450 Btu of external hydrogen and 849 Btu of electricity and coproduced 0.52 lb of char and 1,187 Btu of fuel gas per lb of liquid fuel. When hydrogen was produced internally via reforming of pyrolysis oil, 6.49 lb of dry biomass was needed to produce 1 lb of finished fuel. In such scenario, the integrated process consumed 1,562 Btu of electricity and coproduced 0.94 lb of biochar and 8,325 Btu of fuel gas per lb of liquid fuel product (Wright et al. 2010).

Jones et al. conducted a techno-economic analysis to examine the conversion of hybrid poplar wood chips to liquid fuels via fast pyrolysis. They estimated that 3.19 dry lb of biomass is needed to produce 1 lb of hydrotreated (stable) oil. The conversion process required 5,068 Btu of hydrogen and 736 Btu of electricity and coproduced 4,201 Btu of fuel gas. All of the biochar co-product generated was used to satisfy process heat requirements. Further upgrading of the oil to produce liquid fuels required an additional 847 Btu of hydrogen (Jones et al. 2009).

Neither of these two design cases correlated the use of hydrogen with the slate of liquid fuel products (e.g., gasoline, diesel, jet, naphtha); this topic requires further research and investigation.

This page intentionally left blank.

3 ENERGY USE AND EMISSIONS DURING AIRCRAFT OPERATION (PTWa)

This section presents a consolidated discussion of multiple studies conducted to quantify changes in combustion emissions on the basis of fuel composition and engine type (compared with conventional jet fuel). Figure 10 illustrates the various environmental impacts of aviation that result from emissions, noise, and resource use. The red and blue-boxed emissions are the PTWa and WTP emissions estimates for jet fuel combustion. The PTWa species represent combustion emissions from the aircraft in both the LTO cycle and during cruise. Sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter with sizes measuring 10 micrometers or less (PM_{10}) influence both air quality and global climate change. Primary PM_{10} is assumed to be equivalent to black carbon or soot. Volatile primary and secondary particulate matter are not considered in our analysis. Volatile organic compounds (VOC) and carbon monoxide (CO) affect air quality, while CH_4, N_2O, and CO_2 influence global climate change through either cooling (blue arrows) or warming (red arrows). As is typical within GREET, no attempt is made to combine the relative impacts of these combustion emissions into a single value. Instead, the focus is on the development of an emissions inventory for jet fuel combustion for both conventional and alternative jet fuels.

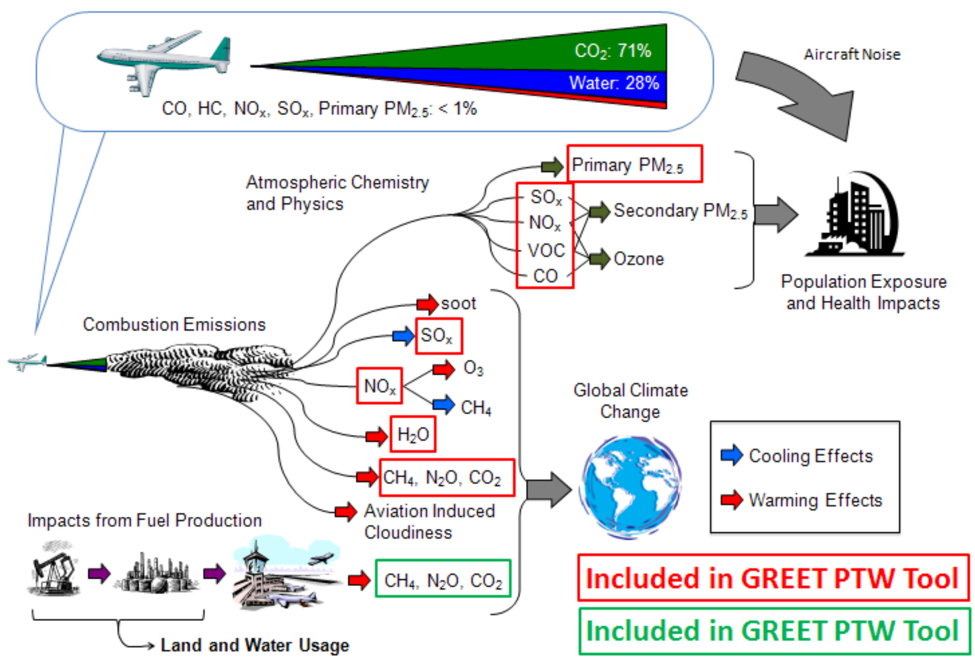


FIGURE 10 Environmental Impacts of Aviation ($PM_{2.5}$, also known as fine soot or black carbon, is a subset of PM_{10}; thus aviation $PM_{2.5}$ emissions also count as PM_{10} emissions.)

The PTWa module in GREET provides values for pollutant formation in two major categories: LTO and cruise emissions. Figure 11 illustrates how these categories are derived within the PTWa module from various inputs and toggled to estimate the combined PTWa combustion emissions outputs. Aircraft operations and fuel composition inputs are provided to derive LTO and cruise emissions estimates for conventional jet fuel. For the purposes of this analysis, conventional jet fuel could be Jet A, Jet A-1, jet propulsion fuel type 8 (JP-8), or jet propulsion fuel type 5 (JP-5), which are used respectively by domestic commercial aviation, international commercial aviation, the U.S. Air Force, and the U.S. Navy.[5] Urban emissions shares represent air quality emissions that directly impact urban areas near airports. The conventional jet fuel LTO and cruise emissions are estimated in units of g of pollutant per kg payload per km aircraft great-circle distance[6]. Emissions of SPK fuel blends are estimated using linear interpolations of 50 percent and 100 percent SPK emissions (relative to conventional jet fuel) from various tests.

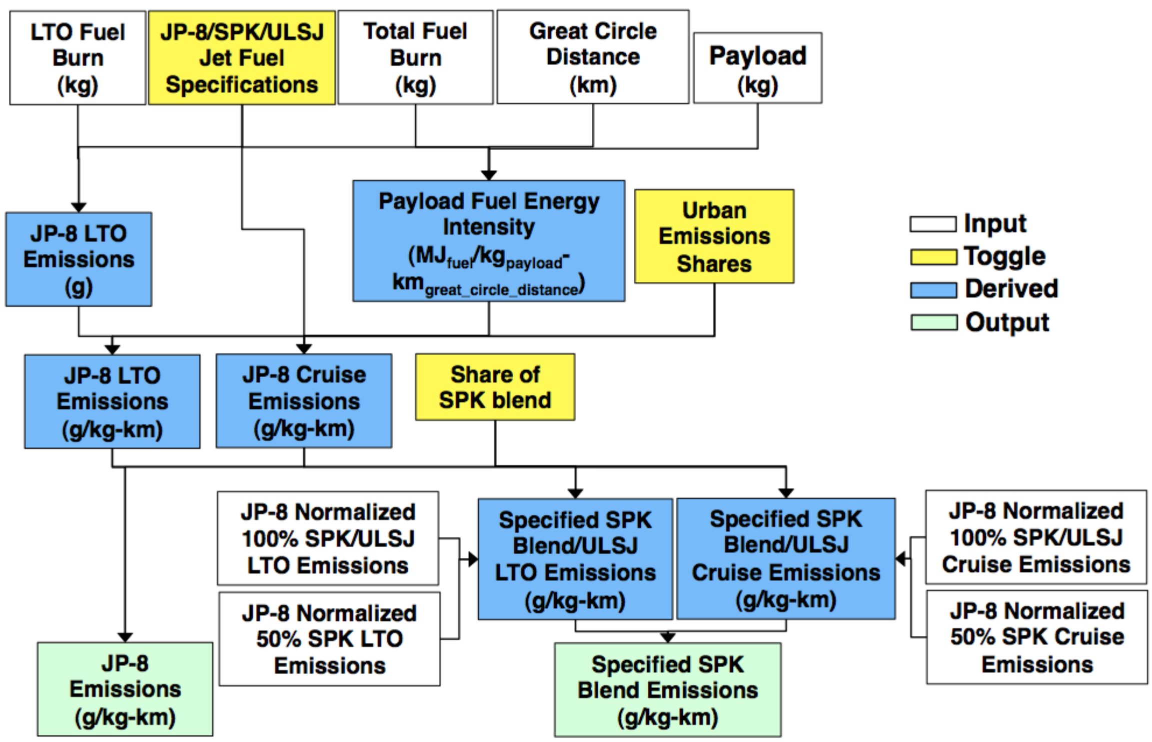


FIGURE 11 PTWa Emissions Calculation Method (Note that "JP-8" could refer to Jet A, Jet A-1, JP-8, or JP-5.)

---

[5] From Hileman et al., 2010, "Jet fuel, like all petroleum products, varies in chemical composition; it is required to meet specifications based on its use. Depending on the user, jet fuel must meet slightly different specifications. JP-8 and Jet A-1 are essentially identical in their specification, while Jet A has a higher freeze point. The specification for Jet A provides a minimum specific energy (42.8 MJ/kg), whereas that of JP-5 and JP-8 are based on a minimum fuel hydrogen content (13.4 percent). The specification for JP-5 differs in that it has a higher flash point to enhance safe operations on aircraft carriers."

[6] Great-circle distance is the shortest distance between any two points on the surface of a sphere measured along a path on the surface of the sphere.

The model also has the ability to estimate LTO and cruise emissions for 100 percent ultra-low sulfur jet (ULSJ) fuel.[7] The remainder of this section includes key assumptions, methodology and references used in estimating PTWa emissions within the jet fuel combustion module of the GREET model.

Table 4 lists the various fuel property input values. The default input values in this table were obtained from Hileman et al. (2010). The SPK blend portion can also be specified in GREET, as discussed later.

TABLE 4 Specifications for Jet Fuels

	Properties				
Fuel	LHV [MJ/kg]	HHV [MJ/kg]	Density [Kg/L]	C ratio [by wt]	S ratio [ppm wt]
Conventional Petroleum Jet Fuel	43.2	46.2	0.802	86.2%	700
ULSJ	43.3	46.3	0.792	86.0%	11
SPK	44.1	47.2	0.757	84.7%	0

Table 5 lists the 2009 U.S. origin aircraft operations performance data estimates developed by the U.S. Department of Transportation's Volpe Center for various aircraft class averages (Malwitz 2011). The data from the Volpe Center are assigned to aircraft categories using FAA's Aviation Environmental Design Tool (AEDT) conventions (FAA 2011c). A detailed list of the AEDT aircraft classifications can be found in Table A-1 of Appendix A. Table 5 also provides inputs for average aircraft operations, payload, great-circle distance, total fuel consumption, and LTO fuel consumption. The default values in Table 5 for the various aircraft reflect U.S. domestic operations in 2009. These are used to compute the payload fuel energy intensities (PFEIs) listed in Table 6; these values represent average flight efficiencies for each aircraft class on the basis of fuel energy intensity, payload capacity, and great-circle distance. Further information on this metric can be found in Hileman et al. (2008).

Table 7 provides estimates of LTO cycle combustion emissions (in grams) using conventional jet and ULSJ fuels. Average emissions estimates for VOCs, CO, NO_x, and PM_{10} were developed by using AEDT for each aircraft class, in a manner similar to that used to develop the fuel use data in Table 5. LTO emissions averages for CH_4 and N_2O were estimated by using the first Alternative Aviation Fuels Experiment (AAFEX-1) from installed-engine ground testing on a DC-8; the testing was conducted using CFM56-2C1 high-bypass turbofan engines, as shown in Figure A-1 in Appendix A (Anderson et al. 2011). These species were calculated using the ICAO

[7] ULSJ fuel is assumed to have the same maximum fuel sulfur content as ultra-low-sulfur diesel fuel, (15 ppm), while meeting all of the specifications of ASTM D1655. Conventional jet fuel has a maximum allowable sulfur content of 3,000 ppm, while most jet fuel has a sulfur content of 700 ppm (Hileman et al. 2010).

fuel-burn-weighted averages listed in Table A-2 of Appendix A and multiplied by the number of engines for each aircraft class. All aircraft classes were assumed to have two engines except for the large quad (LQ) category, which was assigned four engines. CO_2 emissions were estimated using a carbon balance of the CH_4, VOC, and CO species. SO_x emissions are a function of sulfur content in the fuel and were calculated from the values listed in Tables 4 and 5 for LTO. All LTO emissions are assumed to contribute to urban emissions. We do not have reliable inputs for the greyed-out ULSJ PM_{10} rows in the tables, but values may be input when more information becomes available. Table 8 uses the values in Tables 7 and 5 to convert to the default units (g/kg-km).

Table 9 provides inputs for various species in a fashion similar to Table 8 but for the cruise condition. As in Tables 5 and 7, VOC, CO, NO_x, and PM_{10} emissions estimates were developed using AEDT, as operated by the Volpe Center, and CH_4 and N_2O emissions were estimated by means of the AAFEX study. However, CH_4 emissions were assumed to be negligible at cruise based on the values in Figure A-1FIGURE A-1. In developing the GREET module, cruise is assumed to be at 65 percent of maximum thrust for each aircraft. At this thrust setting, the aircraft apparently consumes CH_4 during combustion, as indicated by the negative values; note that we are assuming that ground-level testing at higher thrust settings behaves similarly at cruise altitudes. We also assume that cruise operations do not contribute to urban emissions.

TABLE 5 2009 U.S. Origin Only AEDT Aircraft Types and Operational Performance Data from the Volpe National Transportation Systems Center

Aircraft Type	Aircraft Class	Aircraft Operations	Average Payload (kg/operation)	Average Trip Great Circle Distance (km/operation)	As-Operated Aircraft Average Trip Petroleum Jet Fuel Consumption (kg/operation)	Aircraft LTO Cycle Average Petroleum Jet Fuel Consumption (kg/operation)
Passenger Aircraft	Single Aisle (SA)	3,838,461	18,230	1,366	4,986	565
	Small Twin Aisle (STA)	131,481	30,389	2,804	14,590	982
	Large Twin Aisle (LTA)	120,266	57,999	7,132	59,468	1,731
	Large Quad (LQ)	46,721	82,210	7,520	91,642	2,484
	Regional Jet (RJ)	3,382,535	7,017	755	1,728	257
	Business Jet (BJ)	95,238	1,581	1,177	1,730	273
Freight Aircraft	Single Aisle (SA-F)	22,074	21,036	723	3,389	598
	Small Twin Aisle (STA-F)	220,272	44,848	1,415	9,769	949
	Large Twin Aisle (LTA-F)	41,782	89,596	3,317	31,414	1,496
	Large Quad (LQ-F)	31,067	99,663	5,019	60,771	2,271

TABLE 6 As-Operated Aircraft Average Trip Fuel Consumption Intensity Using Petroleum Jet Fuel

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
PFEI (Payload Fuel Energy Intensity) (kJ/kg$_{payload}$-km$_{great\text{-}circle\ distance}$)	8.65	7.40	6.21	6.40	14.09	40.18	9.62	6.65	4.57	5.25

TABLE 7 Operation-Weighted Aircraft LTO Cycle Emissions Using Petroleum Jet Fuel

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
CH_4 (g)	46	79	140	402	21	22	48	77	121	368
N_2O (g)	90	156	275	789	41	43	95	151	238	721
CO_2 (kg)	1,775	3,088	5,444	7,824	806	850	1,879	2,977	4,701	7,142
VOC (g)	628	982	1,662	2,192	325	1,533	1,217	2,064	2,761	4,026
CO (g)	4,642	8,413	13,635	13,010	3,344	5,098	5,522	9,123	12,423	14,908
NO_x (g)	8,357	16,893	41,760	55,106	2,615	3,805	7,260	17,046	32,804	49,872
Conv. Jet PM_{10} (g)	21	28	39	79	7	20	37	37	70	80
ULSJ PM_{10} (g)	21	28	39	79	7	20	37	37	70	80
SO_x (g)	791	1,375	2,423	3,478	360	382	838	1,328	2,095	3,180

TABLE 8 LTO Cycle Contribution of Emissions Using Petroleum Jet Fuel ($g/kg_{payload}$-km)

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
CH_4 (g/kg-km)	9.17E-07	4.66E-07	1.69E-07	1.63E-07	1.96E-06	5.94E-06	1.59E-06	6.05E-07	2.04E-07	1.84E-07
N_2O (g/kg-km)	1.80E-06	9.15E-07	3.32E-07	3.19E-07	3.85E-06	1.16E-05	3.12E-06	1.19E-06	4.00E-07	3.60E-07
CO_2 (g/kg-km)	7.13E-02	3.62E-02	1.32E-02	1.27E-02	1.52E-01	4.57E-01	1.24E-01	4.69E-02	1.58E-02	1.43E-02
VOC (g/kg-km)	2.52E-05	1.15E-05	4.02E-06	3.55E-06	6.13E-05	8.24E-04	8.00E-05	3.25E-05	9.29E-06	8.05E-06
CO (g/kg-km)	1.86E-04	9.87E-05	3.30E-05	2.10E-05	6.31E-04	2.74E-03	3.63E-04	1.44E-04	4.18E-05	2.98E-05
NO_x (g/kg-km)	3.36E-04	1.98E-04	1.01E-04	8.91E-05	4.94E-04	2.05E-03	4.77E-04	2.69E-04	1.10E-04	9.97E-05
PM_{10} (g/kg-km)	8.46E-07	3.24E-07	9.42E-08	1.27E-07	1.29E-06	1.05E-05	2.42E-06	5.83E-07	2.35E-07	1.61E-07
SO_x (g/kg-km)	3.18E-05	1.61E-05	5.86E-06	5.63E-06	6.79E-05	2.05E-04	5.51E-05	2.09E-05	7.05E-06	6.36E-06

TABLE 9 Cruise Contribution of Emissions Using Petroleum Jet Fuel ($g/kg_{payload}$-$km_{great\ circle\ distance}$)

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
CH_4 (g/kg-km)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
N_2O (g/kg-km)	1.11E-05	9.98E-06	8.72E-06	1.80E-05	1.73E-05	4.90E-05	1.15E-05	8.69E-06	6.29E-06	1.46E-05
CO_2 (g/kg-km)	5.60.E-01	5.04.E-01	4.41.E-01	4.55.E-01	8.75.E-01	2.44.E+00	5.77.E-01	4.38.E-01	3.18.E-01	3.69.E-01
VOC (g/kg-km)	8.63E-05	3.79E-05	2.05E-05	3.26E-05	9.16E-05	2.62E-03	2.04E-04	8.34E-05	3.72E-05	3.99E-05
CO (g/kg-km)	6.05E-04	3.93E-04	1.82E-04	2.18E-04	1.24E-03	1.51E-02	1.11E-03	4.31E-04	2.38E-04	1.88E-04
NO_x (g/kg-km)	2.77E-03	2.41E-03	2.66E-03	2.21E-03	3.43E-03	1.19E-02	2.41E-03	2.50E-03	1.55E-03	1.80E-03
Conv. Jet PM_{10} (g/kg-km)	3.64E-05	3.23E-05	2.80E-05	2.90E-05	5.68E-05	1.67E-04	3.91E-05	2.84E-05	2.04E-05	2.36E-05
ULSJ PM_{10} (g/kg-km)	3.64E-05	3.23E-05	2.80E-05	2.90E-05	5.68E-05	1.67E-04	3.91E-05	2.84E-05	2.04E-05	2.36E-05
SO_x (g/kg-km)	2.49E-04	2.24E-04	1.95E-04	2.02E-04	3.89E-04	1.10E-03	2.57E-04	1.95E-04	1.41E-04	1.64E-04

Tables 10 through 13 provide flight PFEI and emission factors for various blends of SPK fuel relative to those of conventional jet fuel. Table A-3 in Appendix A presents the tests used to approximate the normalized emissions in Tables 10 through 13. Table A-4 in Appendix A defines the surrogate SPK test engine values that were used to produce the values for each aircraft class in Tables 10 through 13. Tables 10 and 11 are for 100 percent SPK fuel emissions in LTO and cruise modes; these emissions have been normalized by those from conventional fuel. Tables 12 and 13 present combustion emissions from a blend of SPK and conventional jet fuel (50 percent by volume), which are also normalized by emissions from conventional fuel. These values are greyed out in the tables to reflect the lack of sufficient emissions test data.

Tables 10 through 13 also provide conventional-fuel-normalized PFEI values for 50 percent and 100 percent SPK fuels. The values are taken from Hileman et al. (2010) and are applied to both LTO and cruise modes. The emissions values listed in Tables 10 and 13 are derived from the fuel-burn-weighted averages for the CFM56 and PW308 engines described in TABLE A-2; these averages were applied to the emissions changes from various SPK fuel blends, as shown in Figure A-2 through Figure A-6 in Appendix A (Bester and Yates 2009; Bulzan et al. 2010; Corporan et al. 2007; Corporan et al. 2009; Corporan et al. 2010a,b; Lobo et al. 2011; Moses et al. 2003; Timko et al 2010). A summary of these SPK fuel combustion emissions values can be found in Carter et al. (2011). Note that all SO_x emissions are assumed to be a function of fuel composition and that 50 percent and 100 percent SPK corresponds to a 50 percent and 100 percent reduction in fuel sulfur content compared with conventional jet fuel, respectively. Emissions of CH_4, N_2O, and VOC are assumed to be unchanged with the use of SPK blends for the LTO cycle. Emissions of CO are assumed to be unchanged during cruise with SPK blends because at higher power settings, the CO emission variation with fuel composition becomes negligible.

The emissions from Tables 10 through 13 were aggregated according to Equation 1, in which each SPK emissions factor F_{SPK} is multiplied by the conventional petroleum emissions $Em_{petroleum}$ for each mode and summed to provide the total SPK emissions for the blend percentage, i. Figure A-7 in Appendix A illustrates the linear interpolation used for each species at a specified SPK blend. The final PFEI and total emissions (LTO and cruise) for conventional jet fuel, 100 percent SPK fuel, and a specified SPK blend (currently 50 percent and greyed out) are listed in Tables 14 through 16.

$$Em_{SPK_{Total_i}} = Em_{petroleum_{LTO_i}} F_{SPK_{LTO_i}} + Em_{petroleum_{cruise_i}} F_{SPK_{cruise_i}} \quad (1)$$

TABLE 10 Aircraft PFEI and Emissions for 100% SPK in LTO (Relative to Petroleum Jet Fuel)

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
Full Flight PFEI	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%
LTO CH_4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
LTO N_2O	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
LTO VOC	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
LTO CO	90%	90%	90%	90%	90%	85%	90%	90%	90%	90%
LTO NO_x	92%	92%	92%	92%	92%	97%	92%	92%	92%	92%
LTO PM_{10}	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
LTO SO_x	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

TABLE 11 Aircraft PFEI and Emissions for 100% SPK in Cruise (Relative to Petroleum Jet Fuel)

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
Full Flight PFEI	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%	99.7%
CH_4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
N_2O	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
VOC	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
CO	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
NO_x	92%	92%	92%	92%	92%	94%	92%	92%	92%	92%
PM_{10}	8%	8%	8%	8%	8%	42%	8%	8%	8%	8%
SO_x	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

TABLE 12 Aircraft PFEI and Emissions for 50/50 SPK/Petroleum Jet in LTO (Relative to Petroleum Jet Fuel)

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
Full Flight PFEI	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%
LTO CH_4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
LTO N_2O	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
LTO VOC	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
LTO CO	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
LTO NO_x	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
LTO PM_{10}	35%	35%	35%	35%	35%	72%	35%	35%	35%	35%
LTO SO_x	51%	51%	51%	51%	51%	51%	51%	51%	51%	51%

TABLE 13 Aircraft PFEI and Emissions for 50/50 SPK/Petroleum Jet in Cruise (Relative to Petroleum Jet Fuel)

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
Full Flight PFEI	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%	99.85%
CH_4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
N_2O	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
VOC	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
CO	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
NO_x	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%
PM_{10}	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
SO_x	51%	51%	51%	51%	51%	51%	51%	51%	51%	51%

TABLE 14 Summary of Aircraft PFEI and Emissions for Petroleum Jet

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
PFEI ($kJ/kg_{payload}$-km)	8.65	7.40	6.21	6.40	14.09	40.18	9.62	6.65	4.57	5.25
CH_4 ($g/kg_{payload}$-km)	9.17E-07	4.66E-07	1.69E-07	1.63E-07	1.96E-06	5.94E-06	1.59E-06	6.05E-07	2.04E-07	1.84E-07
N_2O ($g/kg_{payload}$-km)	1.80E-06	9.15E-07	3.32E-07	3.19E-07	3.85E-06	1.16E-05	3.12E-06	1.19E-06	4.00E-07	3.60E-07
CO_2 ($g/kg_{payload}$-km)	6.31E-01	5.40E-01	4.54E-01	4.68E-01	1.03E+0	2.90E+00	7.01E-01	4.85E-01	3.34E-01	3.84E-01
CO_2 with C in VOC and CO ($g/kg_{payload}$-km)	6.33E-01	5.41E-01	4.54E-01	4.69E-01	1.03E+0	2.94E+00	7.04E-01	4.86E-01	3.34E-01	3.84E-01
VOC ($g/kg_{payload}$-km)	1.12E-04	4.95E-05	2.45E-05	3.61E-05	1.53E-04	3.44E-03	2.84E-04	1.16E-04	4.65E-05	4.79E-05
CO ($g/kg_{payload}$-km)	7.91E-04	4.92E-04	2.15E-04	2.39E-04	1.87E-03	1.78E-02	1.47E-03	5.75E-04	2.80E-04	2.18E-04
NO_x ($g/kg_{payload}$-km)	3.10E-03	2.61E-03	2.76E-03	2.30E-03	3.93E-03	1.39E-02	2.89E-03	2.77E-03	1.66E-03	1.90E-03
PM_{10} ($g/kg_{payload}$-km)	3.72E-05	3.26E-05	2.81E-05	2.91E-05	5.81E-05	1.78E-04	4.15E-05	2.90E-05	2.06E-05	2.37E-05
SO_x ($g/kg_{payload}$-km)	2.80E-04	2.40E-04	2.01E-04	2.08E-04	4.56E-04	1.30E-03	3.12E-04	2.15E-04	1.48E-04	1.70E-04

TABLE 15 Summary of Aircraft PFEI and Emissions for 100% SPK

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
PFEI (kJ/$kg_{payload}$-km)	8.62	7.37	6.19	6.38	14.04	40.06	9.60	6.63	4.55	5.23
CH_4 (g/$kg_{payload}$-km)	9.17E-07	4.66E-07	1.69E-07	1.63E-07	1.96E-06	5.94E-06	1.59E-06	6.05E-07	2.04E-07	1.84E-07
N_2O (g/$kg_{payload}$-km)	1.80E-06	9.15E-07	3.32E-07	3.19E-07	3.85E-06	1.16E-05	3.12E-06	1.19E-06	4.00E-07	3.60E-07
CO_2 (g/$kg_{payload}$-km)	6.06E-01	5.18E-01	4.36E-01	4.49E-01	9.86E-01	2.78E+00	6.73E-01	4.66E-01	3.20E-01	3.68E-01
CO_2 with C in VOC and CO (g/$kg_{payload}$-km)	6.07E-01	5.19E-01	4.36E-01	4.50E-01	9.89E-01	2.82E+00	6.76E-01	4.67E-01	3.21E-01	3.69E-01
VOC (g/$kg_{payload}$-km)	1.12E-04	4.95E-05	2.45E-05	3.61E-05	1.53E-04	3.44E-03	2.84E-04	1.16E-04	4.65E-05	4.79E-05
CO (g/$kg_{payload}$-km)	7.73E-04	4.82E-04	2.12E-04	2.37E-04	1.81E-03	1.74E-02	1.43E-03	5.61E-04	2.75E-04	2.15E-04
NO_x (g/$kg_{payload}$-km)	2.84E-03	2.39E-03	2.53E-03	2.11E-03	3.60E-03	1.32E-02	2.65E-03	2.54E-03	1.52E-03	1.74E-03
PM_{10} (g/$kg_{payload}$-km)	2.94E-06	2.52E-06	2.15E-06	2.23E-06	4.59E-06	7.23E-05	3.47E-06	2.28E-06	1.60E-06	1.83E-06
SO_x (g/$kg_{payload}$-km)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

TABLE 16 Summary of Aircraft PFEI and Emissions for 50% SPK in a Blend of SPK with Petroleum Jet Fuel

	Passenger Aircraft						Freight Aircraft			
Aircraft Class	SA	STA	LTA	LQ	RJ	BJ	SA-F	STA-F	LTA-F	LQ-F
PFEI (kJ/$kg_{payload}$-km)	8.64	7.38	6.20	6.39	14.06	40.12	9.61	6.64	4.56	5.24
CH_4 (g/$kg_{payload}$-km)	9.17E-07	4.66E-07	1.69E-07	1.63E-07	1.96E-06	5.94E-06	1.59E-06	6.05E-07	2.04E-07	1.84E-07
N_2O (g/$kg_{payload}$-km)	1.80E-06	9.15E-07	3.32E-07	3.19E-07	3.85E-06	1.16E-05	3.12E-06	1.19E-06	4.00E-07	3.60E-07
CO_2 (g/$kg_{payload}$-km)	6.19E-01	5.29E-01	4.45E-01	4.59E-01	1.01E+00	2.84E+00	6.87E-01	4.75E-01	3.27E-01	3.76E-01
CO_2 with C in VOC and CO (g/$kg_{payload}$-km)	6.20E-01	5.30E-01	4.45E-01	4.59E-01	1.01E+00	2.88E+00	6.90E-01	4.77E-01	3.27E-01	3.76E-01
VOC (g/$kg_{payload}$-km)	1.12E-04	4.95E-05	2.45E-05	3.61E-05	1.53E-04	3.44E-03	2.84E-04	1.16E-04	4.65E-05	4.79E-05
CO (g/$kg_{payload}$-km)	7.73E-04	4.82E-04	2.12E-04	2.37E-04	1.81E-03	1.76E-02	1.43E-03	5.61E-04	2.75E-04	2.15E-04
NO_x (g/$kg_{payload}$-km)	2.85E-03	2.39E-03	2.52E-03	2.10E-03	3.62E-03	1.29E-02	2.67E-03	2.55E-03	1.52E-03	1.74E-03
PM_{10} (g/$kg_{payload}$-km)	3.30E-05	2.91E-05	2.52E-05	2.61E-05	5.16E-05	1.58E-04	3.60E-05	2.57E-05	1.84E-05	2.13E-05
SO_x (g/$kg_{payload}$-km)	1.43E-04	1.22E-04	1.03E-04	1.06E-04	2.32E-04	6.63E-04	1.59E-04	1.10E-04	7.54E-05	8.66E-05

4 AVIATION MODULE IN GREET

Argonne National Laboratory incorporated the aviation module in its most recent release of the GREET model (GREET1_2011) (Wang 2011). The jet fuel production processes from the various feedstock sources are incorporated in a single spreadsheet (JetFuel_WTP). The upstream processes — such as petroleum recovery and transportation for petroleum jet fuel, coal mining or natural gas recovery and processing for FT jet fuel, and bio-oil production from plant or algal feedstocks — are in their original respective spreadsheets within GREET (i.e., in the petroleum, coal, natural gas, and bio-oil spreadsheets, respectively, for these feedstock sources).

The different aircraft classes, their operational characteristics, and the properties of the baseline and alternative jet fuels are incorporated in another spreadsheet (JetFuel_PTWa). The WTWa energy use and emissions results for various jet fuels and blends are shown in a third spreadsheet (JetFuel_WTWa) for the different aircraft types and classes, on the basis of various LCA functional units (i.e., per MJ of fuel use, per kg-km, and per passenger-km). Figure 12 shows the processes associated with the different aviation fuels' WTWa pathways (with the relevant GREET spreadsheet name noted below each process). A user manual for using the aviation module in GREET is being developed and will be posted on the GREET Web site (http://greet.es.anl.gov) upon completion.

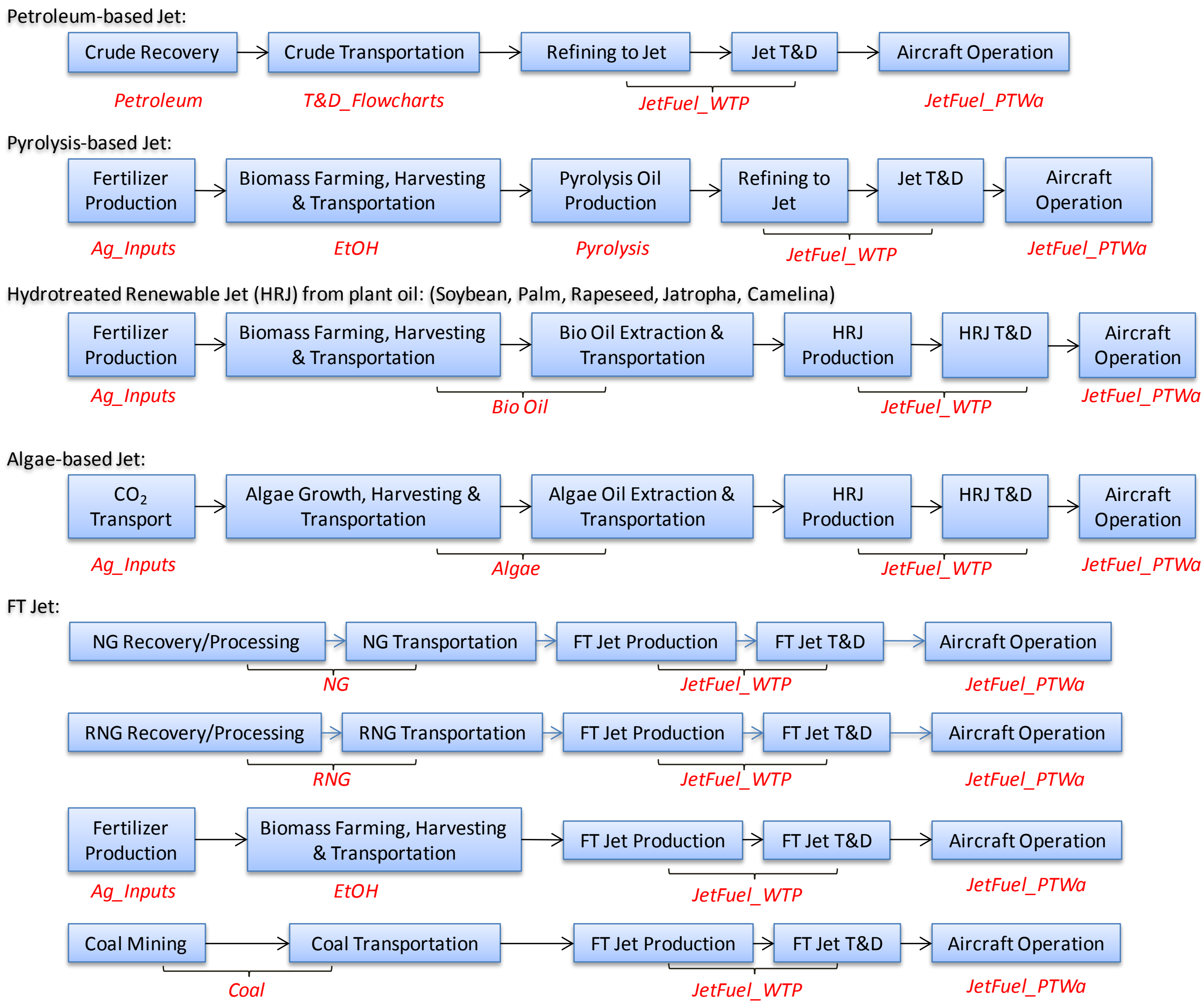


FIGURE 12 Aviation Fuels Pathways in GREET (Name of Relevant GREET Spreadsheet Is Noted Below Each Process)

5 WTWa ENERGY USE AND GHG EMISSIONS ANALYSIS

Functional units are critical when comparing LCA results of various alternative products. For energy products, a common functional unit is a "unit of delivered energy (e.g., gal or MJ of fuel). This is particularly important when comparing fuels that are used in similar combustion technologies with similar end-use efficiencies (e.g., petroleum jet and renewable jet fuel in the same aircraft). In making such comparisons, the energy functional unit is reliable because complications introduced by differences in efficiencies are avoided. However, when fuels are used in different combustion technologies with different efficiencies but similar functions, the energy functional unit may not be appropriate. In such cases, a "service function unit" (e.g., km traveled carrying a specific payload) could be a more reliable metric. In such cases, the LCA results would depend on the aircraft's payload fuel energy intensity, which in turn depends on many factors (e.g., engine technology, load factor, aerodynamics of aircraft design, great-circle distance).

This report provides preliminary WTWa results for jet fuel pathways in three functional units: per MJ of fuel consumed by aircraft, per kg of payload for each km of great-circle distance, and per passenger for each km of great-circle distance. While the per-kg-of-payload-per-km-of-great-circle-distance is the appropriate functional unit for freight aircrafts, the per-passenger-per-km-of-great-circle-distance is a useful metric for passenger aircraft. To allocate energy use and emissions of a trip to a passenger, we assume that 90 kg of the payload represents an average weight of a passenger and belongings (i.e., luggage). This is equivalent to a mass allocation of energy and emissions between the passengers and cargo onboard the aircraft. A simple conversion of per-kg results to per-passenger results can be performed using the fixed weight of a passenger plus luggage. This allocation methodology works for all aircraft classes regardless of the split between passengers and cargo payloads onboard the aircraft. It is important that users understand that multiplying the passenger-based functional unit by the total passenger-distance flown will not provide the total emissions for a flight because this method will not account for the emissions that were allocated to the cargo in the aircraft. To obtain the total emissions from a flight, the user should multiply the payload-based functional unit by the total payload-distance flown.

Figure 13 shows the WTWa fossil energy use per MJ of petroleum jet and alternative jet fuels produced from various fossil and bio-feedstock sources. The lower portion of the stacked bar represents the WTP fossil energy use per MJ of the jet fuel product. The WTP stage accounts for the recovery and conversion of the feedstock to produce the finished fuel. It also accounts for all feedstock and fuel transportation activities. The WTP stage of the conventional jet consumes the least amount of fossil energy (180,000 joules, or 0.18 MJ per MJ of jet fuel product) compared with all other fossil and bio- feedstock sources. The pyrolysis of corn stover consumed 0.5 MJ of fossil energy per MJ of jet fuel product — nearly double the energy consumed in the soybean and algae pathways. The corresponding fossil energy use in the gas-to-liquid (GTL), CTL, CTL with CCS, and biomass-to-liquid (BTL) pathways are 0.7, 1, 1.1, and 0.7 MJ, respectively, per MJ of jet fuel produced. Note that the CTL with CCS consumes more fossil energy compared with the CTL without CCS because of the electricity consumption for CO_2 capture and compression in the CCS case. While the fossil energy use can be employed as a surrogate for predicting relative CO_2 emissions between pathways, we note few exceptions to such correlation, such as methane venting and flaring in oil and natural gas fields and CO_2 sequestration associated with use of fossil fuels in CCS.

The upper portion of the stacked bars in Figure 13 represents the PTWa fossil energy consumed by the aircraft. The PTWa fossil energy use is the fraction of the 1 MJ of jet fuel that originated from any of the fossil feedstock sources (e.g., petroleum, natural gas, and coal). For example, 80 percent of the FT jet consumed by the aircraft is from fossil sources (coal) if the fuel is produced from the co-feeding of 80 percent coal and 20 percent biomass. The combined WTP and PTWa stages represent the WTWa fossil energy use per MJ of jet fuel consumed by the aircraft.

Figure 14 shows the WTWa petroleum energy use per MJ of petroleum and alternative jet fuels. The petroleum energy use is a subset of the fossil energy use shown in Figure 13. The significance of examining the petroleum energy use is the U.S. dependence on crude oil imports. According to EIA (2011), 49 percent of the crude oil and refined petroleum products consumed in the United States in 2010 were imported from other countries. The balance of the WTWa fossil energy use represents natural gas and coal use, both of which are produced in abundance domestically and at a lower cost per unit of energy compared with petroleum. Figure 14 shows that all of the considered alternatives to petroleum jet fuel nearly eliminate this dependence on petroleum oil.

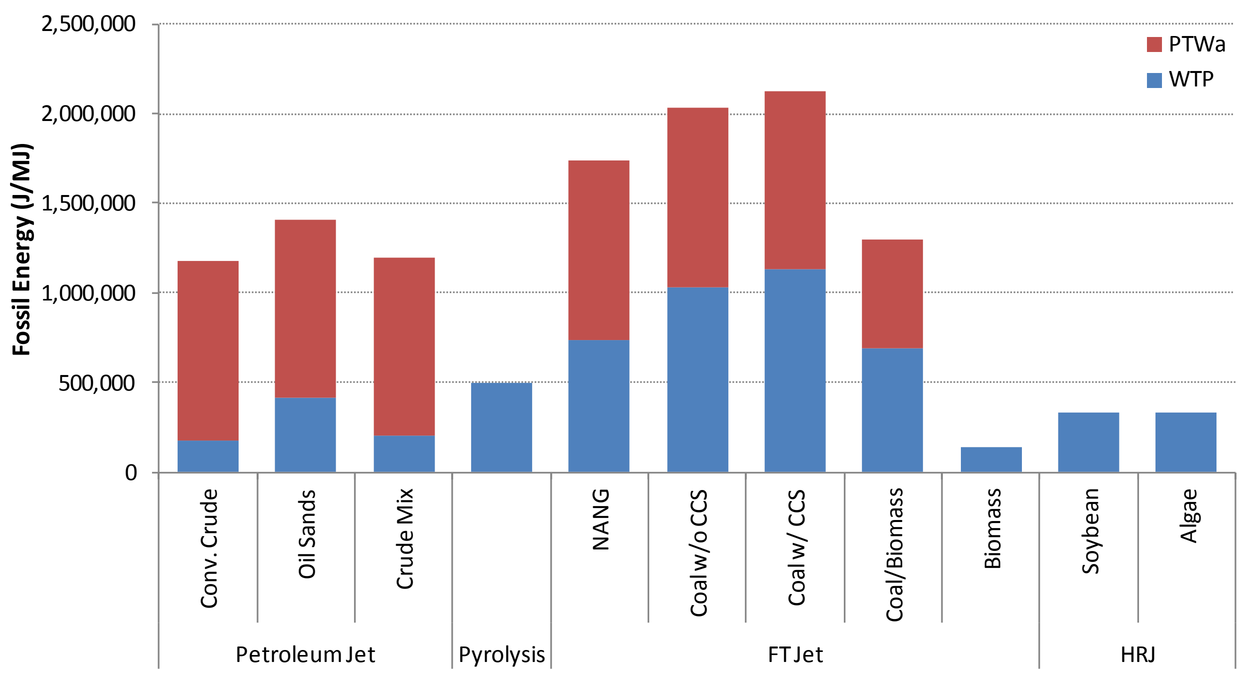


FIGURE 13 WTW Fossil Energy Use by Alternative Jet Fuels

Figure 15 shows the contribution of the WTP and PTWa stages to GHG emissions per MJ of alternative jet fuel products. The WTP stage for all bio-jet pathways appears on the negative side of the GHG emissions scale, mainly because of the CO_2 absorbed from the atmosphere for photosynthesis during the growth phase of the biomass. However, the amount of CO_2 sequestered during the biomass growth is mitigated by the emissions associated with the energy use for biomass farming and collection, fertilizer, and hydrogen needed for fuel upgrading. The carbon sequestered in the biomass ends up in the fuel after the conversion step and returns to the atmosphere in the exhaust stream after the fuel combusts in the engine of the aircraft.

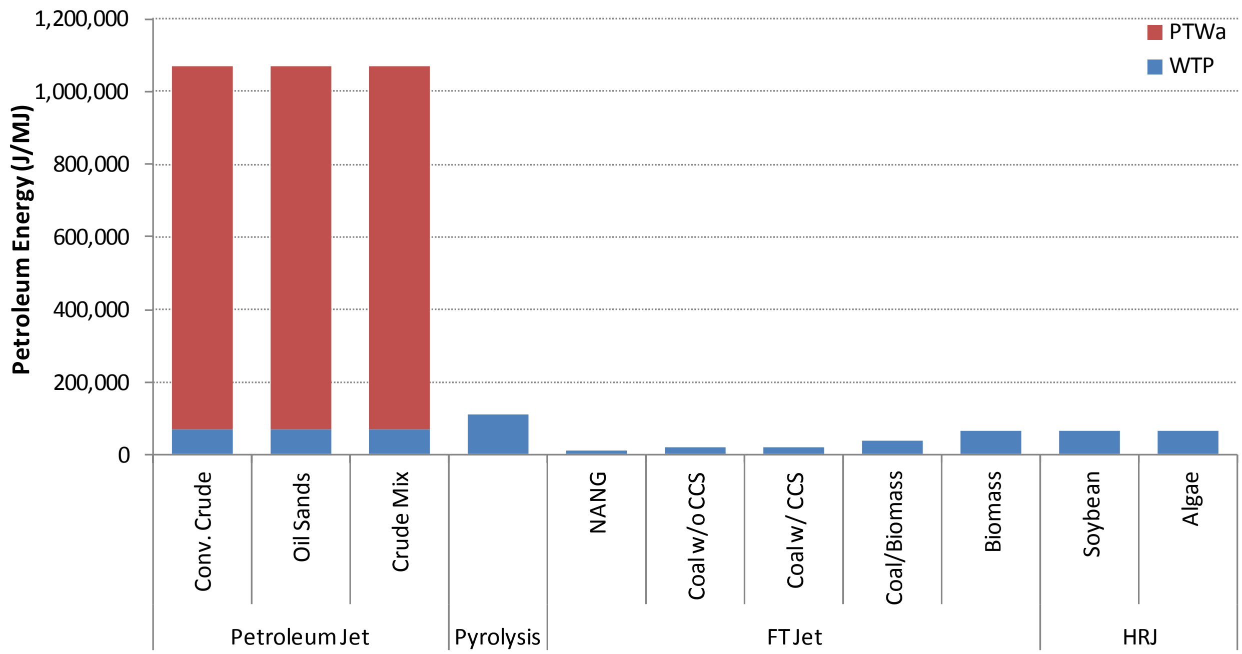


FIGURE 14 WTW Petroleum Energy Use by Alternative Jet Fuels Production Pathways

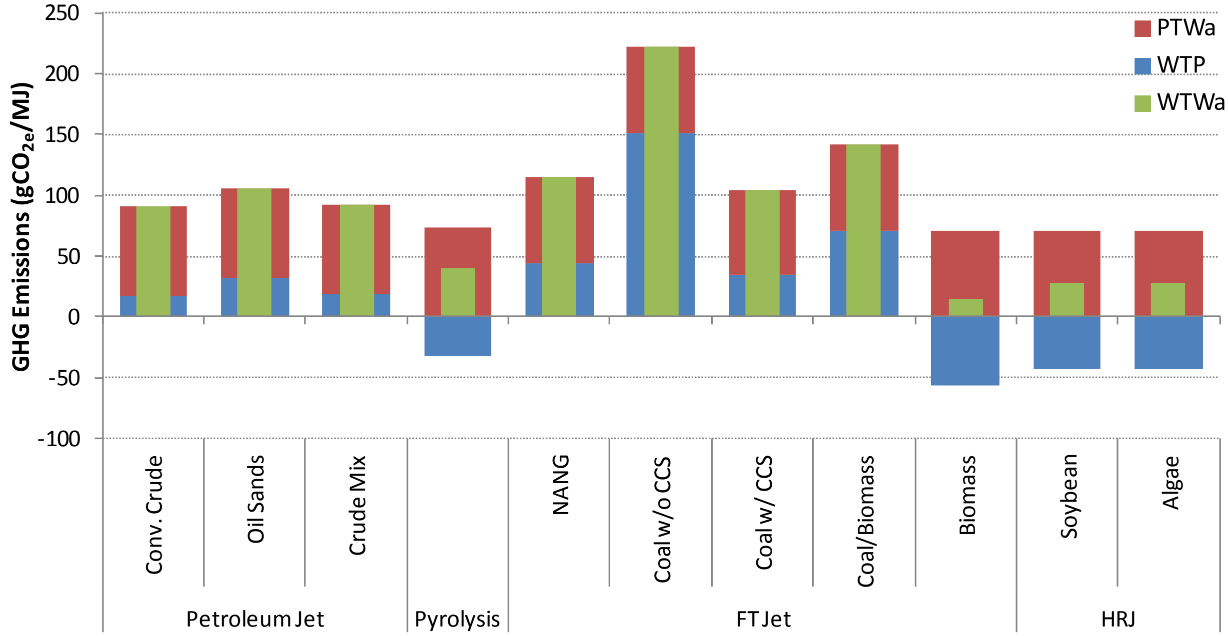


FIGURE 15 WTW GHG Emissions by Alternative Jet Fuels Production Pathways

Depending on the feedstock source, fuel conversion technology, and allocation or displacement credit methodology applied to co-products, alternative bio-jet fuel pathways can reduce life-cycle GHG emissions by 55-85 percent compared with petroleum jet fuel. Jet fuel production via pyrolysis of corn stover reduces WTWa GHG emissions by 55 percent, while hydroprocessing of soybean or algal oil to produce renewable jet fuel reduces WTWa GHG emissions by 70 percent relative to petroleum jet fuel. Although FT jet fuel produced from fossil feedstock sources such as natural gas and coal significantly reduces petroleum energy use, these fossil sources result in greater GHG emissions compared with petroleum jet fuel. Natural gas, coal, and coal with CCS produce 24 percent, 140 percent, and 13 percent higher WTWa GHG emissions compared with petroleum jet fuel.

Figure 16 shows the WTWa GHG emissions per kg-km for various freight aircraft classes using petroleum jet fuel. On the basis of operational performance data from the Volpe Center for these freight aircraft, the large twin aisle aircraft produces lower WTWa GHG emissions compared with the single aisle, the small twin aisle, and the large quad aircrafts, respectively. This change in GHG emissions is a function of the relative energy use of the aircraft class, as explained in more detail for the passenger operations below.

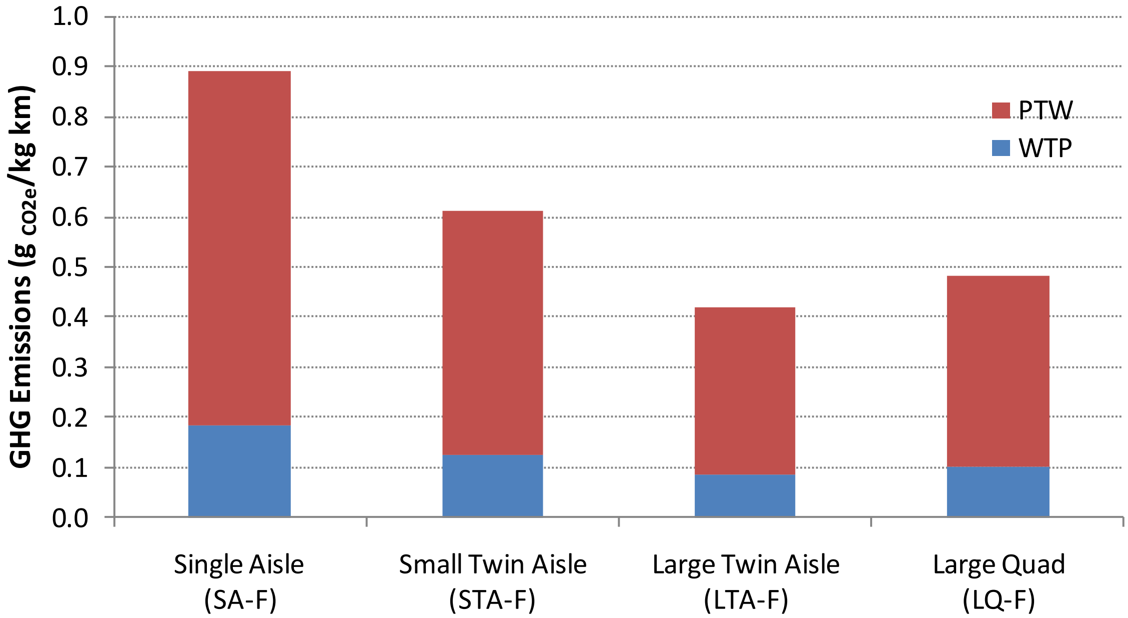


FIGURE 16 WTWa GHG Emissions by Freight Aircraft Classes Using Petroleum Jet Fuel

Figure 17 shows the WTWa GHG emissions per passenger-km for various passenger aircraft classes using petroleum jet fuel. Like the freight aircraft, the large twin aisle class produces the lowest WTW GHG emissions of all the passenger aircraft classes. Again, the variation in these results is attributable to the relative energy efficiency of the aircraft being operated, which in turn is a function of the relative age of the respective portions of the fleet and how these aircraft types are used. Typically, larger aircraft have lower PFEI values than smaller aircraft due to, among other factors, an increase in engine efficiency with size; however, the age of different parts of the fleet varies, with the LQ being older and therefore using less-efficient technologies than the LTA.

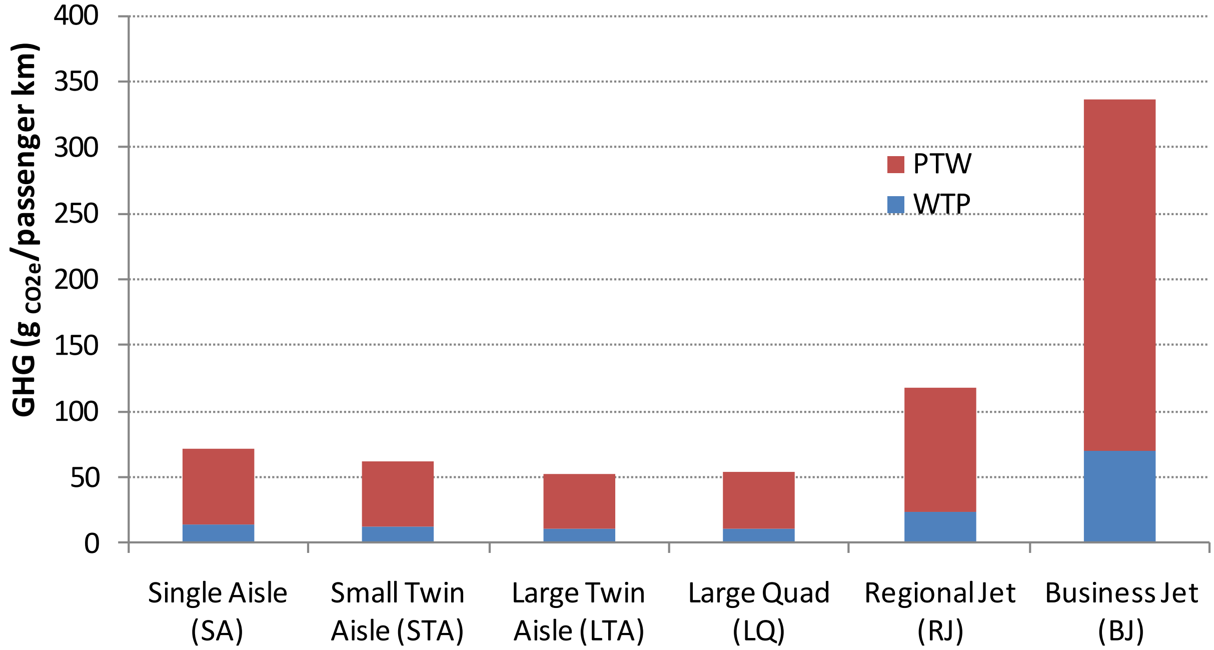


FIGURE 17 WTW GHG Emissions by Passenger Aircraft Classes Using Petroleum Jet Fuel

6 CONCLUSIONS

The GREET model was expanded to include pathways for production of petroleum jet fuel from crude oil; FT jet fuel from natural gas, coal, and biomass; bio-jet fuels from fast pyrolysis of biomass; and hydroprocessed renewable jet fuel from vegetable and algal oil. GREET was also expanded to include energy use and emissions associated with operation of six passenger aircraft classes and four freight aircraft classes. The key stages and assumptions associated with the production pathways for alternative jet fuels and aircraft operation are documented in this report. Depending on the feedstock source, fuel conversion technology, and allocation or displacement credit methodology applied to co-products, preliminary WTWa results show that alternative bio-jet fuel pathways can reduce life-cycle GHG emissions by 55–85 percent compared with petroleum-based jet fuel.

This page intentionally left blank.

7 REFERENCES

ACAM (Air Quality Analysis/Air Conformity Applicability Model), Online Database, [http://www.afcee.lackland.af.mil/air/acam/acam.asp], accessed July 4, 2011.

Anderson, B.E., et al., 2011, *Alternative Aviation Fuel Experiment (AAFEX),* NASA/TM-20011-217059, National Aeronautics and Space Administration, Langley Research Center, Hampton, Va., Feb.

ASTM (American Society for Testing and Materials), 2011, *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons,* ASTM International Standard D7566-11 a DOI: 10.1520/D7566-11A, West Conshohocken, PA.

ASTM, 2010, *Standard Specification for Aviation Turbine Fuels*, ASTM International Standard D1655-11b DOI: 10.1520/D1655-11B, West Conshohocken, PA.

Bester, N., and A. Yates, 2009, "Assessment of the Operational Performance of Fischer-Tropsch Synthetic-Paraffinic Kerosene in a T63 Gas Turbine Compared to Conventional Jet A-1 Fuel," pp. 1–15 in *Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air,* Orlando, Fla., June 8–12.

Boeing, 2011, *Current Market Outlook (CMO) 2011–2030,* Chicago, Ill. [http://www.boeing.com/commercial/cmo], accessed March 2012.

Bulzan, D., et al., 2010, "Gaseous and Particulate Emissions Results of the NASA Alternative Aviation Fuel Experiment (AAFEX)," pp. 1–13 in *Proceedings of ASME Turbo Expo 2010: Power for Land, Sea, and Air,* Glasgow, Scotland, June 14–18.

Burnham, A., et al., 2012, "Life-cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal and Petroleum," *Environmental Science and Technology* 46(2):619–627, DOI:10.1021/es201942m.

CAPP (Canadian Association of Petroleum Producers), 2011, *CAPP Crude Oil Forecast, Markets and Pipeline Report — Production and Supply Data,* Publication No. 2011-0010, June [http://www.capp.ca/library/publications/crudeOilAndOilSands/pages/pubInfo.aspx?DocId=191091], accessed March 2012.

Canadian National Energy Board, 2010, *Estimated Canadian Crude Oil Exports by Type and Destination,* all four quarterly (Q1 through Q4) reports [http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/sttstc/crdlndptrlmprdct/stmtdcndncrdlxprttpdstn-eng.html], accessed March 2012.

Carter, N.A., et al., 2011, "Energy and Environmental Viability of Select Alternative Jet Fuel Pathways," AIAA 2011-5968, presented at 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, San Diego, Calif., July 31–Aug. 3 [http://web.mit.edu/aeroastro/partner/reports/proj281altfuelpathways.pdf], accessed March 2012.

Concil, A., 2006, *Aviation and the Environment — Killing Myths and Setting the Agenda,* Press Release No. 14, International Air Transport Association, Geneva, Switzerland, April 25 [http://www.iata.org/pressroom/pr/Pages/2006-04025-02.aspx], accessed March 2012

Corporan, E., et al., 2010a, "Emissions Characteristics of Military Helicopter Engines with JP-8 and Fischer–Tropsch Fuels," *Journal of Propulsion and Power* 26.2:317–324.

Corporan, E., 2010b, *Alternative Fuels Tests on a C-17 Aircraft: Emissions Characteristics,* AFRL-RZ-WP-TR-2010, Air Force Resource Lab, Wright-Patterson Air Force Base, Ohio.

Corporan, E., et al., 2009, "Chemical, Thermal Stability, Seal Swell, and Emissions Characteristics of Jet Fuels from Alternative Sources," presented at IASH 2009, 11th International Conference on Stability, Handling and Use of Liquid Fuels, Prague, Czech Republic, Oct. 18–22.

Corporan, E., et al., 2007, "DOD Assured Fuels Initiative: B-52 Aircraft Emissions Burning a Fischer-Tropsch/JP-8 Fuel Blend," pp. 26–43 in *Proceedings of IASH 2007: 10th International Conference on Stability, Handling and Use of Liquid Fuels,* Tucson, Ariz., Oct. 7–11.

Dunn, J., et al., 2011, *Updated Sugarcane and Switchgrass Parameters in the GREET Model,* Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

EIA (Energy Information Administration), 2011a, *Refinery Capacity Report 2011,* U.S. Department of Energy, Washington, D.C., Jan.

EIA, 2011b, *Petroleum Supply Annual 2011,* Volume 1, U.S. Department of Energy, Washington, D.C.

EIA, 2011c, *Annual Energy Outlook 2011 with Projections to 2035: Reference Case, April 2011,* DOE/EIA-0383(2011), U.S. Department of Energy, Washington, D.C., detailed tables obtained from [http://www.eia.gov/oiaf/aeo/tablebrowser/], accessed March 2012.

Ensys (EnSys Energy and Systems, Inc.), 2010, *Keystone XL Assessment,* Final Report prepared by Ensys Energy, Lexington, Mass., for U.S. Department of Energy, Office of Policy and International Affairs, Dec. 23.

FAA (Federal Aviation Administration), 2011a, *FAA Aerospace Forecast, Fiscal Years 2011–2031,* U.S. Department of Transportation, FAA, Aviation Policy and Plans.

FAA, 2011b, *FAA Destination 2025* [http://www.faa.gov/about/plans_reports/media/Destination2025.pdf], accessed June 2012.

FAA, 2011c, *Environmental Design Tool (AEDT)* [http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/aedt/], accessed March 2012.

Frank, E., et al., 2012, “Methane and Nitrous Oxide Emissions Affect Life-cycle Analysis of Algal Biofuels,” *Environmental Research Letters* (7), 014030.

Frank, E., et al., 2011, *Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model,* Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

Han, J., et al., 2011, *Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET,* Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

Hileman, J., et al., 2010, “Energy Content and Alternative Jet Fuel Viability,” *Journal of Propulsion and Power* 26.6:1184–1195.

Hileman, J., et al., 2009, *Near Term Feasibility of Alternative Jet Fuels,* technical report prepared by RAND Corporation, Santa Monica, Calif., and Partnership for AiR Transportation Noise and Emissions Reduction, Massachusetts Institute of Technology, Cambridge, Mass., for Federal Aviation Administration [http://web.mit.edu/aeroastro/partner/reports/proj17/altfuelfeasrpt.pdf], accessed March 2012.

Hileman, J.I., et al., 2008, “Payload Fuel Energy Efficiency as a Metric for Aviation Environmental Performance,” in *Proceedings of the 26th International Congress of the Aeronautical Sciences,* Anchorage, Ala.

Huo, H., et al., 2008, *Life Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-derived Biodiesel and Renewable Fuels,* ANL/ESD/08-2, Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

ICAO (International Civil Aviation Organization), 2010, *ICAO Environmental Report 2010: Aviation and Climate Change,* section on alternative fuels in Chapter 5, ICAO Environment Branch in collaboration with FCM Communications [http://www.icao.int/environmental-protection/Documents/Publications/ENV_Report_2010.pdf], accessed March 2012.

ICAO, 1993, *International Standards and Recommended Practices: Environmental Protection – Aircraft Engine Emissions*, ICAO Annex 16: Vol. II.

IATA (International Air Transport Association), 2011, *Annual Report 2011*, presented at International Air Transport Association 67th Annual General Meeting, Singapore, June [http://www.iata.org/pressroom/Documents/annual-report-2011.pdf], accessed March 2012.

IATA (International Air Transport Association), 2009, *A Global Approach to Reducing Aviation Emissions: First Stop: Carbon-Neutral Growth from 2020,* Geneva, Switzerland, Nov. [http://www.iata.org/SiteCollectionDocuments/Documents/Global_Approach_Reducing_Emissions_251109web.pdf], accessed March 2012.

IPPC (Intergovernmental Panel on Climate Change), 2008, *Climate Change 2007: Technical Summary,* Cambridge University Press, Cambridge, UK.

Jones, S.B., et al., 2009, *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case*, PNNL-18284, Pacific Northwest National Laboratory, Richland, Wash.

Larsen, R., et al., 2005, "Might Canadian Oil Sands Promote Hydrogen Production for Transportation? — Greenhouse Gas Emission Implications of Oil Sands Recovery and Upgrading," *World Resource Review* 17(2):220–242.

Lobo, P., et al., 2011, "Comparison of PM Emissions from a Commercial Jet Engine Burning Conventional, Biomass, and Fischer-Tropsch Fuels," *Environmental Science and Technology,* in review.

Malwitz, A., 2011, "2009 U.S. Origin Only Aircraft Operations and Emissions for Various AEDT Aircraft Categories," personal communication from Malwitz (U.S. Department of Transportation, Environmental Measurement and Modeling Division, Volpe Center, Washington, DC) to Argonne National Laboratory, Argonne, Ill.

Moses, C.A., et al., 2003, *Evaluation of Sasol Synthetic Kerosene for Suitability as Jet Fuel*, Report 08-04438, Southwest Research Institute, San Antonio, Tex.

NASS (National Agricultural Statistics Service), 2010, home page, U.S. Department of Agriculture [http://www.nass.usda.gov], accessed March 2012.

Omni Tech International, 2010, *Life Cycle Impact of Soybean Production and Soy Industrial Products,* prepared for United Soybean Board, released Feb.

Palou-Rivera, I., et al., 2011, *Updated Estimation of Energy Efficiencies of U.S. Petroleum Refineries*, Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

Pearlson, M., 2011, *A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels,* Master of Science Thesis, Massachusetts Institute of Technology, Cambridge, Mass.

Pradhan, A., et al., 2011, "Energy Life-Cycle Assessment of Soybean Biodiesel Revisited," *Transactions of the ASABE* 54(3):1031–1039.

Shonnard, D.R., et al., 2010, "Camelina-derived Jet Fuel and Diesel: Sustainable Advanced Biofuels," *Environmental Progress & Sustainable Energy* 29:382–392.

Stratton, R.W., et al., 2010, *Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels,* Partnership for Air Transportation Noise and Emissions Reduction, Massachusetts Institute of Technology, Cambridge, Mass.

Stratton, Russell W., Hsin Min Wong, and James I. Hileman, 2011, *Quantifying Variability in Life Cycle Greenhouse Gas Inventories of Alternative Middle Distillate Transportation Fuels, Environmental Science & Technology* 45(10) 4637–4644.

Timko, M.T., et al., 2010, “Particulate Emissions of Gas Turbine Engine Combustion of a Fischer−Tropsch Synthetic Fuel,” *Energy & Fuels* 24.11:5883–5896.
USAF (U.S. Air Force), 2010, *Air Force Energy Plan 2010,* [http://www.safie.hq.af.mil/shared/media/document/AFD-091208-027.pdf], accessed March 2012.

United States Navy, 2010, *A Navy Energy Vision for the 21st Century,* Oct. [http://greenfleet.dodlive.mil/files/2010/10/Navy-Energy-Vision-Oct-2010.pdf], accessed June 2012.

Vasudevan, V., et al., 2012, “The Environmental Performance of Algal Biofuel Technology Options,” *Environmental Science and Technology* 46: 2451–2459.

Wallace, J., et al., 2001, “Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels — North American Analysis,” Volume 3 in *GM Study: Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems,* General Motors Corporation, Argonne National Laboratory, BP, ExxonMobil, and Shell, June 1 [http://greet.es.anl.gov/publication-wft2tv3v], accessed March 2012.

Wang, M., 2011, *Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version GREET1_2011,* Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

Wang, M.Q., 1996, *GREET 1.0 — Transportation Fuel Cycles Model: Methodology and Use,* ANL/ESD-33, Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

Wang, M., and H. Huang, 1999, *A Full-Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas,* ANL/ESD-40, Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

Wright, M.M., et al., 2010, *Techno-economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels,* NREL/TP-6A20-46586, National Renewable Energy Laboratory, Golden, Colo.

Xie, X., et al., 2011, “Assessment of Fuel-cycle Energy Use and Greenhouse Gas Emissions for Fischer-Tropsch Diesel from Coal and Cellulosic Biomass,” *Environ. Sci. Technol.* 45(7):3047–3053, April 1.

This page intentionally left blank.

APPENDIX A

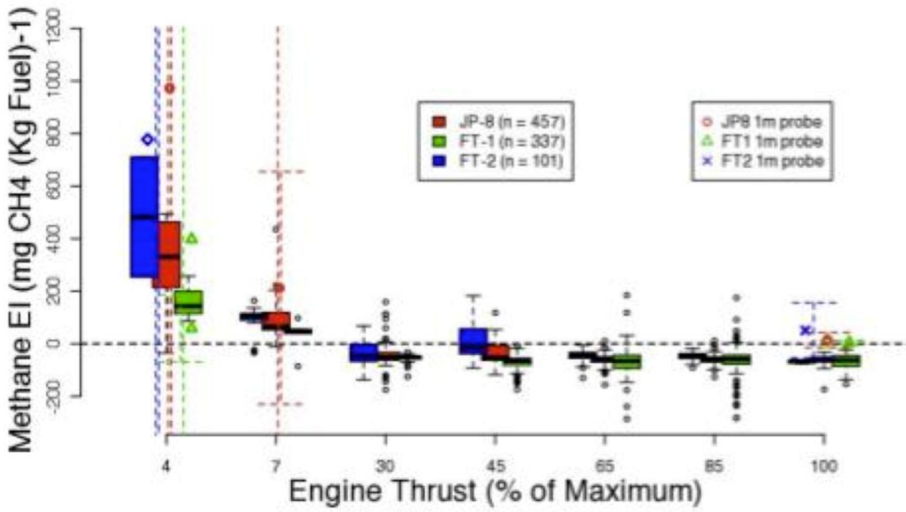
TABLE A-1 AEDT Aircraft Classification List

ACCODE	SEAT_CLASS	ACFamily	Aircraft Classification
B737-7-BBJ	2	B737 G2:SC2	BJ
B737-8-BBJ2	2	B737 G2:SC2	BJ
CNA550	2	N/A	BJ
CNA550-S	2	N/A	BJ
FAL20-C	2	N/A	BJ
FAL20-C	5	N/A	BJ
FAL20-D	2	N/A	BJ
FAL20-E	2	N/A	BJ
FAL20-F	2	N/A	BJ
FAL20-G	2	N/A	BJ
FAL200	2	N/A	BJ
FAL50	2	N/A	BJ
FAL50-EX	2	N/A	BJ
FAL900	2	N/A	BJ
FAL900B	2	N/A	BJ
FAL900C	2	N/A	BJ
GLOBALEXPRESS	2	N/A	BJ
GLOBALEXPRESS	4	N/A	BJ
GULF2	2	N/A	BJ
GULF2-B	2	N/A	BJ
GULF2-SP	2	N/A	BJ
GULF200	2	N/A	BJ
GULF3	2	N/A	BJ
GULF4	2	N/A	BJ
GULF4-SP	2	N/A	BJ
GULF5	2	N/A	BJ
HS125-7	2	N/A	BJ
HS125-8	2	N/A	BJ
IAI1126	2	N/A	BJ
A300F4-2	6	A300:SC6	F
A300F4-6	7	A300:SC7	F
A300F4-6-ST	7	A300:SC7	F
B747-1	8	B747 G1:SC8	LQ
B747-1	9	B747 G1:SC9	LQ
B747-2	6	B747 G1:SC6	LQ
B747-2	7	B747 G1:SC7	LQ
B747-2	8	B747 G1:SC8	LQ
B747-2	9	B747 G1:SC9	LQ
B747-3	6	B747 G1:SC6	LQ
B747-3	7	B747 G1:SC7	LQ
B747-3	8	B747 G1:SC8	LQ
B747-3	9	B747 G1:SC9	LQ
B747-4	6	B747 G2:SC6	LQ
B747-4	7	B747 G2:SC7	LQ
B747-4	8	B747 G2:SC8	LQ
B747-4	9	B747 G2:SC9	LQ
B747-4ER	8	B747 G2:SC8	LQ
B747-SP	6	B747 G1:SC6	LQ
B747-SP	7	B747 G1:SC7	LQ
B747-SR	8	B747 G1:SC8	LQ
A330-2	5	A330:SC5	LTA
A330-2	6	A330:SC6	LTA

ACCODE	SEAT_CLASS	ACFamily	Aircraft Classification
A330-2	7	A330:SC7	LTA
A330-3	6	A330:SC6	LTA
A330-3	7	A330:SC7	LTA
A330-3	8	A330:SC8	LTA
A340-2	6	A340:SC6	LTA
A340-3	6	A340:SC6	LTA
A340-3	7	A340:SC7	LTA
A340-5	5	A340:SC5	LTA
A340-5	6	A340:SC6	LTA
A340-5	7	A340:SC7	LTA
A340-6	6	A340:SC6	LTA
A340-6	7	A340:SC7	LTA
B777-2	6	B777:SC6	LTA
B777-2	7	B777:SC7	LTA
B777-2	8	B777:SC8	LTA
B777-2ER	6	B777:SC6	LTA
B777-2ER	7	B777:SC7	LTA
B777-3	7	B777:SC7	LTA
B777-3	8	B777:SC8	LTA
B777-3	9	B777:SC9	LTA
B777-3ER	6	B777:SC6	LTA
B777-3ER	7	B777:SC7	LTA
B777-3ER	8	B777:SC8	LTA
MD10-3	7	MD-10/11:SC7	LTA
MD11	6	MD-10/11:SC6	LTA
MD11	7	MD-10/11:SC7	LTA
MD11	8	MD-10/11:SC8	LTA
MD11-ER	7	MD-10/11:SC7	LTA
AVRORJ100	4	BAe 146:SC4	RJ
AVRORJ85	3	BAe 146:SC3	RJ
BAE146-100	3	BAe 146:SC3	RJ
BAE146-100Q	3	BAe 146:SC3	RJ
BAE146-200	3	BAe 146:SC3	RJ
BAE146-200	4	BAe 146:SC4	RJ
BAE146-200Q	3	BAe 146:SC3	RJ
BAE146-300	3	BAe 146:SC3	RJ
BAE146-300	4	BAe 146:SC4	RJ
BAE146-300Q	4	BAe 146:SC4	RJ
BAE146-RJ100	3	BAe 146:SC3	RJ
BAE146-RJ100	4	BAe 146:SC4	RJ
BAE146-RJ70	3	BAe 146:SC3	RJ
BAE146-RJ85	3	BAe 146:SC3	RJ
CL600	2	N/A	RJ
CL601	2	N/A	RJ
CL602	2	N/A	RJ
CL604	2	N/A	RJ
CL604	3	N/A	RJ
CRJ1	2	CRJ-100:SC2	RJ
CRJ1	3	CRJ-100:SC3	RJ
CRJ1-LR	2	CRJ-100:SC2	RJ
CRJ2	2	CRJ-200:SC2	RJ
CRJ2	3	CRJ-200:SC3	RJ

ACCODE	SEAT_CLASS	ACFamily	Aircraft Classification
B737-7-BBJ	2	B737 G2:SC2	BJ
B737-8-BBJ2	2	B737 G2:SC2	BJ
CNA550	2	N/A	BJ
CNA550-S	2	N/A	BJ
FAL20-C	2	N/A	BJ
FAL20-C	5	N/A	BJ
FAL20-D	2	N/A	BJ
FAL20-E	2	N/A	BJ
FAL20-F	2	N/A	BJ
FAL20-G	2	N/A	BJ
FAL200	2	N/A	BJ
FAL50	2	N/A	BJ
FAL50-EX	2	N/A	BJ
FAL900	2	N/A	BJ
FAL900B	2	N/A	BJ
FAL900C	2	N/A	BJ
GLOBALEXPRESS	2	N/A	BJ
GLOBALEXPRESS	4	N/A	BJ
GULF2	2	N/A	BJ
GULF2-B	2	N/A	BJ
GULF2-SP	2	N/A	BJ
GULF200	2	N/A	BJ
GULF3	2	N/A	BJ
GULF4	2	N/A	BJ
GULF4-SP	2	N/A	BJ
GULF5	2	N/A	BJ
HS125-7	2	N/A	BJ
HS125-8	2	N/A	BJ
IAI1126	2	N/A	BJ
A300F4-2	6	A300:SC6	F
A300F4-6	7	A300:SC7	F
A300F4-6-ST	7	A300:SC7	F
B747-1	8	B747 G1:SC8	LQ
B747-1	9	B747 G1:SC9	LQ
B747-2	6	B747 G1:SC6	LQ
B747-2	7	B747 G1:SC7	LQ
B747-2	8	B747 G1:SC8	LQ
B747-2	9	B747 G1:SC9	LQ
B747-3	6	B747 G1:SC6	LQ
B747-3	7	B747 G1:SC7	LQ
B747-3	8	B747 G1:SC8	LQ
B747-3	9	B747 G1:SC9	LQ
B747-4	6	B747 G2:SC6	LQ
B747-4	7	B747 G2:SC7	LQ
B747-4	8	B747 G2:SC8	LQ
B747-4	9	B747 G2:SC9	LQ
B747-4ER	8	B747 G2:SC8	LQ
B747-SP	6	B747 G1:SC6	LQ
B747-SP	7	B747 G1:SC7	LQ
B747-SR	8	B747 G1:SC8	LQ
A330-2	5	A330:SC5	LTA
A330-2	6	A330:SC6	LTA
A330-2	7	A330:SC7	LTA
A330-3	6	A330:SC6	LTA
A330-3	7	A330:SC7	LTA
A330-3	8	A330:SC8	LTA
A340-2	6	A340:SC6	LTA
A340-3	6	A340:SC6	LTA
A340-3	7	A340:SC7	LTA
A340-5	5	A340:SC5	LTA
A340-5	6	A340:SC6	LTA
A340-5	7	A340:SC7	LTA
A340-6	6	A340:SC6	LTA
A340-6	7	A340:SC7	LTA
B777-2	6	B777:SC6	LTA
B777-2	7	B777:SC7	LTA
B777-2	8	B777:SC8	LTA
B777-2ER	6	B777:SC6	LTA
B777-2ER	7	B777:SC7	LTA
B777-3	7	B777:SC7	LTA
B777-3	8	B777:SC8	LTA
B777-3	9	B777:SC9	LTA
B777-3ER	6	B777:SC6	LTA
B777-3ER	7	B777:SC7	LTA
B777-3ER	8	B777:SC8	LTA
MD10-3	7	MD-10/11:SC7	LTA
MD11	6	MD-10/11:SC6	LTA
MD11	7	MD-10/11:SC7	LTA
MD11	8	MD-10/11:SC8	LTA
MD11-ER	7	MD-10/11:SC7	LTA
AVRORJ100	4	BAe 146:SC4	RJ
AVRORJ85	3	BAe 146:SC3	RJ
BAE146-100	3	BAe 146:SC3	RJ
BAE146-100Q	3	BAe 146:SC3	RJ
BAE146-200	3	BAe 146:SC3	RJ
BAE146-200	4	BAe 146:SC4	RJ
BAE146-200Q	3	BAe 146:SC3	RJ
BAE146-300	3	BAe 146:SC3	RJ
BAE146-300	4	BAe 146:SC4	RJ
BAE146-300Q	4	BAe 146:SC4	RJ
BAE146-RJ100	3	BAe 146:SC3	RJ
BAE146-RJ100	4	BAe 146:SC4	RJ
BAE146-RJ70	3	BAe 146:SC3	RJ
BAE146-RJ85	3	BAe 146:SC3	RJ
CL600	2	N/A	RJ
CL601	2	N/A	RJ
CL602	2	N/A	RJ
CL604	2	N/A	RJ
CL604	3	N/A	RJ
CRJ1	2	CRJ-100:SC2	RJ
CRJ1	3	CRJ-100:SC3	RJ
CRJ1-LR	2	CRJ-100:SC2	RJ
CRJ2	2	CRJ-200:SC2	RJ
CRJ2	3	CRJ-200:SC3	RJ

ACCODE	SEAT_CLASS	ACFamily	Aircraft Classification
B727-2RE-SUPER27	4	B727:SC4	STA
B757-2	2	B757:SC2	STA
B757-2	3	B757:SC3	STA
B757-2	4	B757:SC4	STA
B757-2	5	B757:SC5	STA
B757-2	6	B757:SC6	STA
B757-3	5	B757:SC5	STA
B757-3	6	B757:SC6	STA
B767-2	5	B767:SC5	STA
B767-2	6	B767:SC6	STA
B767-2ER	4	B767:SC4	STA
B767-2ER	5	B767:SC5	STA
B767-2ER	6	B767:SC6	STA
B767-3	5	B767:SC5	STA
B767-3	6	B767:SC6	STA
B767-3ER	5	B767:SC5	STA
B767-3ER	6	B767:SC6	STA
B767-3ER	7	B767:SC7	STA
B767-4	6	B767:SC6	STA
B767-4ER	6	B767:SC6	STA
DC10-1	7	DC-10:SC7	STA
DC10-3	6	DC-10:SC6	STA
DC10-3	7	DC-10:SC7	STA
DC10-3ER	6	DC-10:SC6	STA
DC10-3ER	7	DC-10:SC7	STA
DC10-4	7	DC-10:SC7	STA
L1011-3	6	L-1011:SC6	STA
ATR42-2	2	ATR:SC2	TP
ATR42-3	2	ATR:SC2	TP
ATR42-320	2	ATR:SC2	TP
ATR42-4	2	ATR:SC2	TP
ATR42-5	2	ATR:SC2	TP
ATR72-2	3	ATR:SC3	TP
BEECH1900-C	2	N/A	TP
BEECH1900-C	3	N/A	TP
BEECH1900-D	2	N/A	TP
BEECH1900-D	3	N/A	TP
BEECH200	4	N/A	TP
DHC8-1	2	DHC Dash:SC2	TP
DHC8-2	2	DHC Dash:SC2	TP
DHC8-3	3	DHC Dash:SC3	TP
DHC8Q-1	2	DHC Dash:SC2	TP
DHC8Q-2	2	DHC Dash:SC2	TP
DHC8Q-3	2	DHC Dash:SC2	TP
DHC8Q-3	3	DHC Dash:SC3	TP
DHC8Q-4	3	DHC Dash:SC3	TP
DO328-1	2	Dornier 328:SC2	TP
F27	2	Fokker F27:SC2	TP
F27-1	2	Fokker F27:SC2	TP
F27-2	2	Fokker F27:SC2	TP
F27-3	2	Fokker F27:SC2	TP
F27-4	2	Fokker F27:SC2	TP
F27-5	3	Fokker F27:SC3	TP
F27-50	3	Fokker F27:SC3	TP
F27-6	2	Fokker F27:SC2	TP
F27-60	2	Fokker F27:SC2	TP
F27-7	2	Fokker F27:SC2	TP
FH227	3	Fokker F27:SC3	TP
SA226	2	N/A	TP
SA227	2	N/A	TP
SAAB2000	2	Saab:SC2	TP
SAAB2000	3	Saab:SC3	TP
SAAB340-A	2	Saab:SC2	TP
SAAB340-B	2	Saab:SC2	TP
SAAB340-B+	2	Saab:SC2	TP



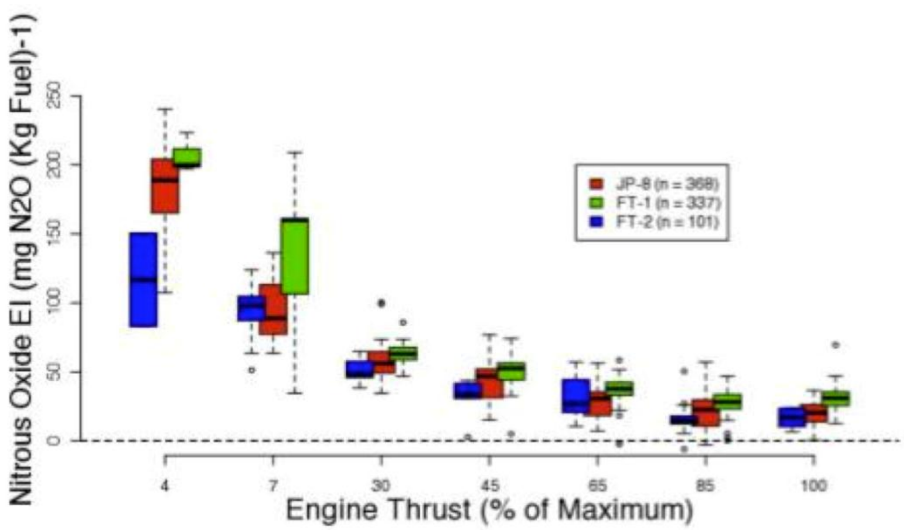


FIGURE A-1 CFM56-2C1 Methane (top) And Nitrous Oxide (bottom) Emissions Indices as a Function of Engine Thrust (Anderson et al. 2011)

TABLE A-2 ICAO Time and Fuel Burn Weighting Factors for Each LTO Stage (ICAO 1993; ACAM 2011)

LTO Stage	Thrust (%)	Time Weighting Factor (%)	CFM56-2C1/7B Fuel Burn Weighting Factor (%)	PW308 Fuel Burn Weighting Factor (%)
Take-Off	100	2.1	9.8	9.7
Climb Out	85	6.7	25.7	25.9
Approach	30	12.2	17.7	18.3
Taxi/Idle	7	79.0	46.8	46.1

TABLE A-3 Static Aircraft Combustion Emission Tests Using SPK Fuel Blends

Experiment	Engine	Representative Military Aircraft	Representative Civil Aircraft
Bulzan et al. 2010	CFM56-2C1	Boeing KC-135R	Douglas DC-8-70
Lobo et al. 2011	CFM56-7B	Boeing C-40	Boeing 737-600 to 900
Corporan et al. 2010b	F117 PW-100| (PW2000 series)	Boeing C-17	Boeing 757
Timko et al. 2010	PW308	Hawker C-29A	Hawker 4000, Dessault Falcon 7X
Bester and Yates 2009 Corporan et al. 2009	RR-Allison T63-A-700	Sikorsky S-75	Bell 206, MD 500, MBB Bo 105
Moses et al. 2003 Corporan et al. 2010b	T700-GE-701 T700-GE-701C	Boeing AH-64, Sikorsky UH-60/SH-60	Saab 340
Corporan et al. 2009	TF33 P-103 (JT3D)	B-52H Stratofortress Boeing KC/NKC/RC/OC/RE-135E/U/N/V/X	Boeing 707

TABLE A-4 Engine Surrogates Used for Each Aircraft Class

PTW Engine used for Scaling Factor	SA, STA, LTA, LQ, RJ, SA-F, STA-F, LTA-F, LQ-F	BJ
CFM56-2C1/7B Average	X	
PW308		X

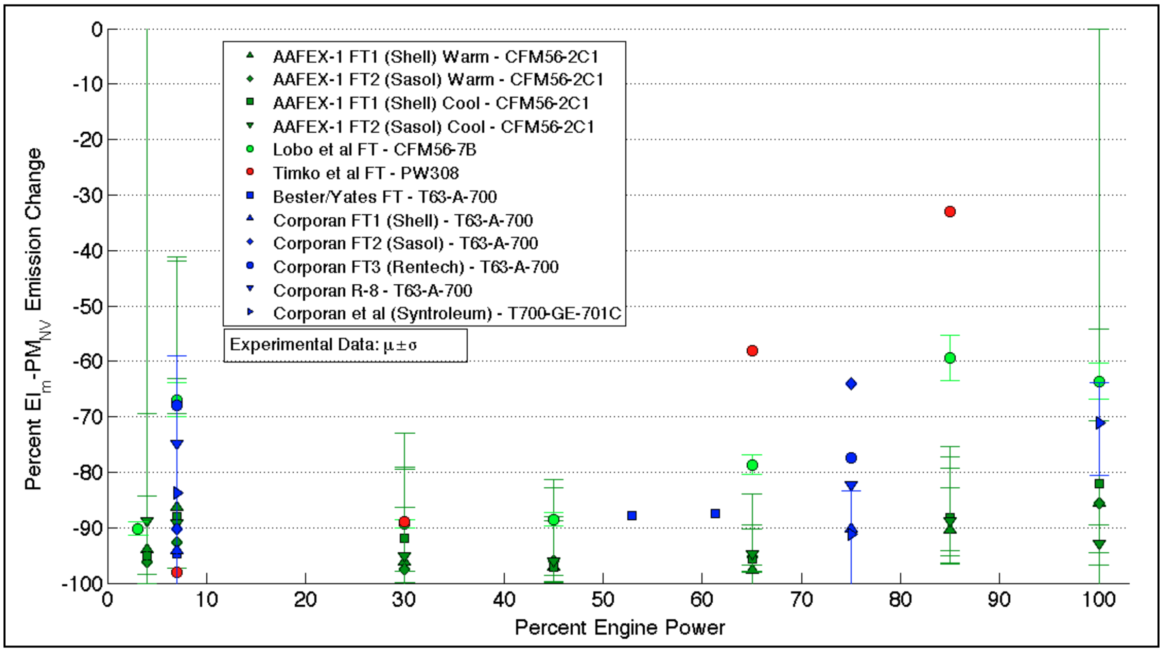


FIGURE A-2 Non-Volatile Particulate Matter Emission Change from Conventional to 100% SPK Jet Fuel

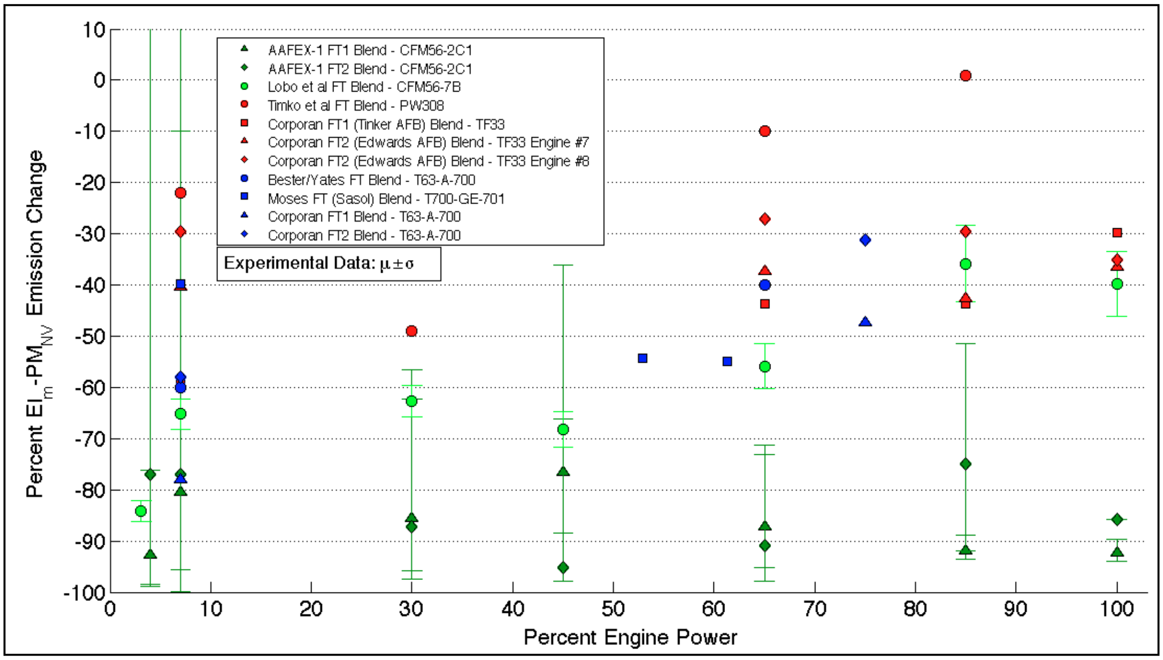


FIGURE A-3 Non-Volatile Particulate Matter Emission Change from Conventional to 50% SPK Jet Fuel

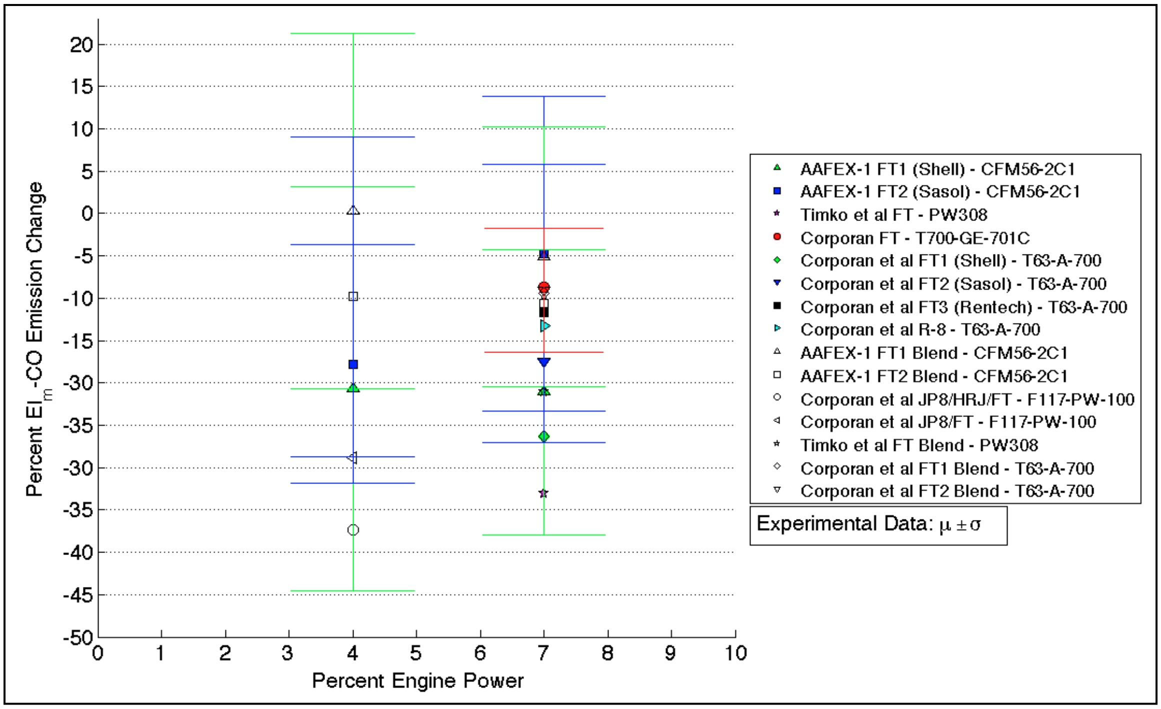


FIGURE A-4 Percent CO Emissions Change from Conventional to 50% and 100% SPK Jet Fuel

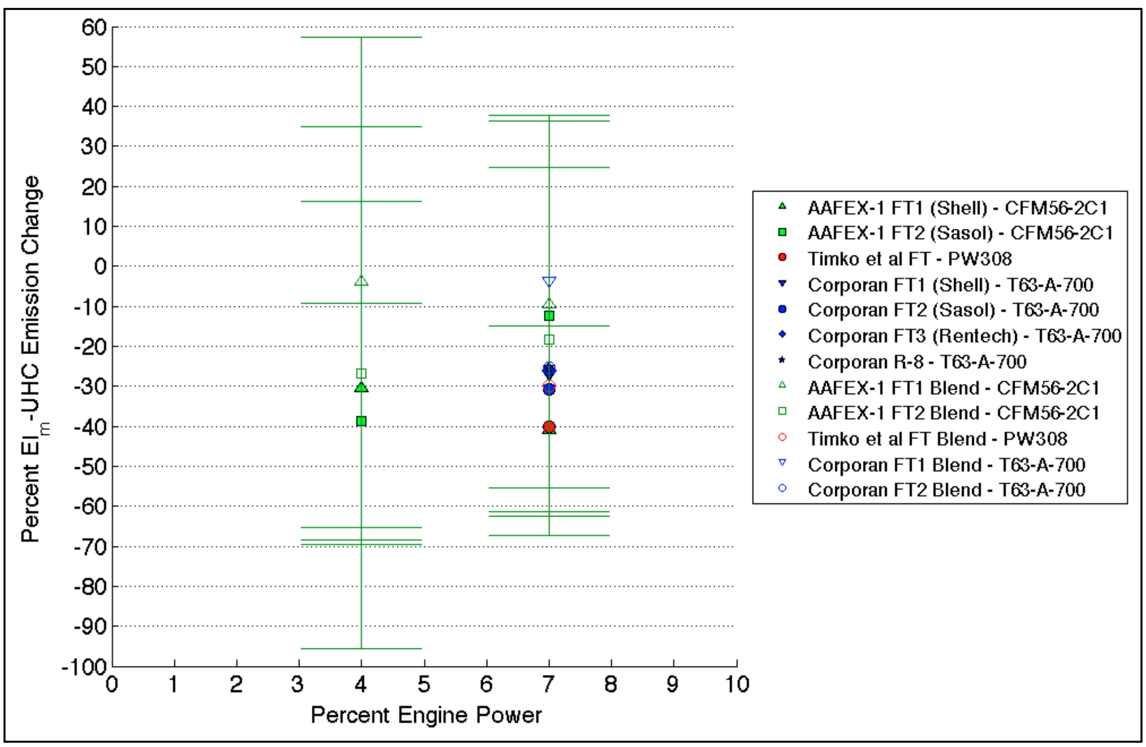


FIGURE A-5 Percent Unburned Hydrocarbon Emissions Change from Conventional to 50% and 100% SPK Jet Fuel

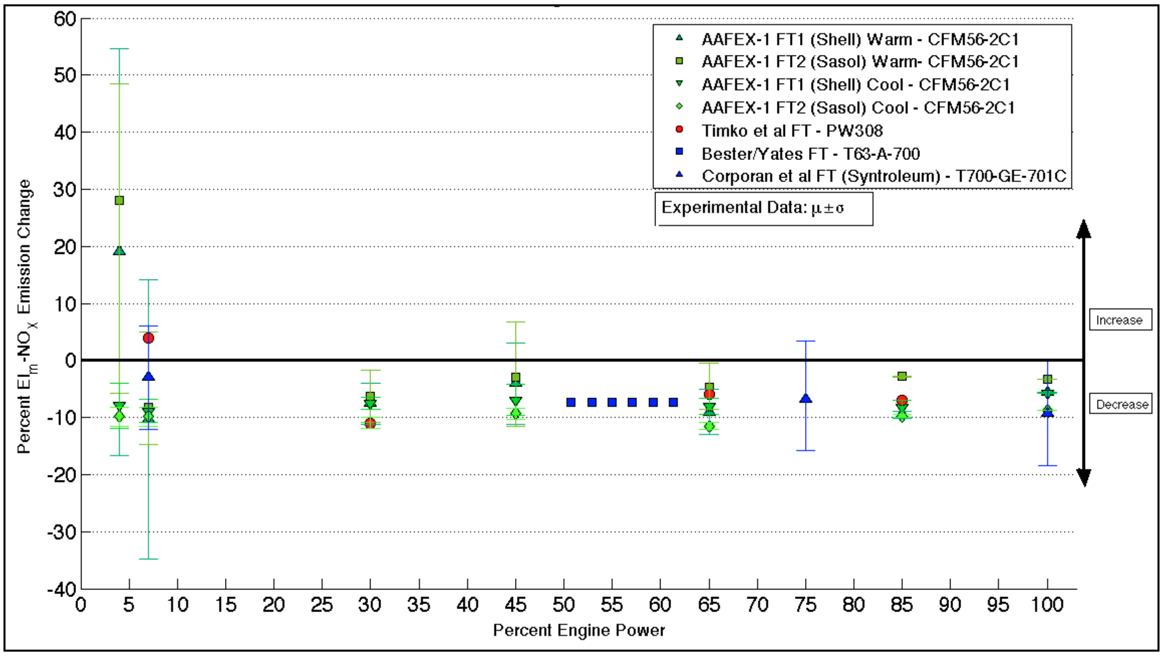


FIGURE A-6 Percent NO_x Emissions Change from Conventional to 100% SPK Jet Fuel

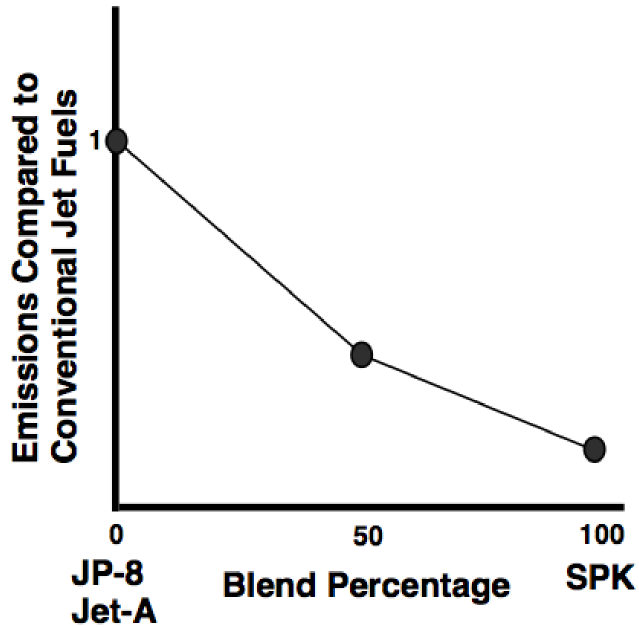


FIGURE A-7 Qualitative Schematic of the Linear Interpolation of Various Emissions Based on Specified SPK Fuel Blend

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC