

TECHNICAL REPORT

Near-Term Feasibility of Alternative Jet Fuels

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INFRASTRUCTURE, SAFETY, AND ENVIRONMENT



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Preface

Two primary concerns motivate the consideration of alternatives to conventional petroleum-derived jet fuel in commercial aviation: price and environmental effects. From 2003 through mid-2008, the rise in world oil prices led to a commensurate rise in the price of petroleum products, including jet fuel. In the process, the high price of jet fuel contributed to the bankruptcy of several airlines and was one factor motivating other airlines to merge. All economic sectors, including aviation, are experiencing growing pressure to reduce their greenhouse-gas (GHG) emissions. Aviation, however, has fewer alternative-energy options to petroleum-based fuels. In addition to contributing to global climate change, emissions from aviation degrade air quality.

Alternative fuels, if available in sufficient quantities, could reduce the world demand for petroleum, consequently reducing the world price of oil and products derived from it and therefore benefiting commercial aviation. Alternative jet fuels derived from biomass or renewable oils offer the potential to reduce life-cycle GHG emissions and therefore reduce aviation's contribution to global climate change. Several alternative jet fuels have reduced fuel sulfur content and fuel aromatic content; using these fuels could result in reduced contributions to ambient particulate matter, lessening aviation's impact on air quality.

This technical report documents the results of a joint study by the Massachusetts Institute of Technology (MIT) and the RAND Corporation on alternative fuels for commercial aviation. The study compared potential alternative jet fuels on the basis of compatibility with existing aircraft and infrastructure, near-term production potential, near-term production costs, life-cycle GHG emissions, emissions affecting air quality, and the relative merit of using the fuel in aviation versus ground transportation. The focus is on alternative jet fuels that could be available commercially in the next decade using primarily North American resources.

Of the alternative jet fuels that we considered, three that are not derived from conventional petroleum may be available in commercial quantities during the next decade: (1) Jet A derived from Canadian oil sands and Venezuela's very heavy oils (VHOs); (2) Fischer-Tropsch (FT) jet fuel produced from coal, a combination of coal and biomass, or natural gas; and (3) hydroprocessed renewable jet (HRJ) fuel produced by hydroprocessing renewable oils. All of these fuels are compatible with the current infrastructure or easily can be made compatible through the use of additives. Of these fuels, (1) FT jet fuel produced from biomass or from a combination of coal and biomass with carbon capture and sequestration (CCS) and (2) HRJ fuel may reduce aviation's impact on climate, but they are likely to be available only in limited quantities. Producing fuels yielding a net reduction in GHG emissions requires that biomass and renewable oil resources be produced so as not to incur land-use changes that would result in releases of carbon dioxide (CO₂) and other GHGs. Alcohol fuels, due to their low energy

density, high volatility, and high flash points, pose operational and safety issues that make them inappropriate for use in aircraft. Similarly, biodiesel and biokerosene, because they may break down during storage or operations and because of their high freezing temperatures, are also inappropriate for use in aviation.

Regarding the benefits derived from producing and using alternative jet fuels, the study found that the economic benefits of producing alternative liquid fuels extend to all petroleum users. In particular, producing alternative liquid fuels yields benefits to commercial aviation, whether or not those fuels are used in aviation. Finally, moving to an ultralow-sulfur (ULS) specification for Jet A would reduce aviation's impact on air quality.

From its findings, the research team recommends the following:

- Measures designed to lower GHG emissions should be broad and place a price on GHG emissions, allowing economically efficient choices to be made across multiple sectors. Aviation should not be treated differently from other sectors.
- Measures designed to promote alternative-fuel use in aviation should consider the potentially large GHG releases associated with land-use changes required for cultivating crops for producing biomass or renewable oils.
- A standard methodology should be developed for assessing life-cycle GHG inventories and impacts of producing and using aviation fuels that takes into account key inputs in producing the fuels and aviation-specific effects associated with high-altitude emissions of gases other than CO₂.
- To improve air quality, the adoption of a reduced-sulfur standard or a ULS jet fuel should be considered, but economic and climate costs and benefits must be weighed carefully.
- Research and testing should be performed using emission measurements from alternative jet fuels to understand the influence of fuel composition on emissions, enabling more-effective assessments of the likely effects of deploying alternative aviation fuels.
- Long-term fundamental research should be supported on the creation of alternative middle-distillate fuels for use in ground transportation and aviation.

Although the near-term prospects for alternative jet fuels are limited, more opportunities may be available in the longer term. Multiple alternative jet fuels, biomass-to-liquids and coal-biomass-to-liquids via FT synthesis, and HRJ fuels from renewable oil sources could conceivably reduce aviation's impact on both global climate change and air quality. The production potential and cost of these fuels depends on their being certified for use in jet engines; on the development of viable, low-cost feedstocks that do not require the use of land that would otherwise be used for food production; and on competition with other potential uses that may be more or less attractive from energy-efficiency, GHG, and economic perspectives. If these criteria are met, then aviation appears to be a ready market for their use. However, the value of using these resources for aviation should be considered in light of potential benefits of use in other parts of the energy sector. Such a comparative analysis was not performed as part of this study.

This work was performed at the request of the Federal Aviation Administration (FAA). It is the result of research and analysis performed under the Partnership for AiR Transportation Noise and Emission Reduction (PARTNER) at MIT and RAND. This report should be of interest to members of the commercial aviation community, including airlines, equipment

manufacturers, and decisionmakers at the federal, regional, state, and local levels who are responsible for energy and environmental policy with respect to commercial aviation.

This report draws on a 50-plus-year history of research and analysis performed by MIT and RAND on alternative fuel resources for aviation and the effects of fuel use on operations. Examples of this previous work include the following:

- *Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions* (Waitz et al., 2004)
- “Assessing the Impact of Aviation on Climate” (Marais et al., 2008)
- *On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies* (Weiss et al., 2000)
- *Liquid Fuels from Coal: Prospects and Policy Issues* (Bartis, Camm, and Ortiz, 2008)
- *Oil Shale Development in the United States: Prospects and Policy Issues* (Bartis, LaTourrette, et al., 2005)
- *Some Cost, Energy, Environmental, and Resource Implications of Synthetic Fuels Produced from Coal for Military Aircraft* (Stanley, 1976)
- *Future Sources of Military Jet Fuels* (Stanley, 1978).

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The RAND Environment, Energy, and Economic Development Program

This research was conducted under the auspices of the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE). The mission of RAND Infrastructure, Safety, and Environment is to improve the development, operation, use, and protection of society’s essential physical assets and natural resources and to enhance the related social assets of safety and security of individuals in transit and in their workplaces and communities. The EEED research portfolio addresses environmental quality and regulation, energy resources and systems, water resources and systems, climate, natural hazards and disasters, and economic development—both domestically and internationally. EEED research is conducted for government, foundations, and the private sector.

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Contents

| | |
|--|-------|
| Preface | iii |
| Figures | xi |
| Tables | xiii |
| Summary | xv |
| Acknowledgments | xxv |
| Abbreviations | xxvii |
| | |
| CHAPTER ONE | |
| Introduction | 1 |
| Background | 1 |
| Price and Price Volatility | 1 |
| Environmental Impacts of Aviation | 4 |
| Competing Uses for Alternative Fuels | 7 |
| Technical/Methodological Approach | 7 |
| Contents of This Report | 8 |
| | |
| CHAPTER TWO | |
| Alternative Fuels for Commercial Aviation | 11 |
| Candidate Alternative Fuels | 11 |
| Metrics for Comparing Alternative Fuels | 12 |
| Compatibility with Current Systems | 13 |
| Fuel Readiness Level | 14 |
| Production Potential | 14 |
| Production Cost | 15 |
| Well-to-Wake Greenhouse-Gas Emissions | 16 |
| Air-Quality Emissions | 18 |
| Merit for Aviation Use | 18 |
| | |
| CHAPTER THREE | |
| Conventional Petroleum | 21 |
| The Benchmark Fuel: Jet A | 21 |
| Refining Jet A from Crude Oil | 21 |
| Variability in Jet A Composition | 23 |
| Well-to-Wake Greenhouse-Gas Emissions | 23 |
| Consumption of Petroleum Products | 24 |
| Ultralow-Sulfur Jet A | 25 |

| | |
|---|----|
| Compatibility and Operability in Current Systems | 26 |
| Production Potential..... | 27 |
| Production Cost..... | 27 |
| Well-to-Wake Greenhouse-Gas Emissions..... | 28 |
| Air-Quality Emissions..... | 28 |
| Readiness of Technology..... | 28 |
| Merit for Aviation Use..... | 28 |
| CHAPTER FOUR | |
| Unconventional Petroleum | 31 |
| Jet A from Canadian Oil Sands or Venezuelan Very Heavy Oils | 31 |
| Compatibility and Operability in Current Systems | 31 |
| Production Potential..... | 31 |
| Production Cost..... | 32 |
| Well-to-Wake Greenhouse-Gas Emissions..... | 32 |
| Air-Quality Emissions..... | 32 |
| Readiness of Technology..... | 33 |
| Merit for Aviation Use..... | 33 |
| Jet A from Oil Shale | 33 |
| Compatibility and Operability in Current Systems | 33 |
| Production Potential..... | 34 |
| Production Cost..... | 34 |
| Well-to-Wake Greenhouse-Gas Emissions..... | 35 |
| Air-Quality Emissions..... | 35 |
| Readiness of Technology..... | 35 |
| Merit for Aviation Use..... | 36 |
| CHAPTER FIVE | |
| Fischer-Tropsch Synthetic Fuels | 37 |
| Common Characteristics..... | 37 |
| The Fischer-Tropsch Synthesis..... | 37 |
| Compatibility and Operability in Current Systems | 38 |
| Air-Quality Emissions..... | 39 |
| Merit for Aviation Use..... | 40 |
| Fischer-Tropsch Fuels from Natural Gas | 41 |
| Production Potential..... | 41 |
| Production Cost..... | 41 |
| Well-to-Wake Greenhouse-Gas Emissions..... | 42 |
| Readiness of Technology..... | 42 |
| Fischer-Tropsch Fuels from Coal..... | 42 |
| Production Potential..... | 42 |
| Production Cost..... | 42 |
| Well-to-Wake Greenhouse-Gas Emissions..... | 43 |
| Readiness of Technology..... | 43 |
| Fischer-Tropsch Fuels from Biomass and Coal | 44 |
| Production Potential..... | 45 |

| | |
|---|-----------|
| Production Cost..... | 45 |
| Well-to-Wake Greenhouse-Gas Emissions..... | 46 |
| Readiness of Technology..... | 46 |
| CHAPTER SIX | |
| Fuels from Renewable Oils..... | 47 |
| Biodiesel and Biokerosene..... | 47 |
| Compatibility and Operability in Current Systems | 48 |
| Merit for Aviation Use..... | 49 |
| Hydroprocessed Renewable Jet Fuel | 49 |
| Compatibility and Operability in Current Systems | 50 |
| Production Potential..... | 51 |
| Production Cost..... | 51 |
| Well-to-Wake Greenhouse-Gas Emissions..... | 51 |
| Air-Quality Emissions..... | 53 |
| Readiness of Technology..... | 53 |
| Merit for Aviation Use..... | 53 |
| CHAPTER SEVEN | |
| Alcohols..... | 55 |
| Ethanol | 55 |
| Compatibility and Operability in Current Systems | 55 |
| Readiness of Technology..... | 56 |
| Merit for Aviation Use..... | 56 |
| Butanol | 56 |
| Compatibility and Operability in Current Systems | 57 |
| Readiness of Technology..... | 57 |
| Merit for Aviation Use..... | 57 |
| CHAPTER EIGHT | |
| Findings and Recommendations..... | 59 |
| Key Findings..... | 59 |
| In the Next Decade, Up to Three Alternative Jet Fuels May Be Available in Commercial Quantities..... | 59 |
| In the Next Decade, Alternative Fuels to Reduce Aviation’s Impact on Climate Will Be Available, Although Supplies Are Limited..... | 63 |
| Drop-In Fuels Have Considerable Advantages over Other Alternatives | 64 |
| Some Fuel Feedstocks May Provide Greater Benefits If Used for Purposes Other Than Alternative Jet Fuels | 64 |
| Alcohols Do Not Offer Direct Benefits to Aviation | 65 |
| Biodiesel and Biokerosene Are Not Appropriate for Use in Aviation..... | 65 |
| The Economic Benefits of Producing Alternative Transportation Fuels Extend to All Petroleum Users..... | 66 |
| Alternative-Fuel Production Yields Large Benefits to Commercial Aviation, Whether or Not Those Fuels Are Used in Aviation | 66 |
| The Ability of Alternative Jet Fuels to Reduce Price Volatility Is Limited | 66 |

| | |
|--|-----------|
| An Ultralow-Sulfur Specification for Jet A Would Reduce Aviation’s Impact on Air Quality | 67 |
| Recommendations | 67 |
| Measures Designed to Lower Greenhouse-Gas Emissions Should Not Treat Commercial Aviation Separately from Other Sectors..... | 67 |
| Any Measures Designed to Promote Alternative-Fuel Use in Aviation Should Consider the Potentially Large Greenhouse-Gas Releases Associated with Land-Use Changes Required for Cultivating Crops for Producing Biomass or Renewable Oils..... | 68 |
| Establish a Standard Methodology for Assessing Life-Cycle Greenhouse-Gas–Emission Inventories and Impacts..... | 68 |
| For Improved Air Quality, Consider the Adoption of a Reduced-Sulfur Standard or an Ultralow-Sulfur Jet Fuel | 69 |
| Utilize Emission Measurements from Alternative Jet Fuels to Understand the Influence of Fuel Composition on Emissions | 69 |
| Support Long-Term Fundamental Research on the Creation of Middle-Distillate Fuels for Use in Ground Transportation and Aviation | 70 |
| Conclusions | 70 |
| APPENDIXES | |
| A. Resource Base, Production Potential, and Estimated Production Costs..... | 73 |
| B. Well-to-Wake Greenhouse-Gas Emissions | 89 |
| Bibliography..... | 97 |

Figures

| | | |
|------|--|----|
| 1.1. | Airline Average Unit Operating Costs for Fuel and Labor | 2 |
| 3.1. | Typical Distillation Ranges (Degrees C) and Carbon-Number Ranges for Fuels | 22 |
| 8.1. | Normalized Life-Cycle Greenhouse-Gas Emissions for the Low-, Baseline, and High-Emission Cases for Jet-Fuel Pathways | 62 |
| B.1. | Baseline Life-Cycle Greenhouse-Gas Emissions for Jet-Fuel Pathways | 92 |
| B.2. | Normalized Life-Cycle Greenhouse-Gas Emissions for the Low-, Baseline, and High-Emission Cases for Jet-Fuel Pathways | 93 |

Tables

| | | |
|------|---|----|
| 2.1. | Alternative Fuels Considered in This Report..... | 11 |
| 2.2. | Definitions: Compatibility with Current Systems..... | 14 |
| 2.3. | Definitions: Fuel Readiness Levels..... | 15 |
| 2.4. | Production-Potential Ratings..... | 15 |
| 2.5. | Production-Cost Ratings..... | 16 |
| 2.6. | Well-to-Wake Greenhouse-Gas–Emission Ratings as a Percentage of Jet A Emissions... | 17 |
| 2.7. | Air-Quality Ratings, Based on Number of Sources, That Increase or Decrease Particulate-Matter Emissions by More Than 10 Percent..... | 18 |
| 5.1. | Fuel Readiness Levels of Coal to Liquids, Based on Disposition of Carbon Dioxide.... | 44 |
| 6.1. | Recent Hydroprocessed Renewable Jet-Fuel Test Flights..... | 50 |
| 8.1. | Rating-System Definitions..... | 60 |
| 8.2. | Near-Term Alternative Jet-Fuel Comparison Matrix..... | 61 |
| A.1. | Current and Projected Consumption and Price of Crude Oil and Jet Fuel in the United States..... | 74 |
| A.2. | Alternative-Fuel Production Potential to Meet U.S. 2017 Jet-Fuel Demand..... | 75 |
| A.3. | Coal-to-Liquid and Coal Biomass–to-Liquid Facilities That Have Advanced to the Front-End Engineering Design Phase..... | 79 |
| A.4. | Current and Projected Prices of Jet Fuel and Cost Estimates for the Production of Alternative Jet Fuels..... | 84 |
| A.5. | Parameters Used to Estimate Production Costs of Fischer-Tropsch Liquids from Coal and Biomass..... | 86 |
| B.1. | Fuel Pathways Investigated..... | 90 |
| B.2. | Land-Use–Change Scenarios Explored for Hydroprocessed Renewable Jet-Fuel Pathways..... | 91 |
| B.3. | Life-Cycle Greenhouse-Gas Emissions of Fischer-Tropsch Liquid Fuels from Coal..... | 94 |
| B.4. | Feedstock and Fuel Properties..... | 95 |

Summary

Prior to 2004, the spot price of jet fuel rarely exceeded \$1.00 per gallon. The next four years saw spot prices for Jet A climb to a peak in July 2008 of more than \$4.00 per gallon. Since then, jet-fuel prices have been highly volatile, swinging to below \$1.20 per gallon in March 2009. High spot prices, the corresponding increase in contract prices for jet fuel, and price volatility have wreaked havoc on the commercial aviation industry. Coincident with price increases and volatility has been a growing awareness of the importance of further reducing the adverse environmental impacts of aviation. Important environmental issues include improving air quality in and around airports and addressing aviation's contribution to GHG emissions.

Such concerns prompted FAA's support of a joint MIT/RAND research effort on what alternatives to kerosene-type jet fuel derived from conventional petroleum may be available in the next decade to help reduce price and price volatility as well as the environmental impact of commercial aviation operations. We evaluated five different groups of fuel—those derived (1) from conventional petroleum; (2) from unconventional petroleum; (3) synthetically from natural gas, coal, or combinations of coal and biomass via the FT process; (4) renewable oils; and (5) alcohols—using seven different criteria.

Criteria for Alternative Fuels

For a prospective aviation fuel to have an impact on aviation within the next few decades, the most important criterion to address is *compatibility with current systems*—that is, the existing commercial aviation infrastructure, including fuel delivery and storage and, most importantly, the existing fleet of aircraft. Use of certain fuels that we examined would so significantly degrade safety or adversely affect efficient aircraft operations as to preclude their use in aviation.

The second criterion we examined is the current *maturity of the fuel-production technology*. In a couple of cases, we found that small amounts of the alternative fuel are being commercially produced. But, for most of the alternative fuels we examined, further research and development (including process scale-up) is required before large-scale commercial production of that fuel can occur.

The third criterion we examined is the *production potential* of the fuel in the next decade. In some cases, this is limited by resource constraints; in others, by the maturity of the fuel-production technology, which may limit the number of commercial plants that can be built in the next decade. With regard to this criterion, we also examined the extent to which the prospective fuel could be produced from North American resources.

Whether an alternative aviation fuel will be competitive depends on its *production costs*. Where adequate information was available, we estimated production costs or cost ranges.

To examine the environmental benefits, if any, that would be associated with the use of an alternative aviation fuel, we reviewed potential performance against two criteria: *life-cycle GHG emissions* and *emissions affecting air quality*. Life-cycle GHG emissions covered the GHG emissions associated with land-use change, extraction, processing, delivery, and combustion of a fuel as compared to those of conventional jet fuel. With regard to other emissions, we focused on particulate matter smaller than 2.5 micrometers (PM_{2.5}) released during airport operations (especially landing, taxi, and takeoff), since aviation PM_{2.5} emissions have a larger impact on air quality than do other factors, such as ozone.

Early in our study, we recognized that certain fuels may be more appropriate for automotive applications than for aviation. Moreover, supplies are limited for nearly all the alternative fuels we examined. To address the potentially adverse economic or societal impacts of diverting limited supplies of fuels from automotive or other uses to aviation applications, we added the criterion *relative merit for aviation use*.

Prospective Jet Fuels

Conventional Petroleum Fuels

Jet A, the standard commercial jet fuel in North America, is the benchmark fuel against which we compared alternatives.

An ultralow-sulfur (ULS) version of Jet A fuel is an alternative fuel that may be produced from conventional and unconventional petroleum sources. In the past few years, sulfur levels in Jet A sold in the United States have been about 700 parts per million (ppm) on average. Lowering jet-fuel sulfur content would reduce PM_{2.5} emissions, yielding improved air quality at airports. To understand the implications of a lower-sulfur standard for jet fuel, we examined a ULS case—namely, 15 ppm, which is comparable to the U.S. standard for road diesel.

The process of hydrodesulfurization may lead to a slight loss of 1 percent in energy per unit volume of fuel. A small reduction of fuel lubricity may also result, but this can be overcome with appropriate additives. Because of hydrotreating, we anticipated that a ULS Jet A would have greater thermal stability and reduced aromatic content, which may lead to a reduction in certain maintenance costs. ULS fuel may improve multiuse pipeline operations, which currently are complicated by the transport of fuels with varied fuel sulfur standards.

The technology for hydrodesulfurization is in widespread commercial use today, and full introduction of a ULS Jet A could easily occur by 2017. The cost of sulfur reduction is approximately \$0.05 per gallon. The net impact of a shift to a ULS Jet A on aviation economics, air quality, and global climate change is uncertain and remains a subject of investigation.

Unconventional Petroleum Fuels

Three unconventional sources of petroleum—Canadian oil sands, Venezuelan VHOs, and oil shale—may offer alternative jet fuels.

Oil sands and VHOs already yield a fuel meeting all current specifications for Jet A. Processing oil sands and VHOs for fuel is likely to be profitable as long as world oil prices exceed \$50 per barrel. Once capacity is in place, production is likely to be profitable even if crude-oil prices decrease.

Due to the additional energy required to extract and process oil sands and VHO, the use of Jet A derived from these resources would have life-cycle GHG emissions ranging from 10 to 25 percent greater than those of conventional Jet A. Once the fuel reaches the tank, there are no differences in emissions or effect on air quality.

Oil shale is a solid sedimentary rock containing an organic material called kerogen. When the kerogen is heated sufficiently, it decomposes to form an oil that can be distilled like conventional petroleum. Because of work performed by the U.S. Department of Defense (DoD) in the 1980s, shale oil is included in the specification for Jet A as a conventional source of jet fuel that would be fully compatible with current aviation systems.

The prospects for oil-shale production in the United States remain uncertain. The conventional approach, consisting of mining and heating the recovered material in large retorts, is both expensive and environmentally intrusive. Promising approaches are under development, but their technical and economic viability have not yet been established. Oil-shale production requires significant energy inputs. If this energy is supplied from fossil fuels, life-cycle GHG emissions associated with oil-shale use could be 50 percent higher than those from Jet A. But life-cycle GHG emissions could be slightly below those of Jet A if oil-shale production includes methods to manage or prevent CO₂ emissions.

Considering the technical maturity of oil-shale production methods, oil shale is unlikely to support appreciable production of jet fuel prior to 2020. But the U.S. oil-shale resource base is very large, and success in ongoing technology-development efforts could lead to a commercial oil-shale industry that could eventually provide appreciable amounts of jet fuel.

Fischer-Tropsch Synthetic Fuels

The FT process produces liquid fuels from carbonaceous feedstocks, such as natural gas, coal, and biomass. The FT process begins with gasifying the feedstock and ends with a mix of hydrocarbon products that can be used to produce gasoline, diesel, and jet fuel. All jet fuels produced by FT synthesis have similar characteristics. In particular, they contain neither sulfur (less than 1 ppm) nor the aromatic compounds that tend to increase soot formation. Choice of feedstock does not affect fuel quality but does affect production costs and life-cycle GHG emissions.

Since 1999, blends that are up to 50 percent FT liquids have been used by commercial airlines leaving O. R. Tambo International Airport in South Africa. Standards and approval for this use is limited to FT fuels produced by Sasol production facilities. Efforts are under way to extend this standards-and-approval process to blends based on any FT fuel. In comparison to conventional jet fuels, pure FT fuels have reduced lubricity and do not contain aromatic compounds; the absence of aromatic compounds can cause leaks in certain types of fuel systems. Both of these issues may be resolved by blending the fuel with conventional jet fuel and may be addressed with the appropriate use of fuel additives.

The availability of FT jet fuels within the next decade depends on feedstock, the world price of oil, resolving uncertainties in production costs, and regulatory and technical issues associated with capturing and sequestering large quantities of CO₂. Existing and planned plants in Malaysia, Qatar, and South Africa can be configured to produce 75,000 barrels of jet fuel daily from natural gas within the next decade at a cost of \$1.40 to \$2.50 per gallon (in 2005 dollars). Assuming near-term construction of pioneer coal-to-liquids facilities in the United States, we estimate that approximately 75,000 barrels of jet fuel could be produced daily from coal within the next decade at a cost of \$1.60 to \$1.90 per gallon. Under similar

assumptions, plants accepting a combination of coal and biomass may be able to produce approximately 12,000 barrels of jet fuel daily at a cost of \$2.00–2.40 per gallon.

The life-cycle GHG emissions of FT jet fuel depend on the feedstock and whether options for permanently sequestering plant-site CO₂ emissions are available and utilized. For FT fuels produced from natural gas, life-cycle GHG emissions are comparable to those of conventional Jet A from oil sands. Jet fuel produced at a coal-to-liquids facility employing CCS could have life-cycle GHG emissions that are comparable to those of conventional Jet A, but, if the facility is less efficient, the emissions could exceed those of conventional Jet A from oil sands; without CCS, the life-cycle GHG emissions would be more than twice those of conventional Jet A. Depending on the amount of biomass that is used and whether CCS is employed, fuel produced from a combination of coal and biomass at a production facility employing CCS could have life-cycle GHG emissions that are less than 50 percent of those of conventional Jet A; however, achieving large reductions in GHG emissions requires considerable biomass use and would result in increased production costs.

Fuels from Renewable Oils

Biodiesel and *biokerosene* are fuels produced from fatty acids and triglycerides obtained from plants or animal processing. Biodiesel is typically produced by chemically processing the feedstock oil with methanol. Biodiesel inherits the properties of its feedstock oil, so biodiesels created from plant oils with carbon chain lengths in the kerosene range have been termed *biokerosenes*.

Biodiesel and biokerosene have been suggested as appropriate for blending with conventional jet fuel. Our research indicated that neither fuel is appropriate for use in aviation, even when used in light (i.e., low-concentration) blends. These fuels may break down during storage or during use in aircraft fuel systems, leaving deposits that could compromise performance and safety. Pure biodiesel would freeze at temperatures typical of high-altitude flight, and some tests of light blends have indicated freezing at typical operating temperatures as well. These issues are not present in most ground-based applications of biodiesel.

Hydroprocessed renewable jet (HRJ) fuel is produced by methods common in petroleum refining. In the first step, the fatty acids and triglycerides are hydrotreated to remove oxygen. The resulting paraffinic hydrocarbons are next processed to yield a mixture of straight-chain, branched-chain, and cyclic paraffinic hydrocarbons with collective properties that are similar to those of conventional jet fuel.

The properties of HRJ are similar to those of FT jet fuel: near-zero sulfur, high thermal stability, reduced lubricity, and near-zero aromatic content. As in the case of FT jet fuels, issues posed by the reduced lubricity and aromatic content may be addressed through the use of blending with conventional jet fuel or the appropriate use of additives. Several aircraft and airline companies have tested HRJ fuels, and DoD is in the process of procuring a large quantity of HRJ for testing and certifying for use in its aircraft.

Current and planned production capacity of HRJ is nearly 60,000 barrels per day (bpd), but reaching that production assumes the availability of appropriate feedstocks at competitive prices.

Current feedstocks for both biodiesel and HRJ include soybeans, rapeseed (canola), and palm-kernel oils. Additional feedstock options include camelina, a plant similar to rapeseed; babassu, a type of palm tree; and jatropha, a shrub, which all produce seeds with high oil content. Future feedstocks could include salicornia and algae. Significantly increased produc-

tion of plant oils from current feedstocks would displace food production or require the conversion of tropical lands to farming, both of which would require changes in land uses and result in emissions of soil-based carbon. These so-called land-use–change emissions dominate the life-cycle GHG emissions of fuels derived from renewable oils, which can be two to eight times those of conventional jet fuel. If emissions due to land-use change are ignored, life-cycle GHG emissions of HRJ are roughly half those of conventional jet fuel.

Alcohols

Ethanol is not suitable for aviation operations. It has a low flash point, making it dangerous to handle and posing a risk to crew and passengers. Its high volatility could lead to problems during high-altitude flight. Moreover, its energy content per unit mass and per unit volume is approximately 40 percent less than that of jet fuel. Ignoring incompatibilities, if ethanol were used as an aviation fuel, range would be reduced and the amount of energy used to fly a given distance would increase relative to Jet A. These issues are not present when ethanol is used in ground-transportation applications.

Butanol is a simple, four-carbon, straight-chain alcohol that can also be made by fermentation of sugars. Research and technology-development activities are under way that are aimed at automotive use of blends of butanol and conventional gasoline. While butanol may be an attractive automotive fuel (especially in comparison to ethanol), butanol is not suitable for aircraft operations. While not as incompatible as ethanol, it still poses unacceptable safety risks due to its low flash point and high volatility.

Key Findings

In the Next Decade, Up to Three Alternative Jet Fuels May Be Available in Commercial Quantities

The alternative aviation fuels that are not derived from conventional petroleum that have the greatest production potential over the next decade are as follows: (1) Jet A derived from Canadian oil sands and Venezuela’s VHOs; (2) FT jet fuel produced from coal, a combination of coal and biomass, or natural gas; and (3) HRJ produced by hydroprocessing renewable oils. All three are or can easily and inexpensively be made fully compatible with current aircraft and fuel-delivery systems. Canadian oil sands and Venezuelan VHOs have the largest potential of several hundred thousand barrels per day of jet fuel, but their use would result in increased GHG emissions. The prospects for FT jet fuels depend crucially on construction of a few pioneer commercial plants in the next few years. Production of commercial quantities of HRJ depends on the availability of appropriate feedstocks at competitive prices.

In the Next Decade, Alternative Fuels Will Be Available to Reduce Aviation’s Impact on Climate, Although Supplies Are Limited

Certain HRJ and FT fuels are able to reduce the GHG emissions from aviation. For HRJ to be effective in reducing GHG emissions, it must be produced from oils that do not incur land-use changes, either directly or indirectly, that cause a large release of other GHGs. This constraint places a severe limit on the amount of climate-friendly HRJ that can be produced within the next decade. For FT jet fuels to be effective agents for GHG reduction, they must be produced from biomass or a combination of coal and biomass. In the former case, the fuels will

be expensive and demand extensive cultivation of biomass for inputs. In the latter case, capture and sequestration of plant-site carbon emissions would be required, but overall costs would be much less, as would biomass consumption. As with HRJ, the provision of biomass must not incur land-use changes, either directly or indirectly, that cause a large release of GHGs.

Some Fuel Feedstocks May Provide Greater Benefits If Used for Purposes Other Than Alternative Jet Fuels

All of the alternative fuels considered in this study, regardless of feedstock, could be used to generate electricity, heat, fuels for ground transportation, or fuels for aviation. FT fuels and HRJ are attractive aviation fuels because they have specific energies that are slightly greater than current petroleum-derived jet fuel; however, high-performance diesel fuels can also be made via either FT synthesis or hydroprocessing of renewable oils. Both ground and aviation users of these fuels would benefit from the low sulfur and low aromatic content of these fuels, but, because of current U.S. and European regulations, ground-transportation users of these fuels pay a premium for these qualities. Since the potential supplies of all of the alternative fuels, other than ULS Jet A, examined in this study will be limited in the next decade, if not longer, forcing certain feedstocks and fuels into one or another application (e.g., aviation versus automotive) may result in diseconomies and reduce progress toward reducing overall GHG emissions and increasing energy security.

Alcohols Do Not Offer Direct Benefits to Aviation

Alcohol fuels, due to their incompatibilities with aircraft fuel systems and their low energy content, are more appropriate for ground-transportation applications than for use in gas-turbine applications.

Biodiesel and Biokerosene Are Not Appropriate for Use in Aviation

Biodiesel and biokerosene have poor thermal stability and high freezing points, leading to problems in transportation, storage, and use of these fuels. HRJ may be produced from the same feedstocks and poses none of these issues.

The Economic Benefits of Producing Alternative Fuels Extend to All Petroleum Users

The major societal economic benefit of producing alternative fuels is a reduction in the demand for conventional petroleum, which would cause world oil prices to be lower than they would otherwise be. This effect of reduced world oil prices is independent of whether the alternative-fuel production and use occur in the United States or in some other country. This effect is also independent of whether the alternative fuel is used in aircraft or in some other application in which conventional petroleum is currently used, such as ground transportation, building heating, and industrial-process heating. Further, it is independent of whether the reduction in demand is due to additional supply or to conservation. The world oil price reduction stemming from each additional 1 million barrels of alternative-fuel supply is estimated to be 0.6 to 1.6 percent of the oil price that would otherwise prevail.¹

¹ The wide range in the estimate is due to uncertainties in the behavior of OPEC and the price elasticities of petroleum.

Alternative-Fuel Production Yields Large Benefits to Commercial Aviation, Whether or Not Those Fuels Are Used in Aviation

In the next decade, large amounts of alcohol-based fuels and fuels derived from oil sands and VHOs will likely enter the world oil market: The Energy Information Administration's (EIA's) 2009 projection of future supplies of liquid fuels shows unconventional sources yielding about 7.5 million bpd in 2017. Based on prior RAND analyses, it is estimated that this level of production would cause long-term world oil prices to be between 5 and 12 percent lower than what they would be in the absence of such production. For world crude oil prices in the range of \$100 per barrel, this amounts to a price impact of roughly \$5 to \$13 per barrel. In 2017, jet-fuel consumption in the United States (commercial aviation plus military) is projected to be about 1.9 million bpd. Applying the per-barrel savings to this consumption yields net annual jet-fuel cost savings of between \$3.2 billion and \$8.3 billion.

An Ultralow-Sulfur Specification for Jet A Would Reduce Aviation's Impact on Air Quality

ULS jet fuel would virtually eliminate secondary particulate matter due to sulfur-oxide emissions while also reducing primary particulate emissions due to sulfur. The introduction of a ULS jet-fuel specification would act to ease the introduction of FT synthetic fuels and HRJ into commercial aviation, as they pose similar concerns in terms of infrastructure compatibility of lubricity and effect on seals due to their low sulfur and reduced aromatic content. Finally, unlike new aircraft and engine technologies, which take some time to diffuse into the fleet, the air-quality benefits of sulfur elimination could be realized as soon as a ULS jet fuel were introduced. Adverse consequences of a ULS jet fuel would be higher fuel prices (by about \$0.05 per gallon), an increase (about 1 percent) in the fuel volume purchased and consumed, a reduction (about 1 percent) in the aircraft range with full fuel tanks, an increase (by about 2 percent) in life-cycle GHG emissions, and the elimination of sulfur aerosols, which have a short-term cooling effect. This study did not attempt to assess the balance among these effects to determine whether introduction of a ULS jet-fuel standard is cost beneficial.

Recommendations

From the findings, the research team makes the following recommendations.

Measures Designed to Lower Greenhouse-Gas Emissions Should Not Treat Commercial Aviation Separately from Other Sectors

Our findings on alternative fuels in the near term show that the opportunities that are available to reduce the life-cycle well-to-wake (WTW) GHG emissions from aviation operations are costly and could potentially be counterproductive. Over at least the next decade, the feedstocks (and associated land requirements) used to produce low-GHG alternatives to Jet A, such as FT jet fuel from coal and biomass or HRJ, are limited in supply. These same feedstocks can also be used to make low-GHG automotive fuels or for other energy needs. Rather than legislating or regulating the sector to which these feedstocks should be directed, we suggest broader-based mechanisms that place a price on GHG emissions and allow economically efficient choices to be made across multiple sectors. Examples of these approaches include cap-and-trade systems and carbon-tax-and-rebate systems.

Any Measures Designed to Promote Alternative-Fuel Use in Aviation Should Consider the Potentially Large Greenhouse-Gas Releases Associated with Land-Use Changes Required for Cultivating Crops for Producing Biomass or Renewable Oils

Although understanding the magnitude of the GHG releases associated with land-use changes remains a topic of research, sufficient information is available to warrant a precautionary approach. This is a special concern for any fuel produced from energy crops grown in carbon-rich soils, such as palm oils. The potential magnitude of GHG release is sufficiently large that we recommend that no GHG credit be given to any biofuel production from deforested areas until the U.S. Environmental Protection Agency establishes criteria for accounting for direct and indirect land-use changes.

Establish a Standard Methodology for Assessing Life-Cycle Greenhouse-Gas–Emission Inventories and Impacts

At present, uncertainties associated with the treatment of fuel production and in-flight GHG emissions allow for a broad range of emission estimates and impacts for alternative jet fuels. To better prepare commercial aviation for potential regulation of GHG emissions, a standard methodology for estimating life-cycle GHG-emission inventories and impacts is required. Such a methodology would include standards for accounting for key inputs, setting system boundaries, allocating emissions among alternative fuel products and co-products, all combustion emissions, and the effects of land-use change. Additionally, such a methodology should include explicit means for accounting for key uncertainties.

For Improved Air Quality, Consider the Adoption of a Reduced-Sulfur Standard or an Ultralow-Sulfur Jet Fuel

Given the human-health impact of aviation emissions of particulate matter (PM) and gaseous PM precursors during takeoff, landing, and ground operations, the aviation community should consider the adoption of a ULS jet fuel.

A ULS specification for jet fuel could have the effect of bringing aviation to a similar specification to that for highway diesel fuel, potentially improving refinery scheduling and operations and multiuse pipeline operations. The introduction of a ULS jet-fuel specification would act to ease the introduction of FT synthetic fuels and HRJ into commercial aviation, as they pose similar concerns in terms of infrastructure compatibility of lubricity and effect on seals due to their low sulfur and reduced aromatic content. Finally, unlike new aircraft and engine technologies, which take some time to diffuse into the fleet, the air-quality benefits of sulfur elimination could be realized as soon as ULS jet fuel were introduced.

The benefits of ULS jet-fuel use in reducing air-quality impact need to be balanced against the potential positive and negative impacts on global climate change and economic considerations.

Utilize Emission Measurements from Alternative Jet Fuels to Understand the Influence of Fuel Composition on Emissions

As part of the certification process for general FT aviation fuels, the FAA, U.S. Air Force (USAF), NASA, and some international organizations are currently funding research to measure the emissions from burning alternative jet fuels. Continuing emission measurements are essential to assess accurately the impact of alternative-fuel combustion on both air quality and climate change.

Support Long-Term Fundamental Research on the Creation of Middle-Distillate Fuels for Use in Ground Transportation and Aviation

Middle distillates represent about 30 percent of the petroleum products used in the United States. They are essential not only to commercial aviation but also to the movement of freight by land and water. Moreover, middle distillates power the aircraft, ships, and fighting vehicles of the armed forces. At present, the technical options to provide these applications with low-GHG emission fuels are severely limited. The extensive use of first-generation feedstocks, such as soy and palm, will incur land-use changes that will cause a large increase in GHG emissions. Next-generation biomass feedstocks are needed that do not compete with food production and that consume little fresh water.

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Abbreviations

| | |
|---------------|---|
| μm | micrometer |
| ABE | acetone-butanol-ethanol |
| ASTM | American Society for Testing and Materials |
| ATA | Air Transport Association |
| AvGas | aviation gasoline |
| BLM | Bureau of Land Management |
| bpd | barrel per day |
| BTL | biomass to liquid |
| Btu | British thermal unit |
| CAAFI | Commercial Aviation Alternative Fuels Initiative |
| CBTL | coal biomass to liquid |
| CCS | carbon capture and sequestration |
| CH_4 | methane |
| CO_2 | carbon dioxide |
| CTL | coal to liquid |
| Def. Stan. | defence standard (UK) |
| DESC | Defense Energy Support Center |
| DoD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| EBB | European Biodiesel Board |
| EEED | Environment, Energy, and Economic Development Program |
| EIA | Energy Information Administration |

| | |
|------------------|---|
| EISA | Energy Independence and Security Act of 2007 |
| EOR | enhanced oil recovery |
| EPA | U.S. Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FAME | fatty acid methyl ester |
| FEED | front-end engineering design |
| FRL | fuel readiness level |
| FT | Fischer-Tropsch |
| FY | fiscal year |
| GDP | gross domestic product |
| GHG | greenhouse gas |
| REET | Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation |
| GTL | gas to liquid |
| H ₂ O | water |
| HDS | hydrodesulfurization |
| HHV | higher heating value |
| HRD | hydroprocessed renewable diesel |
| HRJ | hydroprocessed renewable jet |
| ICP | in situ conversion process |
| IEA | International Energy Agency |
| IGCC | integrated gasification combined cycle |
| ISE | Infrastructure, Safety, and Environment |
| JAL | Japan Airlines |
| JP-4 | jet propellant 4 |
| JP-5 | jet propellant 5 |
| JP-8 | jet propellant 8 |
| kbpd | thousand barrels per day |
| L | liter |
| LHV | lower heating value |
| LNG | liquefied natural gas |

| | |
|-------------------|---|
| MIT | Massachusetts Institute of Technology |
| MJ | megajoule |
| N ₂ O | nitrous oxide |
| NAAQS | National Ambient Air Quality Standards |
| NASA | National Aeronautics and Space Administration |
| NG | natural gas |
| NO _x | nitrogen oxide |
| NRDC | Natural Resources Defense Council |
| OPEC | Organization of the Petroleum Exporting Countries |
| PARTNER | Partnership for AiR Transportation Noise and Emission Reduction |
| PM | particulate matter |
| PM _{2.5} | particulate matter smaller than 2.5 micrometers |
| PM ₁₀ | particulate matter smaller than 10 micrometers |
| PMNV | nonvolatile particulate matter |
| ppm | parts per million |
| PQIS | Petroleum Quality Information System |
| RD&D | research, development, and demonstration |
| SO ₂ | sulfur dioxide |
| SO _x | sulfur oxide |
| SPK | synthetic paraffinic kerosene |
| TTW | tank to wake |
| UK | United Kingdom |
| ULS | ultralow sulfur |
| USAF | U.S. Air Force |
| USDA | U.S. Department of Agriculture |
| VHO | very heavy oil |
| WTW | well to wake |
| WTI | West Texas Intermediate |

Introduction

Background

The world commercial aviation fleet uses fuel derived from conventional petroleum. Within the United States, the jet fuel is Jet A; in Europe and much of the rest of the world, the jet fuel is Jet A-1.¹ Jet A has satisfactorily met the needs of the commercial aviation fleet for about 50 years; however, in recent years, there has been a renewed interest in alternative jet fuels derived from sources other than conventional petroleum, such as oil sands, oil shale, coal, natural gas, and biomass.

Fuel prices and environmental impacts are the major forces driving this development. There is concern over the recently elevated levels and volatility of the price paid for Jet A. There is also concern that prices and price volatility may increase in the future. If available in sufficient quantities, alternative fuels offer the potential to reduce fuel prices and volatility; in addition, they could potentially reduce aviation's impact on the environment in terms of both global climate change and air quality near airports.

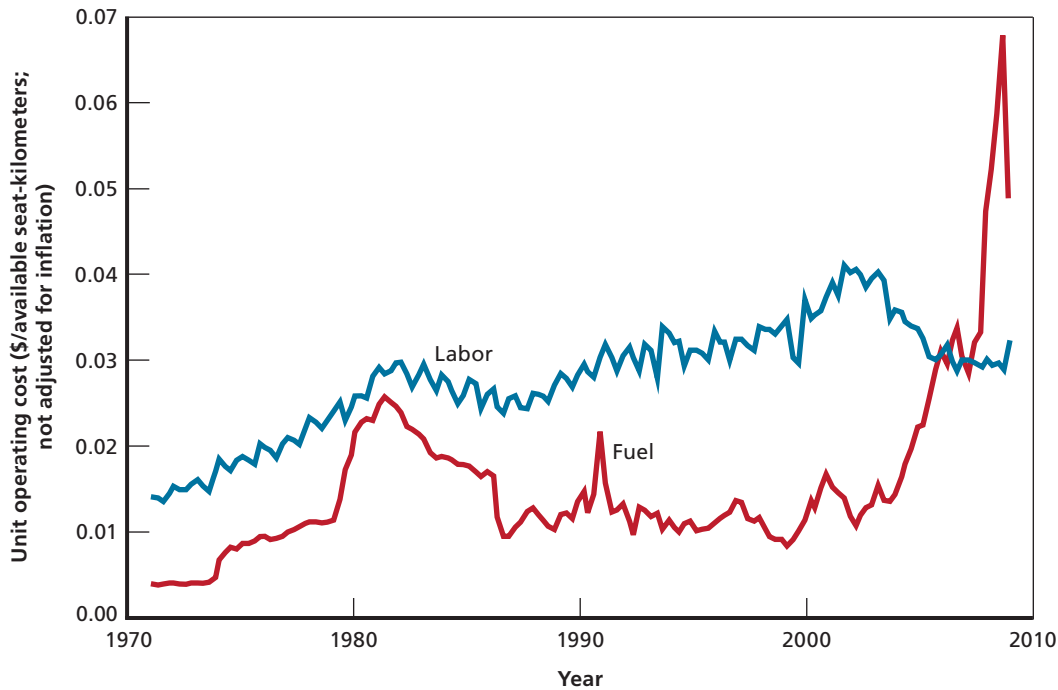
These forces define the central question of this study: Within the next decade, will there be alternatives to conventional petroleum-based, kerosene-type jet fuel that may help to reduce price and price volatility and the environmental impact of commercial aviation operations?

Price and Price Volatility

Higher prices for jet fuel increase costs for airlines. As shown in Figure 1.1, the recent price increases for Jet A have resulted in fuel overtaking labor as the primary expense for airlines (ATA, 2009b). The Air Transport Association (ATA) estimated that U.S. airlines would spend \$60 billion on fuel in 2008, a 43-percent increase from 2007 (ATA, 2008). In addition to the increased operating costs resulting from higher fuel prices, volatility in fuel price complicates airline planning for future fuel purchases because the trajectory of future fuel prices is uncertain. From January 2005 through May 2008, spot prices for jet fuel ranged from \$1.31 per gallon to \$3.66 per gallon in nominal dollars (EIA, 2009c). Though spot prices have been volatile, the overall trend between January 2002 and July 2008 was a consistent rise in prices (EIA, 2009c).

¹ The primary difference between Jet A and Jet A-1 is that the freeze-point specification for Jet A-1 is lower than that for Jet A. The lower freezing temperature of Jet A-1 makes it more suitable for long-range, high-altitude flight, especially over polar regions. The principal U.S. military turbine fuel is jet propellant 8 (JP-8), which is essentially Jet A-1 with special-purpose military additives to improve performance. For most of this report, we make no distinction between Jet A, Jet A-1, and JP-8. Of note, the U.S. Navy uses jet propellant 5 (JP-5), which has a higher flash point than does either JP-8 or Jet A; this enhances safe operations on aircraft carriers. Jet B is an aviation fuel sometimes used in colder climates; it contains some lighter hydrocarbon components that are also found in gasoline.

Figure 1.1
Airline Average Unit Operating Costs for Fuel and Labor



SOURCE: ATA (2009b).
 RAND TR554-1.1

Fuel price and volatility also affect the military. Procurement of fuel for the U.S. military is subject to federal regulation and occurs only in the form of short-term purchase contracts, which complicates planning and limits the availability of financial instruments, such as futures contracts to address price volatility. In fiscal year (FY) 2004, the U.S. Air Force (USAF) consumed about 180,000 bpd of aviation fuel at an annual cost of \$2.6 billion; in FY 2008, it consumed a smaller amount (about 10 percent less) at an annual cost of \$7.6 billion (Klapper, 2008; Lewis, 2008). Every increase of \$10 per barrel of jet fuel drives up USAF fuel costs by an additional \$600 million per year.

Fuel prices dropped significantly during the latter part of 2008. However, the supply of low-cost petroleum for the long term remains a concern. Both the International Energy Agency (IEA) and the Energy Information Administration (EIA) project that liquid-fuel supplies would be sufficient to meet demand, including jet-fuel demand, throughout their forecast periods—about 20 years. However, in some of the future scenarios examined by these agencies, liquid-fuel demand is attenuated by high oil prices, and some of the demand is met by alternative sources, including oil sands, coal-derived liquids, and biomass-derived liquid fuels. For example, the 2008 U.S. government forecast of 113 million bpd for worldwide demand in 2030 holds only under the assumption that world oil prices are in the range of \$70 per barrel for premium crude oil (EIA, 2008a).² At higher prices, world oil demand decreases. For exam-

² World oil prices are in year-2006 dollars per barrel and represent the average price of imported, low-sulfur, light crude oil similar in quality to West Texas Intermediate (WTI). On average, the price paid for all imported oil would be considerably less. Specifically, the \$70-per-barrel price for premium crude corresponds to an average imported crude price of \$59 per barrel, and the \$120 price for premium crude corresponds to an average imported crude price of \$96 per barrel.

ple, EIA projects that global demand for liquid fuels will be in the range of 100 million bpd in 2030 if, in the long term, prices for premium crude oil are in the range of \$120 per barrel.

If the production and delivery costs—net of any subsidies—of an alternative fuel are competitive with fuels derived from crude oil, the alternative fuel can displace petroleum-based fuels in the market. If the alternative were produced in sufficient quantities, the demand for conventional crude oil would decrease, with the result being a lower prevailing price for crude oil, benefiting all users of petroleum products. The same holds for conservation and efficiency improvements. Every barrel of additional production of fuels or savings of a barrel of fuel serves to lower world oil prices. This effect provides a benefit to all fuel users. Thus, if ethanol or any other petroleum alternative is able to displace conventional fuels or petroleum in the automobile sector, then aviation—along with other fuel-using sectors—would benefit economically.

A recent analysis published by RAND provides estimates of the magnitude of this benefit (Bartis, Camm, and Ortiz, 2008). For each million barrels per day of reduction in demand for Organization of the Petroleum Exporting Countries (OPEC)–produced oil, world oil prices are estimated to fall by between 0.6 and 1.6 percent. The range in the price reduction reflects uncertainties regarding OPEC’s behavior and how the supply and demand for liquid fuels respond to prices. For example, the low end of the estimate assumes that OPEC can act cohesively to optimize its revenues by slightly reducing its production and that supply and demand respond well to prices. The high end of the estimate assumes that OPEC is unable to reduce production and that supply and demand are minimally responsive to prices.

These estimated-percentage price reductions can be applied to recent EIA projections of world oil prices (EIA, 2008a). For example, using EIA’s 2008 reference-case projection of \$70 (2006 dollars) for imported, low-sulfur light crude oil and adding global production of an additional 10 million bpd of alternative fuels would reduce prices by between \$4 and \$11 per barrel. For the EIA 2008 high–oil price case of \$119 per barrel, adding an additional 10 million bpd would reduce prices by between \$7 and \$19 per barrel.³

This price reduction occurs even if the alternative-fuel production were for fuels that are not appropriate for use in aircraft: All users of petroleum and petroleum products would directly benefit from the reduction in oil price. Given projected jet-fuel consumption in the United States in 2030 of 1.9 million bpd (EIA, 2008a), the annual savings to aviation in 2030 would be between \$3 billion and \$8 billion for the EIA reference case and between \$5 billion and \$13 billion for the EIA high-price case. Again, we emphasize that these benefits to commercial aviation would accrue even if commercial aviation were to continue using fuels derived from conventional petroleum and did not consume any of the additional production or contribute to conservation. In the context of this study, in which alternative jet fuels are considered in the 2017 time frame, the following observations may be made:

- These results hold for 2017, the time frame of this study, because this is sufficiently far into the future that the assumed relationships (i.e., long-term elasticities) between supply and demand would be similar to those applied for 2030.

³ The price reductions in this paragraph are for a low-sulfur, light crude oil similar to WTI. The average crude oil imported into the United States sells at a price significantly below this benchmark. For example, EIA projects that the average price for all crude imports in 2030 will be \$59 and \$96 per barrel, respectively, in its reference-case and high–oil price scenarios. These average imported crude prices are used in the following paragraph to calculate net savings to the aviation sector.

- Price benefits associated with alternative fuels for aviation cannot be decoupled from price benefits for all users of petroleum and petroleum products. Therefore, measures to decrease demand for conventional petroleum, through the production of alternative fuels and through conservation, should be directed at the fuel-using sector in which use of the alternative fuel is most cost-effective.

Because of the long time needed to develop alternative-fuel technology and build capacity and, similarly, to develop and build energy-efficient aircraft, investments are required soon for significant alternative-fuel production in the post-2020 time frame.

Environmental Impacts of Aviation

There is pressure on the aviation sector to reduce greenhouse gas (GHG) emissions. Aviation contributes approximately 2 percent of the world's carbon dioxide (CO₂) emissions (Penner et al., 1999) but has received considerable attention regarding these emissions. For example, in November 2007, the European Parliament voted to bring aviation into the European GHG-emission trading system. The legislation would take effect in 2011, and it would require that all airlines flying within or into Europe cut their GHG emissions by 10 percent or buy CO₂ allowances on the open market (Roosevelt, 2007; Wald and Kanter, 2007).

In Europe, and especially in the United Kingdom (UK), public demonstrations and legislation show the pressure on aviation to reduce its GHG emissions. Airport expansion in the London area is a concern for the UK government; a recent white paper by the British government estimated that congestion at UK airports costs the UK economy £1.7 billion per year, whereas increasing capacity will benefit the economy by £13 billion (Milmo, 2007). In November 2006, a project to build a second runway at Stansted Airport near London was blocked by the local government on the grounds that it would contribute to global climate change ("Stansted Expansion Plan Refused," 2006). In August 2007, more than 1,200 protesters descended on London's Heathrow Airport to try to block expansion on the basis of global warming ("Flying and Climate Change," 2007; Roosevelt, 2007). In two separate incidents in February 2008, protestors violated security at Heathrow, climbed onto an airplane, and then mounted a banner onto the aircraft to protest expansion, on the grounds of climate change; a few days later, protestors violated security at the UK Parliament and unfurled a similar protest banner from the roof of the building ("Climate Protest on Heathrow Plane," 2008; "Parliament Rooftop Protest Ends," 2008).

In the United States, aviation has been under less pressure to reduce its GHG emissions than in Europe, but that may be changing. In December 2007, the attorney general of the state of California filed a petition with the U.S. Environmental Protection Agency (EPA) "to crack down on rising aircraft emissions that contribute to global warming" (Roosevelt, 2007). The petition was submitted in association with the states of Connecticut, New Jersey, New Mexico, and Pennsylvania, as well as air-pollution officials from New York City, the District of Columbia, and Southern California.

Some of the fuels considered in this report have lower life-cycle GHG emissions than Jet A.⁴ In general, these fuels are derived from renewable resources, such as sugars, plant oils, and other biomass. However, recent studies (Fargione et al., 2008; Searchinger et al., 2008)

⁴ The life-cycle GHG emissions of a fuel include those created during the extraction of raw fuel feedstock, the processing of the feedstock to create the fuel, the fuel's transportation, and its combustion.

call into question the nature and magnitude of the GHG-related benefits associated with biomass-derived fuels. These studies show that biofuels made from food sources, and even nonfood biomass crops, can lead to a significant increase in GHG emissions when their production results in direct and indirect land-use changes.⁵ Land-use changes often result in the net emission of CO₂ that had previously been stored in the biomass and soils. In an extreme case, if the displacement of food crops occurs as a result of biofuel production results in the destruction of peatland rainforest for new farmland (e.g., in Indonesia or Malaysia), significant CO₂ will be released not only by the clearing of the rain forest but also by the draining of the peatland. For this case, offsetting the emitted CO₂ is estimated to require more than four centuries of biodiesel production and use (Fargione et al., 2008). However, these GHG emissions can be avoided by using feedstocks that do not lead to land-use changes, such as municipal waste, agricultural waste, grass harvests from marginal lands, and algae (Searchinger et al., 2008). It is also possible to grow biomass crops on degraded lands (Tilman, Hill, and Lehman, 2006) to reconstitute soil carbon levels, but doing so comes at the expense of lower yields than would be the case on active farmland.

The impacts of feedstock and fuel composition on life-cycle GHG emissions are already shaping legislation in both Europe and North America regarding the use of alternative fuels. The European Commission recently revised its target of supplying 10 percent of Europe's road-transportation energy from biofuels to include a provision that these fuels must provide a carbon savings of at least 35 percent over conventional fuels ("EU Reveals Energy Plan of Action," 2008). In addition, Australia, parts of Canada, Switzerland, and several countries in the European Union, including Britain, France, Germany, and the Netherlands, are basing their biofuel subsidies on the reduction in life-cycle GHG emissions provided by the fuel (Doornbosch and Steenblik, 2007; Rosenthal, 2008). In the United States, the Energy Independence and Security Act of 2007 (EISA) (Pub. L. No. 110-140, §526) restricts the alternative fuels that federal agencies can use on the basis of their life-cycle GHG emissions. The Energy Independence and Security Act also adapts the renewable-fuel mandate to require life-cycle analysis of fuels and creates classes of fuels based on GHG emissions.

In a carbon-constrained world, the same biomass feedstock could conceivably be used to generate electricity, for combined heat and power located near the facility, to produce fuels for ground transportation, or to produce fuels for aviation. Although not considered in this study, comparative analyses of the use of biofuels for different segments of the energy sector suggest that it may be more effective, from perspectives of energy efficiency and CO₂ mitigation, to use scarce biofuels for heat and electricity than for transportation. The extent to which policies and market forces relating to biofuels will align with efficiency and CO₂-mitigation potential is uncertain, but the prospects for using biofuels for aviation (and surface transport) must be considered in light of these broader issues.

The impact of aviation on air quality is also an area of concern. EPA, through the Clean Air Act Amendments of 1990 (Pub. L. No. 101-549), sets standards for six common air pol-

⁵ A direct land-use change is one in which land that was not being used for agricultural purposes is used to grow biomass that will be used as a biofuel feedstock. An indirect land-use change occurs when food sources or agricultural lands are diverted to biofuel feedstocks and this results in the conversion of noncropland (e.g., rainforest, grassland) to cropland elsewhere in the world to replace the displaced food.

lutants.⁶ These pollutants are regulated under the National Ambient Air Quality Standards (NAAQS), and areas that do not meet the NAAQS are designated nonattainment areas. Of the six NAAQS criterion pollutants, particle-matter pollution and ground-level ozone are the most widespread health threats (EPA, 2007a). In general, aviation's contribution to ozone levels is viewed as having a slight adverse effect on health; particulate matter from aviation, however, has an appreciable adverse effect (Rojo, 2007b).

Particulate matter (PM) refers to a complex mixture of solid particles and liquid droplets that are suspended in the atmosphere. Sources include transportation, industry, electricity generation, fires, and wind-blown dust. PM is referred to by its size in micrometers, μm , and the NAAQS have two listings for PM pollution, PM_{10} and $\text{PM}_{2.5}$, to reflect PM with diameters less than $10\mu\text{m}$ and $2.5\mu\text{m}$, respectively.⁷ Several major airports (including 18 of the 50 largest airports) operate in $\text{PM}_{2.5}$ nonattainment areas, including Hartsfield-Jackson Atlanta International, Chicago's O'Hare International, Los Angeles International, and John F. Kennedy International in New York (FAA, 2006). Aircraft gas turbines contribute directly to ambient concentrations of $\text{PM}_{2.5}$ (these emissions are referred to as *primary PM*);⁸ they also contribute indirectly to the formation of $\text{PM}_{2.5}$ through gaseous emissions of NO_x , SO_x , and organics, known as *precursor gases*, which undergo chemical and physical processes in the jet plume and atmosphere to form $\text{PM}_{2.5}$. Although the health impacts of primary PM are greater than those of secondary PM on a per-mass basis, the large total mass of secondary PM that is emitted is estimated to cause appreciable effects on the health and welfare of the general public (Rojo, 2007b).

Using statistical relationships derived from air-quality models and emission inventories created with Federal Aviation Administration (FAA) tools, Rojo (2007b) estimated that 120 to 610 premature mortality incidences in the United States may occur yearly due to $\text{PM}_{2.5}$ from aviation. The overall health costs associated with aviation emissions were as follows: 15 percent from primary PM, 62 percent from secondary PM from nitrates, and 23 percent from secondary PM from sulfates. Additionally, Rojo (2007b, p. 72) analyzed emissions by region and found that the "top 25 airports contributed to more than 80 percent of the total health costs and emissions. The top four airports (Chicago O'Hare, Los Angeles International, San Francisco, and Atlanta) were responsible for 30 percent of the total costs."

Notably, aviation contributes a small fraction of the total air-quality health impacts in the United States; for example, PM emissions from highway vehicles were estimated in the same study to lead to 26,000 yearly premature mortality incidences in the United States. However, the recent promulgation of tighter emission limits for automobiles will result in a lowering of this estimate and, consequently, increase the fraction of air-quality health impacts associated with aviation.

⁶ These *criterion pollutants* include particle pollution (often referred to as *particulate matter*), ground-level ozone, carbon monoxide, sulfur oxides (SO_x), nitrogen oxides (NO_x), and lead (EPA, 2001).

⁷ PM is characterized by diameter because smaller-diameter particles have a greater impact on human health and welfare, since they more easily reach deep into human lungs and bloodstreams (Rojo, 2007, Chapter Two; Greco et al., 2007; NCEA, 2004; Bickel, 2005; Pope and Dockery, 2006). Of note, the primary PM emissions from aircraft typically have aerodynamic diameters of $0.04\mu\text{m}$ (Holve and Chapman, 2005).

⁸ Primary PM is comprised of nonvolatile emissions of soot-like particles (PMNV) as well as volatile organic compounds that result from incomplete fuel combustion and conversion of fuel-bound sulfur to sulfuric acid (ICAO, 2006).

Sequeira (2008) reported on results of a study mandated by the Energy Policy Act of 2005 (Pub. L. No. 109-58). Among other objectives, the study estimated the health impacts of aviation associated with surface-air quality. The study used emission inventories that were estimated in a manner similar to Rojo (2007b) but used more-detailed air-quality modeling and a different concentration-response relationship for PM health impacts. As reported by Sequeira (2008), the study found that “aviation is responsible for 160 yearly incidences (with a 90% confidence interval of 64 to 270 incidences) of premature mortality of adults age 30 and over” and costs the U.S. economy roughly \$900 million per year (2001 dollars, with a 91-percent confidence interval of \$196 million to \$1,830 million) due to exposure to PM_{2.5} in the continental United States. Of these incidences, roughly half (46 to 69 percent) were estimated to be due to secondary PM from SO_x emissions, roughly one-fifth (18 to 20 percent) were estimated to be due to secondary PM from NO_x emissions, and the remainder (11 to 38 percent) were due to primary PM. Both the Rojo study and the study reported by Sequeira illustrate the greater role played by PM precursor gases, SO_x and NO_x, relative to the direct emissions of primary PM.

Many of the fuels considered in this analysis have the potential to reduce PM because of reduced sulfur content or because their chemical composition results in reduced emissions of primary PM. Such fuels offer the opportunity to reduce aviation’s impact on air quality.

Competing Uses for Alternative Fuels

A complicating factor in the consideration of alternative jet fuels is that aviation would compete with ground transportation for fuel itself or the feedstocks used to produce that fuel. Because they have similar properties, a fuel that is a suitable substitute for kerosene-type jet fuel is also a potentially suitable substitute for diesel fuel. In fact, the U.S. military uses a jet fuel, jet propellant 8 (JP-8), to power both turbine and diesel engines. The analysis in the following chapters explores the relative attractiveness of potential alternative fuels to competing end-use transportation sectors. The analysis does not consider the broader issue that using potentially scarce biofuels to produce heat and electricity and using the displaced petroleum for transportation may be more effective, from perspectives of energy efficiency and CO₂ mitigation, than using biofuels directly in transportation applications (see, for example, Hedegaard, Thyø, and Wenzel, 2008).

By considering the benefits of using alternative fuels in aviation or ground transportation, one can understand how different applications provide more or less public benefit. This issue is especially relevant for the next few decades, since the amount of renewable resources that can be used to produce liquid fuels will be limited and conventional petroleum will most likely be the primary source of transportation fuels.

Technical/Methodological Approach

The Massachusetts Institute of Technology (MIT) and RAND collaborated in the execution of this study. The focus of the study was on alternative fuels for commercial aviation that may be commercially available within ten years, with an emphasis placed on North American resources. The choice of a ten-year horizon forced the study team to focus on fuels that may be available fairly soon and that could exploit existing infrastructure for transportation and distribution.

This study examined the ability of alternative fuels to reduce price and price volatility of jet fuel and to reduce the impact of commercial aviation operations on the environment. The research team performed several related analyses for these examinations. To address the competitiveness of alternative fuels, the production costs for alternative fuels were obtained from the literature or derived using standard methodologies. Often, the source for a cost estimate is a low-definition, conceptual design of a fuel-production facility. When this is the case, we have modified the estimate to take into account the expected cost increases that have occurred historically during plant siting, detailed design, construction, and start-up; details are provided in Appendix A. The analyses in general do not consider incentives (e.g., tax breaks, emission credits), as these were beyond the scope of the study.

To assess GHG emissions, a well-to-wake (WTW) fuel life-cycle analysis was conducted by employing standard production pathways (e.g., Brinkman et al., 2005). Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET)⁹ methodology was used to estimate the GHG emissions per unit of fuel energy delivered to the aircraft tank. The GREET framework was chosen because of its general acceptance in the ground-transportation industry for conducting well-to-wheel analyses of vehicle fuel systems (ANL, 2007). The standard GREET inputs and approach were revised and augmented, based on an extensive evaluation of the literature, to allow the WTW analysis to (1) incorporate the latest information (including developments in Fischer-Tropsch [FT] technology and the impact of land-use changes on GHG emissions), (2) include new fuel pathways (such as oil shale as a feedstock), (3) evaluate the importance of uncertainties (such as feedstock properties and process efficiencies), and (4) calculate combustion-released CO₂ emissions appropriate to jet fuel. The WTW analysis is presented in Appendix B. A tank-to-wake (TTW) analysis was also performed for the purpose of estimating how fuel formulations affect emissions of GHGs other than CO₂.

To assess effects on local air quality, the research team considered how changing fuel composition would affect ground-level ambient PM_{2.5}. The approach uses a TTW analysis to examine relevant emissions that are created under a height of 3,000 feet¹⁰—i.e., during takeoff and landing. The approach to addressing the issue of the competition between aviation and ground transportation for alternative-fuel usage is to consider a range of properties of the fuels under consideration to identify characteristics that might favor use in aviation over ground transportation.

Contents of This Report

The remainder of the report is organized as follows. Chapter Two presents the metrics used to examine the candidate alternative fuels for commercial aviation and uses those metrics to summarize the major findings of the study. The remaining chapters investigate the properties of selected fuels and are grouped by fuel type. Chapter Three covers jet fuel and ultralow-sulfur (ULS) jet fuel derived from conventional-petroleum resources. Chapter Four considers jet fuel derived from unconventional petroleum (i.e., oil sands, very heavy oil [VHO], and oil shale).

⁹ GREET is available from ANL (2009).

¹⁰ Emissions created by aircraft flying above the atmospheric mixing layer (here taken as 3,000 feet, although it varies from location to location and with time of year) have a smaller impact on air quality.

Chapter Five examines synthetic fuels created from the FT process. Chapter Six reviews fuels created from renewable oils. Chapter Seven examines two alcohols—ethanol and butanol—that can be created from renewable resources. Chapter Eight discusses the implications of the preceding analyses and offers recommendations. Appendixes contain supporting information and analysis. Appendix A presents details of the production supply and cost analyses. Appendix B presents a summary of results from recent analysis at MIT about WTW fuel life-cycle analysis.

Alternative Fuels for Commercial Aviation

For an alternative fuel to be used safely and effectively in the air-transportation industry, it needs to meet a range of characteristics. The first part of this chapter provides a listing of candidate fuels considered in this study. The second part identifies the characteristics and metrics used to compare the candidate fuels to each other and to current-specification jet fuel (i.e., Jet A) produced from conventional petroleum. The chapter concludes by providing the template for the remainder of the analysis.

Candidate Alternative Fuels

Only fuels that could likely be commercially available within ten years are considered. Table 2.1 summarizes the list of candidate fuels judged by the MIT-RAND research team as likely to meet this requirement and their potential sources. These fuels are derived from one of five sources: conventional petroleum, unconventional petroleum (oil sands, VHO, or oil shale), the FT indirect liquefaction process (of coal, natural gas, or biomass), renewable oils from biomass, and alcohols from fermentation of biomass. As a result of refining operations, fuels produced from unconventional-petroleum sources listed in Table 2.1 would be indistinguishable

Table 2.1
Alternative Fuels Considered in This Report

| Fuel | Source | Notes |
|--------------------------------|---|---|
| Jet A | Refined conventional and unconventional petroleum (oil sands, VHO, oil shale) | Through refining, all petroleum sources yield fuels that meet Jet A specifications. |
| ULS Jet A | Refined conventional and unconventional petroleum (oil sands, VHO, oil shale) | Through refining, all petroleum sources can yield fuels with similar range of properties. |
| FT synthetic fuels | FT synthesis of natural gas (NG), coal, coal with CO ₂ sequestration, biomass | This is synthetic paraffinic kerosene (SPK) fuel. |
| Biodiesel/biokerosene | Chemical reaction of plant oils or animal fats | This is in use as a blend stock and substitute for automotive diesel fuel. |
| HRJ fuel | Hydroprocessing of plant oils or animal fats to create an oxygen-free automotive diesel or jet fuel | This is also SPK fuel. |
| Alcohols (ethanol and butanol) | Fermentation of sugars, grains, and treated cellulosic feedstocks | This is in use as a gasoline-blend stock. |

from those produced from conventional petroleum after entering the fuel-distribution system; for example, fuels derived from Canadian oil sands are already part of the global petroleum supply. FT synthetic fuels and hydroprocessed renewable jet (HRJ) fuel from renewable oils are highly paraffinic kerosene fuels (see Table 2.1) and have the potential to be used in concentrated blends with either Jet A or diesel. In this report, these fuels are referred to collectively as *synthetic paraffinic kerosene* (SPK) fuels. Biodiesel and ethanol are currently being used as a substitute for conventional diesel automotive fuel and in blends with gasoline, respectively.

Cryogenic liquids were not considered in this study because they are incompatible with the existing aircraft and pipeline infrastructures. Although liquid hydrogen and liquid methane both have positive attributes in terms of potential fuel availability and potentially lessened environmental impacts, they would require drastic changes to the aircraft and the fueling infrastructure. Cryogenic fuels would require larger, heavier fuel tanks that would displace passengers in conventional aircraft. They would also require engine modifications to vaporize and heat the fuel prior to combustion. These changes would necessitate completely new aircraft designs (e.g., Hadaller and Momeny, 1993; Daggett et al., 2008). The Cryoplane project conducted by Airbus concluded that high production and infrastructure costs inhibit the use of hydrogen in aviation: “The results of the project confirmed that liquid hydrogen, from the technical side, could be an alternative future fuel. Because of today’s high hydrogen production costs and the missing infrastructure it remains not attractive for operation at this time” (Westenberger, 2003, p. 6). It is highly unlikely, therefore, that cryogenic fuels for commercial aviation would be available commercially in the next decade, if not longer.

Metrics for Comparing Alternative Fuels

This study focused on the ability of alternative fuels to reduce the price and price volatility of jet fuel and to reduce the impact of commercial aviation operations on the environment. For an alternative fuel to have an appreciable reduction on either fuel price or the environmental impact of aviation, it must be available in significant quantities. To determine whether any of the alternative fuels listed in Table 2.1 could reduce either price or environmental impacts, a set of metrics was created that assesses near-term fuel availability in terms of technological readiness of the fuel-production process and the near-term production potential, fuel-production cost, and the environmental consequences of fuel use. An additional metric was created to assess the qualitative merit of using the alternative fuel for aviation versus using it in ground transportation. This metric addresses the question of whether an alternative fuel might be better used in ground transportation than for aviation. The study did not address the relative value of using the fuels or feedstocks from which they are derived for other parts of the energy sector.

For a fuel to be available in the near term, it needs to be compatible with current infrastructure, the technology for the fuel creation must be mature, and ample raw materials must be available to ensure a large production potential. For a fuel to be viable, it must have a production cost that is competitive with the currently prevailing fuel, Jet A refined from conventional petroleum. The environmental consequences considered in this study focus on air quality and global climate change. These are considered in terms of WTW and TTW emissions. Therefore, the following seven metrics were selected for comparing alternative fuels for aviation:

- compatibility with current systems
- fuel readiness level (FRL)
- production potential
- production cost
- WTW GHG emissions
- air-quality emissions
- merit for aviation use.

Each of these metrics is defined and considered in the following subsections.

Compatibility with Current Systems

The metric *compatibility with current systems* refers to the compatibility of a fuel with the existing fueling infrastructure downstream from the fuel-processing facility; this includes pipelines, airport fueling systems, aircraft and engines, and the operability of the aircraft in terms of range capabilities. Alternative fuels that do not satisfy the performance characteristics offered by conventional jet fuel would need to provide considerable offsetting benefits because of the changes in aircraft equipment, operations, and infrastructure that would be required for their safe use.

To enable the safe operation of current aircraft, an alternative jet fuel must possess an array of characteristics that include the following:

- high energy density, which facilitates long-range flight
- high flash point, which is the temperature above which the fuel produces a vapor that can ignite and is an essential safety consideration¹
- low freezing point and vapor pressure, which facilitate high-altitude flight
- high thermal stability, which allows the fuel to be used to cool engine components without a change in its chemical properties, thus increasing overall aircraft performance.

Other important aviation-fuel characteristics include lubricity, which is a measure of a fuel's ability to reduce wear in engine components, and viscosity, which determines fuel-pumping requirements. The specification for Jet A, issued in the 1960s by the American Society for Testing and Materials (ASTM) (2007a), is a set of characteristics that balance such operational requirements with the requirement for widespread availability (Maurice et al., 2001).

The compatibility of any alternative fuel also needs to be considered with regard to fueling infrastructure. The current pipeline system, tanks, and fueling equipment are designed for conventional jet fuel. Alternative fuels may require different transmission, distribution, and delivery infrastructure. Additionally, current procedures are specified for the handling of a fuel to reduce risks at airports.

Ideally, an alternative fuel would be completely compatible with the existing aircraft and fueling infrastructures and could be “dropped into” the existing system. This ideal has led to the definition of the term *drop-in replacement fuel*. The large installed base of Jet A-specific infrastructure heavily favors drop-in fuels.

¹ Jet fuels are hazardous flammable liquids to be handled carefully, but the properties of a fuel can facilitate safe handling and use. The minimum flash point that is specified for Jet A and Jet A-1 is 38 degrees Celsius; by comparison, the flash point of automotive gasoline is -7 degrees Celsius.

For rating fuel compatibility, a neutral rating indicates that the fuel could be used in the existing system without impact, and the most negative rating means that the fuel would require a complete overhaul of the system. Intermediate negative values fall between these extremes. Positive ratings are not defined. The compatibility-rating descriptions are summarized in Table 2.2.

Fuel Readiness Level

FRL is used to assess the *current* technological maturity of a fuel and its production process. The concept of FRL spans technology readiness from synthesis or isolation in a laboratory to large-scale, commercial fuel processing. The FRL value for a fuel-production process is determined by the least developed part of that process. The FRL ratings are defined in Table 2.3 in terms of both a description and an example. Note that the process of selecting fuel candidates precludes fuels that would meet the lowest rating of this metric.

Production Potential

Alternative fuels with a large and distributed resource base may have the potential to displace a significant amount of conventional fuels, resulting in reductions in the price of petroleum and environmental benefits from using the alternative fuels. To limit the scope of the analysis, the study focuses on North American resources unless otherwise specified. Estimates were created for the production potential for each of the various fuels. Recent projections by the EIA expect the United States to consume approximately 1.9 million barrels of jet fuel per day in 2017 (EIA, 2008a).² The projected U.S. demand in 2017 is used to place alternative-fuel production potentials in the context of conventional petroleum-based jet-fuel production and consumption. The rating system for production potential is shown in Table 2.4.

Because a decade is not sufficient time to establish an industrial base capable of supplying 1 million bpd of a fuel from a fundamentally different source, none of the fuels examined that

Table 2.2
Definitions: Compatibility with Current Systems

| Rating | Description |
|--|---|
| ○ Fully compatible | Fuel is indistinguishable within existing pipeline, storage, and distribution systems from fuels created from conventional petroleum. |
| – Compatible, with fuel additives or blending | Use of fuel additive or 50-50 blending is necessary. |
| --- Not compatible; infrastructure changes needed | Fueling infrastructure needs to be modified; dilute blending required (5 to 20 percent alternative fuel with conventional fuel). |
| ---- Not compatible; complete system overhaul needed | New fueling infrastructure is needed; aircraft modifications are required. |

² Since the research supporting this analysis was completed, the EIA released a revision of its projections that takes into account recent U.S. legislation and the global economic outlook (EIA, 2009e). In the 2009 projections, the oil price trajectories are higher than in the 2008 projections, and, as a consequence, projected jet-fuel consumption is lower: 1.6 million bpd in 2017 in the published reference case.

Table 2.3
Definitions: Fuel Readiness Levels

| Rating | | Example |
|--------|---|--|
| +++ | The fuel is in large-scale, commercial production. | Ethanol production from corn and sugar cane |
| ++ | The fuel is in limited commercial production. | Conversion of coal to synthetic fuels via gasification and FT synthesis |
| + | Commercial pilot plant is under construction or in operation. | Butanol production from sugar beets |
| ○ | All relevant technologies that are necessary for fuel production have been proven. | Conversion of blend of coal and biomass to synthetic fuels via gasification and FT synthesis |
| - | Fuel-creation process is undergoing advanced research and development. | Systems and processes for long-term storage of CO ₂ captured at energy facilities (e.g., FT production plants with CCS) |
| -- | Fuel-creation process is undergoing intermediate research and development to prove viability of individual process steps. | Shell ICP for shale-oil extraction in Colorado |
| --- | Fuel-creation process is undergoing fundamental research and development at laboratory scale to prove viability of fuel-creation concept. | Genetically engineered microorganisms to process cellulosic material for fuel production |

NOTE: ICP = in situ conversion process.

Table 2.4
Production-Potential Ratings

| Rating | +++ | ++ | + | ○ | - | -- | --- |
|---|-------|-------|-----|-----|----|-----|-----|
| Production potential, % anticipated U.S. demand for Jet A in 2017 | 100 | 50 | 10 | 5 | 1 | 0.5 | 0.1 |
| Production potential, kbpd | 2,000 | 1,000 | 200 | 100 | 20 | 10 | 2 |

NOTE: kbpd = thousand bpd. Values are approximate.

are not derived from conventional petroleum is able to achieve a production potential rating higher than +.³

Production Cost

The cost of production is a key measure of the commercial viability of an alternative fuel. The price of conventional jet fuel is directly related to the price of crude oil. The profitable development of alternative fuels requires that the production costs of the fuel be competitive with the price of its conventional counterpart. Alternative jet fuels with production costs higher than the price of conventional kerosene-type jet fuel cannot be produced and sold profitably without government intervention (e.g., investment or production subsidies, production mandates, or taxes on fuels produced from conventional petroleum, which are not examined in this report). For this metric, a key uncertainty is the long-run price of oil. For the purposes of providing

³ In some cases, such as biokerosene and HRJ, the + rating is achieved only by considering global production potential.

Table 2.5
Production-Cost Ratings

| Rating | ++ | + | ○ | - | -- |
|---|-------|-----------|-----------|-----------|-------|
| Percentage of U.S. average Jet A spot price, 2005 | <50 | 50–80 | 80–120 | 120–200 | >200 |
| Production cost, 2005 \$ | <0.90 | 0.90–1.40 | 1.40–2.10 | 2.10–3.50 | >3.50 |

SOURCE: EIA (2009c).

relative ratings of alternative fuels, the fuel-production cost of each alternative jet fuel is compared to the average spot price for jet fuel in 2005, which was \$1.73 per gallon in 2005 dollars (EIA, 2009c). The production cost ratings are given in Table 2.5.

The spot price of \$1.73 per gallon of jet fuel prevailed in a period during which the average cost paid by refiners to acquire crude oil was about \$50 (2005 dollars). Recent history demonstrates the volatility of jet-fuel prices. In 2008, the spot price of Jet A ranged from a high of slightly more than \$4.00 per gallon to a low of less than \$1.50 per gallon.

Additionally, there is great uncertainty regarding the costs of producing certain unconventional fuels, especially those for which there is limited or no recent commercial experience. Considering both of these uncertainties, this metric should be viewed as providing only a rough comparison of alternative options. These comparisons are made on the basis of a per-energy equivalent gallon (i.e., the comparisons are made on a comparable energy basis and not on volume).

Well-to-Wake Greenhouse-Gas Emissions

In selecting a metric for GHG emissions, we initially examined the life-cycle GHG emissions that would be associated with moving a given payload (e.g., 1 kilogram) a given distance (e.g., 1 kilometer), taking an average for the U.S. commercial aviation fleet. This initial approach provided us with a performance-based metric that included not only the extraction, processing, delivery, and combustion of the fuel but also the energy productivity of the aircraft when using the alternative fuel instead of Jet A. For alternative jet fuels, specific energy (energy per unit mass) is the only factor that significantly affects aircraft energy productivity.⁴ Substituting SPK fuels for Jet A would cause a 0.3-percent increase in aircraft energy productivity, which is considered negligible for the purposes of this report. Biodiesel, biokerosene, and alcohols, especially ethanol, have a significantly lower specific energy than Jet A and would further degrade energy productivity (Hileman and Donohoo, 2009). However, on multiple grounds, alcohol fuels are poor substitutes for Jet A, as discussed in Chapter Seven.

Recognizing that aircraft energy productivity was not a discriminating factor for viable alternatives to Jet A, we report on a metric for GHG emissions that uses the more common approach of reporting life-cycle GHG emissions per unit of energy delivered to the fuel tank.

The WTW GHG intensity metric is calculated in two steps. In the first step, we calculate the well-to-tank emissions of CO₂, methane (CH₄), and nitrous oxide (N₂O) that are associated with delivering a unit of energy (namely, 1 megajoule, or MJ) to the fuel tank of an aircraft. Included are emissions associated with obtaining the raw fuel (extracting oil, mining

⁴ Throughout this document, *specific energy* and *energy density* are used in place of net heat of combustion. Specifically, *specific energy* refers to the heat of combustion on a per-unit mass basis (MJ/kg), while *energy density* refers to the heat of combustion on a per-unit volume basis (MJ per liter, or MJ/L).

coal, cultivating and harvesting biomass), transporting the raw fuel, processing the raw fuel to create a jet fuel, and delivery of the jet fuel to aircraft fuel tanks. Estimated emissions of CH₄ and N₂O are converted to CO₂ equivalents (CO₂e) using their relative global-warming potential (IPCC, 2007). In the second step, we add the amount of CO₂ that would be released upon the combustion of the same amount of fuel energy (1 MJ) in the aircraft turbine engines. Calculating CO₂ combustion emissions is straightforward, depending only on the chemical composition of the fuel. At this stage of calculation, we are able to estimate how much more or less GHG emission is associated with the production and use of 1 MJ of the alternative jet fuel as compared to Jet A. Further information on this approach is presented in Appendix B.

Table 2.6 presents our rating system, with positive ratings associated with reduced GHG emissions.

The WTW GHG-emission metric ignores non-CO₂ combustion emissions. The non-CO₂ combustion emissions from aviation may have comparable influence on global climate change as the combustion CO₂ emissions (Penner et al., 1999; Sausen et al., 2005; Wuebbles, Gupta, and Ko, 2007; Marais et al., 2008).⁵ SO_x emissions during cruise tend to cool the climate, while NO_x and PMNV (soot) emissions are generally predicted to warm the climate in terms of globally averaged surface temperature. Depending on where it is emitted within the upper atmosphere, water vapor can be an important GHG (especially when emitted in the stratosphere, where approximately 20 to 40 percent of aircraft emissions are deposited [Penner et al., 1999; Hoinka, Reinhardt, and Metz, 1993; Baughcum, 1996; Schumann, 1997; Gettelman and Baughcum, 1999]). In contrast, water-vapor emissions at the ground and in the troposphere have a minor impact as a GHG because of the naturally large abundance of water in the hydrological cycle (Penner et al., 1999). If a fuel results in significant increases in water-vapor emissions when used in aviation, it might be advantageous from a global climate-change perspective to use that fuel in ground transportation.

Quantitative estimates of the overall impact of emissions during cruise remains a subject of scientific investigation. As such, a quantitative assessment of emissions at cruise altitudes was not performed as part of this study. Additional scientific research is needed to include the non-CO₂ combustion emissions within a WTW life-cycle metric. Within the discussions of each alternative fuel, water-vapor emissions, SO_x emissions, and NO_x emissions are examined either quantitatively or qualitatively.

Table 2.6
Well-to-Wake Greenhouse-Gas-Emission Ratings as a Percentage of Jet A Emissions

| Rating | +++ | ++ | + | ○ | - | -- | --- |
|-------------------------|-----|-------|-------|------|---------|---------|------|
| Change in emissions (%) | <50 | 50–90 | 90–98 | ~100 | 102–110 | 110–150 | >150 |

⁵ Aircraft emissions that affect global climate change include the direct effects from CO₂ and water (H₂O) emissions, the indirect changes in the distributions and concentrations of ozone and CH₄ as a consequence of NO_x emissions, the direct effects (and indirect effects on clouds) from aerosols and aerosol precursors, and the effects associated with condensation trails (contrails) and high-altitude (cirrus) clouds. Each of these emissions and effects has a varied residence time within the atmosphere; CO₂ has a residence time of hundreds of years, methane of decades, ozone on the order of months, water vapor on the order of weeks (except in the stratosphere, where it has a longer residence time), and contrails and cirrus clouds on the order of hours. Taken together, these individual effects act to further increase the warming effect of aviation relative to that associated with CO₂ alone, although the relative amount of this additional warming is still the subject of scientific study (Sausen et al., 2005; Wuebbles et al., 2007; Marais et al., 2008).

Air-Quality Emissions

The impact of alternative fuels on air quality is estimated through analysis of the emissions that contribute to $PM_{2.5}$. The fuel-comparison metric is based on the number of sources (primary, secondary from NO_x , or secondary from SO_x) that could increase or decrease PM emissions by more than 10 percent, as shown in Table 2.7.

Merit for Aviation Use

Alternative fuels that are appropriate for use in aircraft may also be suitable for ground transportation. Whether an available alternative fuel is used in commercial aviation depends on the relative advantages that the fuel offers to aviation over other uses and at what cost. We lump these factors together into a single metric termed *merit for aviation use*. The factors considered in this report do not represent an all-encompassing list, as the dynamics of adoption of alternative energy sources in any particular sector will ultimately be influenced by a large number of factors, some of which are beyond the scope of this study (for example, use of the feedstock or fuel outside of the transportation sector).

Specific properties of liquid fuels make them more attractive for certain applications. Fuels with a high cetane number improve the performance of diesel engines; fuels with a high octane number improve the performance of spark-ignition engines.⁶ We would expect candidate alternative fuels with high cetane or octane numbers to carry a price premium when targeted for use in ground transportation, where these performance benefits will be realized.

Specific energy is a key property of a potential alternative jet fuel (Hileman and Donohoo, 2009). If the specific energy of the fuel is less than that of Jet A, then the use of the alternative fuel would incur a fuel-economy penalty for aviation. Aircraft use a certain percentage of their fuel energy to reach cruise altitude, and heavier aircraft require more fuel energy to reach cruise altitude; they also use more fuel during cruise.⁷ If an aircraft is using a fuel containing less energy per unit mass than Jet A, then that aircraft must be heavier than the Jet A–using aircraft if it is to hold the same amount of energy. Consequently, more energy would be required for takeoff and during cruise. Ground transportation does not suffer such a significant penalty because fuel constitutes a relatively small percentage of the vehicle weight and because a ground vehicle does not expend large amounts of energy overcoming gravity. Furthermore, because ground transportation does not have a strict requirement of traveling set

Table 2.7
Air-Quality Ratings, Based on Number of Sources (primary, secondary from NO_x , secondary from SO_x), That Increase or Decrease Particulate-Matter Emissions by More Than 10 Percent

| Rating | +++ | ++ | + | ○ | - | -- | --- |
|---------------------------------------|-----------------------|--------------------------|--------------------------|-----------|--------------------------|--------------------------|-----------------------|
| Change in $PM_{2.5}$ emission sources | Increase in all three | Increase in two of three | Increase in one of three | No change | Decrease in one of three | Decrease in two of three | Decrease in all three |

⁶ The cetane number is a measure of the delay prior to ignition after injection of the fuel into a cylinder; fuels with higher cetane numbers have a shorter delay of ignition. Octane number is a measure of the resistance of a fuel to preignition, or knocking; fuels with higher octane numbers are more resistant to knocking.

⁷ According to Raymer (1999), a typical commercial aircraft uses roughly 4.5 percent of its total fuel consumption to reach cruise altitude.

distances between refueling, reduced specific energy and energy density are not as critical. In particular, alcohol fuels have a significantly reduced energy density relative to Jet A. Thus, the use of alcohol fuels in aircraft would entail greater energy consumption than using conventional kerosene-based fuels. The result is a decrease in GHG benefits, to the degree that a GHG reduction is realized, as compared to automotive applications of alcohols.

It has been speculated that an alternative fuel suitable for aviation (and ground-transportation) use would benefit from the tightly controlled fuel-distribution infrastructure that supports commercial aviation. However, if the finished fuel satisfies international standards and it is compatible with current engine technology (reciprocating or turbine), the structure of the distribution system should have little or no effect on the overall prospects of the fuel. This is especially the case with FT diesel and jet fuel, which may be suitable for distribution from the plant gate. If the fuel were incompatible with the existing pipeline infrastructure, having a limited number of fueling stations could be beneficial. However, the ten-year time horizon of this study limits viable fuels to those that are compatible with current aircraft and fueling systems.

For rating fuels, this metric takes on three values: A + rating indicates that the use of the fuel in jet aircraft is clearly more attractive, a – rating indicates that ground-transportation use is clearly more attractive, and a ○ rating indicates that available information is not sufficient to allow us to determine whether the fuel falls within one of the two preceding categories. In general, a ○ rating implies that the price premium, if any, for automotive versus aviation applications is likely to be small in the next decade.

Conventional Petroleum

The Benchmark Fuel: Jet A

The selection of a kerosene-based fuel as the jet-fuel standard was the result of a trade-off among aircraft operational characteristics, availability, and cost (Maurice et al., 2001). Initially, jet fuels were chosen because of availability, and both gasoline and kerosene were used. However, lighter fuels, such as gasoline, proved to be suboptimal. They would evaporate at altitude, leading to loss of fuel or vapor lock of engine components; they had poor lubricity, which caused wear of engine components; and their flammability created hazards on the ground (Chevron, 2004; Maurice et al., 2001). Kerosene-type jet fuels do not suffer from these drawbacks and have additional characteristics that favor their application in modern jet aircraft. In the United States, specifications for kerosene evolved by the 1960s to Jet A, which has been the dominant commercial jet fuel ever since.¹

Refining Jet A from Crude Oil

Almost all kerosene and Jet A has been made from conventional petroleum (also called *crude oil*). “As it comes out of the ground, crude oil can be as thin and light-colored as apple cider or as thick and black as melted tar” (Chevron, 1998). Thin, light crudes usually have lower densities, more of the volatile products that make up gasoline and kerosene, and lower concentrations of sulfur and nitrogen. These lower concentrations make them easier to refine. Thicker, heavier, darker crudes also can be and are refined to valuable, volatile, clean products by more-intense processing, but there are economic and environmental costs for the additional processing. For example, among the crude oils listed by BP (undated) and Chevron (undated), straight-run² kerosenes can vary in sulfur content from 0.01 to 0.98 percent, in aromatics from 7.7 to 28.4 percent, and in naphthalenes from 0.51 to 2.65 percent. In each case, the higher numbers would result in increased emissions of primary and secondary PM if the fuel were not further processed.

Crude oil is a mixture of many types of molecules. Each molecule consists of some configuration of carbon atoms and hydrogen atoms (a *hydrocarbon*) and may also contain other atoms, such as sulfur, nitrogen, oxygen, and metals. Individual molecules range from highly volatile compounds, such as CH₄ (the principal constituent of natural gas), to nonvolatile

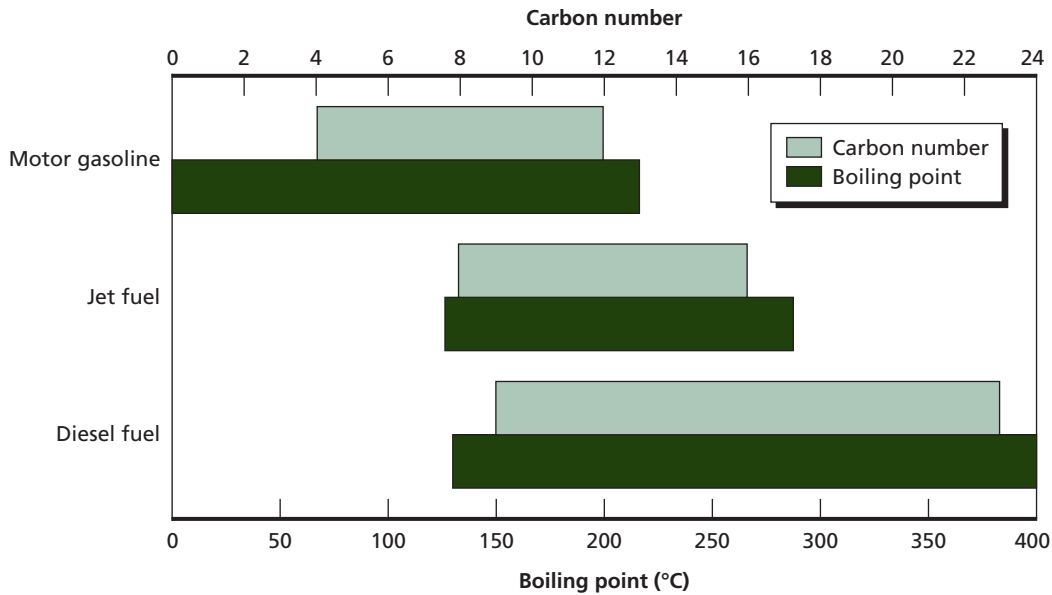
¹ Jet A, Jet A-1, and JP-8 are sufficiently similar that the metrics developed to compare alternative fuels apply equally to all three. Henceforth in this report, the term Jet A can be considered to cover also Jet A-1 and JP-8.

² When a jet fuel is distilled directly from crude oil, is blended with no other refinery products (except small amounts of additives), and undergoes no other refining except to treat contaminants, such as mercaptan sulfur, it is called a *straight-run fuel* and reflects the characteristics of the crude oil of its origin.

waxes, tars, and asphalts. The chemical and physical properties of individual hydrocarbon molecules depend on the number of carbon atoms in each molecule (*carbon number*) and the molecule's configuration—the way in which the carbon atoms are bonded to each other. In general, as the carbon number increases within a group of otherwise similar hydrocarbons, the boiling temperature increases (volatility decreases), the freezing temperature increases, the density (mass per unit volume) increases, the specific energy (energy per mass) decreases, and the energy density (energy per volume) increases. For a given carbon number, there are also systematic changes in moving from one configuration to another. For example, in shifting from six carbon atoms bounded in a row (a paraffin—in this case, normal hexane) to six carbon atoms bounded in a ring (an aromatic—in this case, benzene), the boiling temperature, freezing temperature, and density all increase while the specific energy decreases (see Chevron, 1998, for more background).

The first and most important step in refining crude oil is distillation, which separates molecules by boiling point to separate fractions that conform to the boiling-point specifications for different fuels.³ Figure 3.1 illustrates the boiling range and carbon numbers associated with typical transportation fuels. At the low-boiling point end, the distillation range of a typical jet fuel overlaps the boiling points of the less volatile components found in gasoline. At the higher-boiling point end, jet-fuel boiling points fall within the boiling range of diesel

Figure 3.1
Typical Distillation Ranges (Degrees C) and Carbon-Number Ranges for Fuels



SOURCES: The motor-gasoline and jet-fuel data are from Speight (2002, p. 158, Table 7.1). The diesel-fuel data are for number-2 diesel and were obtained from Chevron (1998).

NOTE: *Jet fuel* includes Jet A as well as other jet fuels, such as JP-8.

RAND TR554-3.1

³ Many nonvolatile molecules cannot be distilled at atmospheric pressure because heat decomposes them before they reach their boiling point. Some of those molecules can be distilled without decomposition at lower temperatures via vacuum distillation.

(distillate) fuel. In fact, if the fuel streams are appropriately treated to remove sulfur compounds, essentially all jet fuel could be used in the diesel-fuel pool after blending with other appropriate refinery streams to meet specifications. Further, the jet-fuel pool can be increased or decreased by shifting parts of the much larger gasoline- and diesel-fuel pools into or out of the narrower jet-fuel pool. The amount that is shifted depends on market demands and prices for the individual products.

Variability in Jet A Composition

The specifications that define Jet A provide for minimum acceptable properties, but the actual properties are governed by a statistical distribution that is attributable to the underlying variability in petroleum and variations that refineries use to produce jet fuel. According to the measurements of Shafer et al. (2006) on a broad sampling of jet fuel, a typical jet composition can be described as 20 percent normal paraffins, 40 percent isoparaffins, 20 percent naphthenes (a.k.a. cycloparaffins), and 20 percent aromatics.⁴ The specifications for Jet A set a maximum limit on total aromatic content of 25 percent.

Characterizing the variability of Jet A composition requires data describing fuels actually used by commercial aviation. The Coordinating Research Council (Taylor, 2009) has recently published comprehensive data on sulfur levels. The Defense Energy Support Center (DESC) conducts surveys of the quality of jet fuel for the U.S. military and publishes its findings in an annual report from its Petroleum Quality Information System, or PQIS (DESC, 1999–2006). The DESC survey data come from U.S. military bases located around the globe, including Europe and the Pacific. In our study, we assume that the statistics of JP-8, as derived from the DESC PQIS, also reflect the properties, other than sulfur levels, of commercial jet fuel. However, the extent to which DESC survey data pertain to commercial jet fuel is uncertain.

Current jet-fuel specifications (e.g., JP-8, Jet A, Jet A-1) limit sulfur to a maximum of 3,000 parts per million (ppm), but the actual level of sulfur in jet fuel is often much lower than this value. The Coordinating Research Council survey of refiners shows that jet-fuel sulfur content varies by location and changes with time. For the United States, sulfur levels in 2006 and 2007 averaged 709 and 677 ppm, respectively. The DESC survey of JP-8 procured in the United States in 2006 and 2007 show average sulfur levels of 700 ppm (Taylor, 2009).

The variations in JP-8 that DESC has recorded have been used to examine the variability in jet-fuel properties. The DESC data reveal that 90 percent of fuel samples (weighted by volume) are within ± 0.5 percent variation in specific energy from the mean, and the mean value is 0.9 percent higher than the minimum specification (Hileman and Donohoo, 2009). This variation in specific energy leads to roughly a ± 0.5 -percent variation (at the 90-percent confidence interval) in fuel weight consumed. Considering accompanying changes in fuel composition (in the form of percentage of hydrogen content), we estimate roughly a ± 1 -percent variation in CO₂-emission index (the amount of CO₂ per unit mass of fuel combusted) and a ± 3 -percent variation in water-emission index.

Well-to-Wake Greenhouse-Gas Emissions

The life-cycle GHG emissions from the production and combustion of jet fuel created from conventional crude are about 87.5 grams (g) CO₂e/MJ (see “Well-to-Wake Greenhouse-Gas

⁴ See Chevron (2004, Appendix B) for additional information about jet-fuel composition.

Emissions” in Chapter Two).⁵ Combustion CO₂ emissions dominate at 73.2 g CO₂/MJ. We estimate that combustion emissions for about 90 percent of Jet A falls within 1 percent of this figure. There is, however, considerable variation in the well-to-tank estimate of 14.3 g CO₂e/MJ (NETL, 2008b). Our analysis also indicates a variation of up to 7 percent based primarily on the quality of the crude oil and how the jet fuel is refined. Specifically, the production of purely straight-run jet fuel in one extreme, and the production of jet fuel through various hydroprocessing steps in the other, will cause WTW GHG emissions to range from a factor of 0.95 to 1.07 of those of the baseline case, respectively. A summary of the life-cycle GHG emissions for many of the fuels considered in this study appears in Appendix B.

Consumption of Petroleum Products

In 2006, world consumption of liquid fuels was about 85 million bpd (EIA, 2009e, Table 3).⁶ Globally, this demand was met through the production of 82 million bpd of conventional crude oil and products, 1.8 million bpd of heavy oil and bitumen, and about 0.9 million bpd of other liquids—primarily alcohol fuels produced from grain and sugar, but also small amounts of liquids derived from coal and natural gas.⁷

In the United States, the consumption of petroleum products averaged 20.7 million bpd in 2007, of which about 7.5 million bpd were derived from domestic production and about 13.2 million bpd were derived from imported crude oil or imported petroleum products.

World consumption of jet fuel is estimated at about 5 million bpd, of which 1.6 million bpd are consumed in the United States (EIA, 2008b, Table 5.11).⁸ Since jet fuel amounts to only about 8 percent of oil-industry production, petroleum refining and marketing are more heavily influenced by larger-volume products, such as motor gasoline, diesel fuel, and distillate heating fuel. For comparison, the United States consumed 4.2 million bpd of distillate (diesel) and 9.3 million bpd of motor gasoline in 2007.⁹

In an analysis that was performed prior to the recent spike in oil prices and financial turmoil, EIA (2008a) projected that U.S. jet-fuel use would grow to approximately 1.9 million barrels of jet fuel per day of consumption in 2017. In a more recent analysis based on fairly high oil prices, EIA lowered its 2017 projection to 1.6 million barrels of jet fuel per day (EIA, 2009a,

⁵ The GHG emissions of conventional-crude recovery adopted in this study were based on the results in the recent NETL study on the life-cycle GHG emissions of petroleum-based transportation fuels, including kerosene-based jet fuel (NETL, 2008b). Specifically, the crude-oil feedstock assumed in the NETL study was based on the 2005 mix of crude input to U.S. refineries, including conventional crude oil from domestic and foreign suppliers, syncrude from oil sands, and blended bitumen from Canada.

⁶ A barrel is the customary unit of volume used in the U.S. oil industry; it is defined as 42 U.S. gallons.

⁷ Natural-gas liquids are those hydrocarbons in natural gas that are separated as liquids during gas processing. Generally, such liquids consist of propane and heavier hydrocarbons and are commonly referred to as *lease condensate*, *natural gasoline*, or *liquefied petroleum gases*. In general, the operations that occur in a petroleum refinery cause the net volume of the products to exceed the net volume of the inputs. This increase is referred to as *refinery gain* and accounts for most of the difference in liquid consumption and production.

⁸ Seventeen thousand barrels per day of specially formulated gasoline, known as *aviation gasoline*, or AvGas, were also supplied within the United States during this time. Since it is such a small component of the fuel supply for commercial aviation, this report does not consider possible alternatives to AvGas.

⁹ Distillate fuel is used for transportation, home heating, agriculture, construction, industry, commercial, and military purposes. Within the United States in 2004, 56 percent of distillate fuel was used for highway use and 9.9 percent was used for rail or off-highway transportation use (EIA, 2008e).

base case). Whether or how much jet-fuel consumption in the United States will grow is uncertain. In the next decade, consumption of jet fuel will depend on demand for air transportation and the rate at which more-energy-efficient procedures and equipment are introduced and implemented in the commercial aviation sector.

Ultralow-Sulfur Jet A

The impetus for considering a ULS jet fuel is improvement to air quality. ULS standards have already been put in place internationally for diesel fuel. For example, EPA (2007c) has recently required that highway diesel fuel be ULS (at or below 15 ppm). Offroad diesel fuel will be required to be ULS in 2010, and locomotives and marine fuels will be required to be ULS in 2012. In Japan, refiners voluntarily reduced diesel-fuel sulfur content to 50 ppm in 2003 and will further reduce it to 10 ppm in 2007 (“Fuel Regulations,” 2006). Within the EU, sulfur-free (below 10 ppm by weight) diesel came onto the market in 2005, and, by 2009, all on-road diesel must meet the sulfur-free standard (European Commission, 2007).

For the purposes of our analysis, we assume that ULS jet fuel is a Jet A-type fuel containing a maximum of 15 ppm (0.0015 percent) of sulfur, which is the same as the sulfur specification for diesel used in ground transportation.¹⁰ We have selected this deep level of sulfur reduction to probe the benefits and issues associated with a major decrease in the sulfur levels of jet fuels. Intermediate levels of reduction for jet fuel—for example, to 30 or 50 ppm—may turn out to yield much of the local air-quality benefits of ULS jet fuel at lower costs and with reduced adverse impacts on aircraft operability and GHG emissions. Elucidating this broader issue is beyond the scope of the research underlying this report.¹¹

Producing ULS jet fuel requires processing at high temperature and pressure in the presence of hydrogen and a catalyst. Hydrogen reacts with sulfur in the fuel to form gaseous hydrogen sulfide, which is separated from the fuel.¹² This process of hydrodesulfurization (HDS) may result in other fuel modifications, such as reduction of naphthalenes, aromatics, and other contaminants, that may yield reduced primary-PM emissions during aircraft operations (see “Air-Quality Emissions” later in this section).

Because many refineries in the United States are now fully equipped to produce a ULS diesel, small amounts of ULS Jet A are being sold. Refiners responding to the Coordinating Research Council survey reported that, for jet fuel produced between September 2005 and February 2008, between 3.4 and 5.4 percent of it was ULS jet fuel (Taylor, 2009).

¹⁰ The ULS specification for diesel automotive fuel establishes 15 ppm as a maximum. To avoid exceeding this specification, the average sulfur level of delivered automotive diesel is somewhat lower.

¹¹ Note that the principal motivation for setting the sulfur standard for automotive diesel fuel at a maximum of 15 ppm was maintaining the performance of catalytic converters that are required on all new diesel engines. Since catalytic converters are not viewed as viable for aircraft turbines, we would expect that a full cost-benefit analysis of the sulfur standard for jet fuel would suggest a significantly higher level for jet fuel.

¹² Much of the sulfur removed during refining is converted to sulfuric acid, which can be marketed as a commodity chemical.

Compatibility and Operability in Current Systems

The main compatibility and operability concerns in switching to ULS fuels are energy density, lubricity, fuel leakage due to reduced elastomeric swelling, and pipeline compatibility.

Within diesel fuels, the HDS process results in a small loss in volumetric fuel economy because of the approximately 1-percent loss in energy density (EPA, 2000b, 2006; BP, 2006; Exxon Mobil Corporation, undated; Chevron, 2007). This decrease was observed for ULS diesel fuels, and it is expected that a ULS jet fuel would have a similar loss. In Hileman and Donohoo (2009), relationships of fuel energy density as a function of hydrogen content were used to estimate the impact of deep HDS on the specific energy of jet fuel. A 1-percent loss in energy density corresponds to a change from 34.8 MJ/L to 34.4 MJ/L. They assumed that a desulfurized jet fuel would follow the trends for hydrocarbons derived from the PQIS database; thus, a 1-percent change in energy density should be accompanied by an increase in mean hydrogen content from 13.8 percent to 14.0 percent and a 0.3-percent increase in mean specific energy. The net result is that 1 percent more fuel volume, but 0.3 percent less fuel weight, is required to fly a typical distance. These estimates take into account the reduction in fuel consumption that would be associated with reduced aircraft weight.

HDS can result in a reduction in fuel lubricity, as it results in the removal of the compounds that provide jet fuel its natural lubricity. However, as noted by Chevron (2004, p. 6),

low sulfur or aromatics levels in jet fuel are not, per se, signs of inadequate lubricity. The boundary lubricity of jet fuel cannot be predicted from bulk physical or chemical properties, it can only be measured in a specially designed test apparatus. Fuels with similar sulfur and aromatics content can have different lubricity.

Further, a near-zero-sulfur, synthetic fuel has been made with similar lubricity properties to conventional jet fuel without the use of fuel additives (Moses, Wilson, and Roets, 2003).

If the lubricity of a ULS jet fuel were found to be less than desired, lubricity additives may be added to the fuel such that the end user does not notice a difference, such as has been done with ULS diesel fuel (BP, 2006; Exxon Mobil Corporation, undated; Chevron, 2007). The additives contain esters (10–50 ppm) or fatty acids (20–250 ppm) (Chevron, 2007). For example, all of Exxon's diesel fuels have incorporated lubricity additives since 2005 (Exxon Mobil Corporation, undated). These fuels all meet the diesel-fuel standard ASTM D975 (ASTM, 2007a). A framework for lubricity additives already exists in aviation; U.S. military standards for jet propellants 4, 5, and 8 (JP-4, JP-5, and JP-8) require a corrosion inhibitor/lubricity improver; lubricity and corrosion inhibitors can also be added to Jet A-1 (Chevron, 2004). For this purpose, the U.S. military has approved RPS 613, produced by Champion Technologies, and DCI-4A, by Octel Starreon, which are also used in civil aviation (DoD, 2006; Moses, Wilson, and Roets, 2003). However, additives usually have not been used in Jet A (Chevron, 2004).

The use of ULS fuel may lead to a reduction in certain maintenance costs (Edwards et al., 2004). A low-sulfur fuel may have increased thermal stability, which would reduce the formation of corrosive deposits, possibly leading to increased component life (EPA, 2000a). The reduced aromatic content of a ULS fuel could lead to reduced combustor-liner temperatures and increased combustor life. Moses and Karpovich (1988) conducted a set of combustor experiments with fuels of varying hydrogen contents, and they found that a 1-percent decrease in fuel-hydrogen content resulted in a combustor-life reduction of between 20 and 80 percent

(ULS fuels have slightly higher hydrogen contents). These results are based on a reduced-fidelity model for older combustors, but the trends should extend to newer designs. The reason for this increase in life is that the wall temperature of the combustor is influenced by the emitted radiant energy and the formation of soot in the primary zone of the combustor. Both of these are related to hydrogen content (Martel and Angello, 1973; Schirmer and Quigg, 1965; Lefebvre, 1984; Moses and Karpovich, 1988). It thus appears that a higher-hydrogen fuel such as would result from the HDS process may lead to increased combustor life.

At present, available testing data are insufficient to provide a foundation for reliable quantitative estimates of the potential impact of ULS Jet A fuel on maintenance costs. Specifically, further study is required to determine whether there is an appreciable positive or negative impact.

Current Jet A, with its relatively high sulfur content, causes problems for pipeline operators. They must use extra steps to flush out sulfur contamination after shipping high-sulfur fuels, such as Jet A, to avoid contamination of low-sulfur fuels, such as ULS diesel (e.g., EIA, 2001). A transfer to ULS Jet A would ease this problem and enable more-efficient pipeline-system use, providing a benefit that might be passed to aviation consumers. ULS jet fuel may also benefit the U.S. Department of Defense (DoD) in its goal of reducing the number of different fuels required during military operations, and it could potentially lead to lower overall procurement and maintenance costs. The U.S. Army uses JP-8 in its diesel equipment, but new diesel engines are designed for ULS diesel fuels. These engines will encounter problems if operated on higher-sulfur fuels. To use current JP-8, which has ~700 ppm sulfur content, the U.S. Army may need to special order diesel engines that can tolerate higher sulfur levels. However, if Jet A were ULS, then JP-8 would likely become ULS as well, and then off-the-shelf diesel engines could be used.

The specification for Jet A, ASTM D1655 (ASTM, 2007b) has a maximum limit for fuel sulfur content, but not a minimum limit. As such, a ULS jet fuel falls within the current specification outlined by ASTM D1655. As previously noted, the degree of hydrotreatment that is necessary to achieve a ULS fuel can affect lubricity. The D1655 standard does not have a lubricity requirement, and lubricity issues can be overcome through the use of appropriate fuel additives.

Because additives may have to be used with ULS jet fuel to meet lubricity requirements and because some seals may need to be replaced due to the potential loss of fuel aromatic content, ULS Jet A is assigned a – rating for compatibility in current systems.

Production Potential

HDS technology is well understood and widely available to refiners in the United States and other locations throughout the world that have ULS diesel standards. U.S. refiners would have to invest in additional desulfurization capacity, which may limit availability initially but should not pose any long-term supply issues. Therefore, ULS Jet A receives a +++ rating for production potential. Because ULS Jet A is not a new source of fuel and it will not augment the current supply, each barrel of ULS Jet A would replace an existing barrel of conventional Jet A.

Production Cost

The additional marginal cost of producing and distributing ULS diesel fuel from then-standard diesel fuel was estimated during rule-making at an additional \$0.054 per gallon. This estimated cost is comprised of a refinery desulfurization cost of \$0.041 per gallon, a distribution

cost of \$0.011 per gallon, and lubricity additives with costs of \$0.002 per gallon (EPA, 2000a; EIA, 2001).

Recently, EPA (2006, p. 1) reiterated that “[ULS] diesel fuel costs an additional \$0.04 to \$0.05 per gallon to produce and distribute.” Given the similarities between jet fuel and diesel fuel, the experience gained in producing ULS diesel fuel is relevant. This small increase in costs is negligible compared to the volatility of jet-fuel prices and warrants a ○ rating for production costs.

Well-to-Wake Greenhouse-Gas Emissions

Producing the hydrogen gas needed for processing and the processing necessary for desulfurization require additional energy in comparison to conventional Jet A, resulting in additional CO₂ emissions. These additional CO₂ emissions would be offset by a small decrease in combustion CO₂ emissions. Overall, WTW GHG emissions are estimated to be 89 g CO₂e/MJ, which are about 2 percent higher than those from conventional, higher-sulfur jet fuels (see Appendix B). This small increase in WTW GHG emissions warrants a – rating.

The near elimination of sulfur emissions would eliminate emissions that have a cooling effect, resulting in an uncertain net increase in global warming due to ULS fuel use. Ongoing research within the PARTNER Center of Excellence is examining the potential impact of using a ULS jet fuel on global climate change (PARTNER, undated).

Air-Quality Emissions

With a ULS jet fuel, SO_x emissions would be virtually eliminated, which should result in a dramatic reduction in secondary PM from aviation.¹³ Overall, volatile primary-PM emissions should be reduced considerably due to the reduced fuel-sulfur content. These are both benefits to air quality. Because of inadequate data, we have not developed a quantitative estimate of the impact of fuel chemistry changes on the formation of PMNV (i.e., soot). The impact of HDS should be increased fuel-hydrogen content with a potential reduction in naphthalene and aromatic-compound content and potentially reduced soot production during combustion. ULS Jet A receives a ++ rating for air quality, as the emissions of both primary PM and secondary PM from SO_x would be reduced by more than 10 percent as compared to the baseline fuel, Jet A. Ongoing research within the PARTNER Center of Excellence is examining the potential impact of using a ULS jet fuel on surface-air quality.

Readiness of Technology

The technology is ready now and is being used to create ULS diesel for ground transportation and small amounts of ULS jet fuel; therefore, the FRL is +++.

Merit for Aviation Use

ULS fuel standards allow the use of high-performance catalytic converters on gasoline- and diesel-powered automobiles and trucks. Comparing a gallon of diesel to a gallon of Jet A, the combination of fuel standards and catalytic converters causes the use of ULS diesel fuel to yield air-quality benefits that are much larger than those that would be obtained by the use of ULS jet fuel in aircraft. Also, through HDS, ULS diesel fuel should have a slightly lower aro-

¹³ The secondary-PM reduction will be less than the SO_x reduction because more atmospheric ammonia will be available to react with aviation NO_x emissions.

matic content and thus a higher cetane number, which is advantageous when used with diesel engines. But cetane number is irrelevant for gas-turbine applications. If HDS capacity were limited, it would be environmentally advantageous to direct ULS fuels to ground transportation. However, provided that they receive sufficient advance notice, there is no inherent reason that petroleum refiners cannot build adequate HDS capacity for ULS Jet A production, and thus a neutral value, ○, is assigned.

Unconventional Petroleum

Jet A from Canadian Oil Sands or Venezuelan Very Heavy Oils

Oil sands are deposits of bitumen in sand or porous rock. Bitumen is a mixture of hydrocarbons that is very dense and viscous. The majority of high-grade Canadian oil sands are in the province of Alberta. The established recoverable reserve base in Alberta is estimated at 174 billion barrels. Bitumen may be recovered from oil sands via surface mining or in situ extraction. Surface mining is usually limited to oil-sand deposits that are relatively close to the surface. After being physically separated from the sands, the bitumen is transported to a central facility for upgrading. In in situ extraction, steam is pumped into the oil-sand deposit, thereby reducing the viscosity of the bitumen so that it can flow to wells and be recovered in much the same manner as is conventional petroleum. Current production of oil sands is approximately 1.3 million bpd. To date, approximately two-thirds of Canadian oil-sand production has been through surface mining, but new capacity additions will rely more on the in situ approach. Appendix A provides further detail.¹

Oils with a density greater than the density of water are known as VHOs. VHOs are viscous and dense and have higher concentrations of oxygen, nitrogen, and sulfur than does light crude oil. Venezuela's VHOs are similar in chemical and physical characteristics to Canadian bitumen and, once recovered, are processed in similar ways. Some methods for recovery are similar to in situ production methods for oil sands. Venezuela holds an estimated 1.2 trillion barrels of VHO resources in place, of which an estimated 200 billion barrels may be recoverable VHO. Venezuela's proven oil reserves, which include conventional, heavy, and very heavy oil, are estimated to be 80 billion barrels (EIA, 2007a). Current production of VHOs from Venezuela is about 0.5 million bpd.

Compatibility and Operability in Current Systems

Jet A produced from oil sands or VHOs currently meets all specifications for Jet A; therefore, it receives a neutral rating for compatibility.

Production Potential

So long as world oil prices exceed \$50 per barrel, we anticipate continued investment directed at increasing production from oil sands in Alberta (Toman et al., 2008). By 2017, bitumen production from oil sands in Alberta will likely be between 2 million and 3 million bpd. For

¹ The United States possesses oil-sand resources. These are fundamentally different from those in Canada. Currently, there is little interest in developing these resources. Refer to Appendix A for further discussion on this topic.

Venezuela's VHOs, production growth is uncertain as a result of recent renationalization of the sector.

In modern refineries, these resources should yield a product slate with a jet-fuel fraction that is similar in magnitude to that associated with refining conventional crude oils. Accordingly, up to several hundred thousand barrels per day of jet-fuel demand will be met by Canadian oil sands and Venezuelan VHOs; these two resources combined, therefore, receive a production potential rating of +.

Production Cost

From published estimates and models of production costs for Canadian oil sands (either bitumen or synthetic crude oil), we anticipate that world crude-oil prices in excess of \$50 per barrel (2005 dollars) are sufficient to motivate the investment required to develop additional production capacity. Similar estimates are not available for Venezuelan VHO. However, since extraction techniques are similar for oil sands and VHO, it is reasonable to assume that its production will also be competitive with world oil prices in a similar range.

Assuming that synthetic crude oil from oil sands is competitive with low-sulfur light crude, such as WTI, selling between \$40 and \$50 per barrel, and assuming per-barrel refining costs ranging from \$10 to \$15 per barrel, we estimate production costs of jet fuel from oil sands to range from \$1.19 to \$1.55 per gallon. As a result, jet fuel from oil sands receives a cost rating of ○/+.

Well-to-Wake Greenhouse-Gas Emissions

During combustion, there should be no significant difference in GHG emissions between oil sand-derived Jet A and conventional Jet A. But there are major differences in the emissions associated with producing Jet A from oil sands and conventional Jet A.

Both surface mining and in situ extraction of oil sands are energy-intensive processes, and the added energy that is required for extraction leads to increased CO₂ emissions. The life-cycle GHG emissions for the extraction and upgrading of bitumen to syncrude are estimated as 16 g CO₂e/MJ for surface-mining technology and 26 g CO₂e/MJ for in situ methods. For reference, about 6 g CO₂e/MJ are required to extract conventional petroleum from the ground, on average. The recovery of bitumen using surface mining, its upgrading to syncrude, and subsequent refining to jet fuel result in WTW GHG emissions that are approximately 1.12 times greater than those of conventional Jet A. When a more energy-intensive in situ production method is used to recover bitumen, the WTW GHG emissions are about 1.24 times greater than those of conventional Jet A (see Appendix B and Wong, 2008). Apportioning according to the Alberta Energy and Utilities Board's (2007) forecast of 56-percent crude bitumen production from surface mining, and the remaining 44 percent from in situ production, the WTW GHG emissions from the production and combustion of jet fuel from Canadian oil sands are about 1.17 times those of baseline conventional jet fuel. Considering recent analyses by RAND (Toman et al., 2008) and the Pembina Institute (McCulloch, Reynolds, and Wong, 2006), an uncertainty of about 5 percent should be associated with this estimate. The life-cycle GHG emissions for this pathway are 103 g CO₂e/MJ. Hence, oil sand-derived Jet A receives a --- rating.

Air-Quality Emissions

There should be no differences between using petroleum-derived Jet A and Jet A derived from either oil sands or VHO; therefore, oil sand/VHO Jet A receives a neutral rating. Although

not a subject of our research, we note that the local and regional environmental impacts associated with oil-sand and VHO production generally exceed those of conventional-oil recovery operations.

Readiness of Technology

The technology is in widespread commercial use; therefore, oil-sand Jet A receives a +++ rating.

Merit for Aviation Use

All uses have equal merit; therefore, oil-sand Jet A receives a neutral rating.

Jet A from Oil Shale

Oil shale is a consolidated (solid) sedimentary rock of mostly carbonate and silicate minerals containing a solid organic material called *kerogen*. When the kerogen is heated sufficiently, in a process known as *retorting*, it decomposes to form an oil that can be distilled like conventional petroleum. The retorting can be performed either after the kerogen has been surface mined or through an in situ process in which the kerogen is heated in the ground and the shale oil is pumped to the surface. In either case, the resulting shale oil is well suited to the production of transportation fuels, including middle-distillate fuels, such as diesel fuel, kerosene, and jet fuel.

The oil-shale resource in the United States is very large and highly concentrated in the Green River Formation, which covers parts of Colorado, Utah, and Wyoming. Recent estimates place the range of recoverable resources at between 500 billion and 1.1 trillion barrels. The midpoint of this range, 800 billion barrels, is three times the size of the proven oil reserves of Saudi Arabia (Bartis, LaTourrette, et al., 2005). The most desirable portion of the oil-shale resource base lies in a small area in western Colorado known as the Piceance Basin.

As a consequence of the oil-price increases associated with the oil embargo that occurred during the winter of 1973 and 1974 and the Iranian revolution in 1979, the U.S. military and various governmental agencies conducted extensive research and development on oil shale; as a result, substantial quantities of oil shale–derived jet fuel were produced (e.g., Solash et al., 1978; Sikonia et al., 1982; Reif, Schwedock, and Schneider, 1982; Moore et al., 1982; Gardner and Whyte, 1990; Bartis, LaTourrette, et al., 2005; Edwards, 2005; Andrews, 2006). As a consequence of this work, oil shale is allowed as a feedstock for the production of jet fuel for both commercial aviation and the U.S. military (ASTM, 2007b; DoD, 2008). Interest in oil shale–derived jet fuel diminished considerably when the price of oil collapsed during the 1980s. As with other alternative fuel sources, recent high oil prices have resulted in renewed interest in these resources.

Compatibility and Operability in Current Systems

The production of jet fuel from shale oil using high-temperature retorting (either surface or in situ) methods requires hydrotreatment to reduce olefin content and organic nitrogen compounds (~2 percent by weight) (Piper and Heistand, 1996); the resulting fuel has moderate levels of aromatic compounds (10 to 25 percent) and should not pose either lubricity or compatibility issues (Harney, 1983). Such fuels are already approved for both commercial and mili-

tary aviation. Shale oil–derived jet fuel appears to have excellent storage stability; fuels from surface retorting still meet the JP-8 specification after more than 20 years of storage (Edwards, 2005).

Limited information is publicly available regarding the properties of jet fuel produced from low-temperature in situ methods, such as Shell’s ICP. A sample provided for DoD Tri-Service evaluation showed low aromatic (about 3 percent) and sulfur (less than 5 ppm) content (Chang et al., 2008; O’Connor, 2009). This sample underwent hydrotreating but not extensive processing, according to Shell. The aromatic content of the refined fuel may not be sufficient to ensure proper elastomer swell in older aircraft (see discussion on p. 38). To ensure adequate lubricity, additives may be required (Gardner and Whyte, 1990).

Because of the potential need for lubricity additives and potential incompatibility with aircraft fitted with nitrile-rubber seals, oil shale (considering jet fuel derived from surface retorting and low-temperature in situ methods) receives a compatibility rating of –/○.

Production Potential

The development of the U.S. oil-shale resource was called for in the Energy Policy Act of 2005 (Pub. L. No. 109-58). In December 2006, the Bureau of Land Management (BLM) within the U.S. Department of the Interior issued small lease tracts in Colorado to Shell, Chevron, and EGL Resources. The purpose of the leases was to conduct research, development, and demonstration (RD&D) of in situ methods for producing fuels from oil shale. In April 2007, BLM awarded an additional RD&D lease in Utah to Oil Shale Exploration Company, which seeks to mine and surface-retort oil shale. In November 2008, BLM announced its intent to make available for commercial leasing nearly 2 million acres of federal lands bearing oil shale (BLM, 2008b). The Department of the Interior also published regulations that would govern the commercial leasing of oil-shale lands (43 C.F.R. 3900, 3910, 3920, 3930). However, when or even whether these regulations will be implemented remains uncertain.

Ultimately, oil-shale resources in the United States might meet a significant portion (10 to 20 percent) of U.S. demand for liquid fuels. But, because oil-shale development currently is at the laboratory and pilot-plant stages, it is unlikely that significant amounts of Jet A from shale oil would be produced within the next ten years (Bartis, LaTourrette, et al., 2005). For this reason, oil shale receives a production potential rating of ——. When produced, shale oil would enter the general market for light crude, of which a portion can be expected to be refined into jet fuel, based on market demands.

Production Cost

Since no U.S. commercial plants producing shale oil exist, estimates of costs of production are extremely uncertain. Like oil sands, oil shale may be surface mined or produced in situ. Bartis, LaTourrette, et al. (2005) derived estimates for the costs of production of shale oil via surface mining and retorting. These estimates range from \$70 to \$95 per barrel of shale oil produced (2005 dollars). With scale and production experience, the price per barrel should decrease from this level. No independent estimates for the cost of production of shale oil via in situ retorting exist. Shell has publicly stated that its in situ retorting process (known as the Shell ICP) can yield “high quality transportation fuels that are estimated to be economical at oil prices in the mid-\$20s” per barrel (Fletcher, 2005a, 2005b). From past experience, currently estimated costs of in situ extraction of oil shale are likely to rise as more site-specific knowledge is obtained and as Shell and others continue in the design process (Morrow, Phillips, and Myers, 1981).

Given current uncertainties regarding the technical viability of in situ oil-shale extraction, we are unable to assign a single cost rating to oil shale. Rather, we assign a range, with ○ reflecting successful development of in situ methods and — reflecting reliance on surface mining and retorting.

Well-to-Wake Greenhouse-Gas Emissions

The GHG emissions that result from shale-oil recovery depend strongly on the technology used for that recovery. The analysis in this report focused on the Shell ICP.² The extraction of shale oil from the in situ electric heating of oil shale requires a significant amount of energy and consequently results in higher GHG emissions than the recovery of conventional crude oil. The GHG emissions produced during in situ shale-oil extraction are approximately 41 g/MJ as compared to approximately 26 g/MJ for in situ extraction of bitumen from oil sands. This high level of GHG emissions is slightly offset by the lower emissions associated with refining oil shale. In particular, shale oil is lighter, contains almost no heavy ends, and is therefore of higher quality and requires less refining energy than the average crude received by U.S. refineries (3 g/MJ versus 6 g/MJ). Overall, the WTW GHG emissions of Jet A from oil shale are estimated to be within a factor of 1.0 and 1.6 times those of conventional jet fuel. Where Jet A from oil shale falls within this range depends on the design of the extraction and processing facility, including whether electric power is used for process heating; how power is generated; how much useful co-product, if any, is produced; and whether the extraction and processing operations employ capture and sequestration of CO₂ emissions. Considering this broad range, oil shale merits a WTW GHG rating of —/○.

Air-Quality Emissions

The severe hydrotreatment that is necessary to produce a jet fuel from shale oil will likely result in fuel sulfur levels of less than 50 ppm (Harney, 1983). If the jet-fuel sample provided by Shell for triservice evaluation is typical of what would be commercially produced, jet fuel derived via the Shell ICP will also have low aromatic content. Because it is low in both sulfur and aromatic content, the combustion of shale oil-derived jet fuel that is derived using the Shell ICP would have reduced emissions of both primary PM and SO_x emissions. Depending on the engine power setting, Chang et al. (2008) measured a 50- to 75-percent reduction in the number of primary-PM particles from a helicopter turbine engine when operating on JP-8 derived using the Shell ICP. Based on the variability of aromatic content in jet fuels produced by alternative retorting and refining schemes, the air-quality metric ranges from + to ++.

Readiness of Technology

At present, oil-shale technology is at the laboratory and pilot-plant stage of development. Based on analyses presented by Bartis, LaTourrette, et al. (2005), initial commercial production of

² Surface retorting operations generally result in higher GHG emissions than would the in situ retorting process, as the former takes place at higher temperatures (up to 750 degrees Celsius), at which carbonate minerals within the oil shale start to decompose, releasing CO₂. (Typical oil shale from the Green River Formation is composed of 23 percent dolomite, a calcium-magnesium bicarbonate, and 16 percent calcite, which is calcium carbonate. The decomposition temperature of calcite is about 620–675 degrees Celsius, and dolomite decomposes at around 565 degrees Celsius.) On the other hand, Shell's ICP takes place at lower temperatures of about 340–400 degrees Celsius. According to a recent analysis, the production of oil from shale using the Alberta Taciuk Process, a surface retorting process, can result in GHG emissions of between 1.2 and about 3 times greater than those from the production of shale oil using the Shell ICP (Brandt, 2007, 2008).

shale oil is at least 12 to 16 years into the future. Moreover, full-scale production may be limited by environmental constraints, especially if the only option available would be mining and surface retorting. The principal environmental issues associated with oil-shale development include impacts on land use and existing ecosystems, the limited availability of water in the areas of Colorado holding the richest oil-shale deposits, the viability of GHG-management options and spent-shale disposal, and the control of air emissions from multiple operations occurring within the Piceance Basin.

The technological barriers and yet-to-be-resolved environmental issues associated with Jet A production from oil shale merit a — FRL rating.

Merit for Aviation Use

All uses have equal merit; therefore, shale-oil Jet A receives a neutral rating.

Fischer-Tropsch Synthetic Fuels

This chapter covers jet fuels produced using FT synthesis. The FT approach provides a means of producing a slate of liquid fuels, including jet fuel, from various carbonaceous feedstocks, of which the most relevant are natural gas, coal, and biomass. All jet fuels produced using FT synthesis have similar characteristics, regardless of which feedstock is used. The small variations in FT jet-fuel properties that might occur are primarily associated with the operating conditions (e.g., catalyst, temperature, and pressure) within the synthesis reactors and how the direct products of the synthesis are treated and processed. Since feedstock choice does not drive fuel properties, FT jet fuels share common characteristics with regard to compatibility with existing infrastructure and aircraft, aircraft emissions, and their relative merit for use in aviation. Feedstock choice, however, does have a strong influence on production potential, production cost, life-cycle GHG emissions, and technology readiness.

Common Characteristics

The Fischer-Tropsch Synthesis

German researchers Franz Fischer and Hans Tropsch developed the method bearing their names in 1923 as a method for making liquid fuels from coal. The FT process has four main steps. The first step is the creation of synthesis gas, which is a mixture of hydrogen and carbon monoxide. When natural gas is the feedstock, this step can be accomplished by one of two well-established commercial methods: partial oxidation or steam reforming. When coal or biomass is the feedstock, this step is accomplished by gasification, during which the feedstock is reacted with steam at elevated temperatures and moderate pressure.

The synthesis gas leaving the coal gasifier contains large amounts of CO_2 as well as small amounts of gaseous compounds derived from impurities, such as sulfur, that are present in the feedstock. Both CO_2 and the impurities have a detrimental effect on FT synthesis. The second main step in the FT process removes these undesired compounds from the synthesis-gas stream. When coal or biomass is the feedstock, a result of this second step is the release of a concentrated stream of CO_2 to the atmosphere. When natural gas is the feedstock, depending on the process employed, synthesis-gas preparation either consumes or causes negligible emissions of CO_2 .

The third step is the FT synthesis. During this step, the synthesis gas is passed over an iron- or cobalt-based catalyst under specific process conditions to form a broad mixture of hydrocarbons ranging from gases (such as ethane) to waxes (longer hydrocarbons). By altering the reaction conditions (catalyst, temperature, pressure, and time), the distribution of carbon

lengths of the resulting hydrocarbons can be shifted to maximize, for example, production of middle distillates. But a broad distribution of products is an inherent output of the FT process. Under certain process design schemes, additional CO₂ is formed during the FT synthesis step (Bartis, Camm, and Ortiz, 2008).

After leaving the FT section of the facility, the hydrocarbon product is upgraded to liquid fuels using well-established methods in common use in petroleum refineries. The outputs of the process can be narrowed to middle distillates and naphtha, both of which have a near-zero level of sulfur. The middle distillates can be separated into a mix of automotive diesel and jet fuel. In general, about one-third of the liquid fuel output of an FT plant is naphtha. The FT naphtha has value as a petrochemical feedstock. It can also be upgraded to gasoline suitable for automobile use.

From publicly available engineering analyses, we are unable to provide an analytic estimate of the magnitude of the jet-fuel fraction that can be economically produced at an FT plant. Attempting to pull too much jet fuel from the middle-distillate fraction would leave behind a middle-distillate mix that would need considerable processing before it could be formulated for use as an automotive diesel fuel. Considering the value of FT diesel as an automotive fuel, the economic optimum for the FT jet-fuel fraction could range from near zero to as high as 25 percent of total plant liquid output.

FT fuels are highly paraffinic—meaning that the chains of carbon atoms are straight—and have few, if any, aromatics, olefins, or naphthenes; this is in contrast to conventional Jet A, the specification of which allows for up to 25 percent aromatics (see Chapter Three). Due to its structure and low carbon content, use of FT jet fuel results in significantly less PM emission. FT jet fuel also has a high thermal stability, which reduces carbonaceous deposits in fuel systems, potentially reducing maintenance requirements (e.g., Edwards et al., 2004).

Compatibility and Operability in Current Systems

FT jet-fuel blends are considered to be drop-in fuels. At concentrations up to a 50-50 blend, they meet the performance specifications of Jet A. The use of a neat FT fuel (i.e., unblended, 100-percent FT fuel), would have implications for aircraft fuel systems because of the reduced aromatic content. Certain types of elastomers used as seals in aircraft fuel systems expand in the presence of aromatic compounds found in conventional petroleum-derived jet fuel. If an FT fuel were used, the elastomers would contract, possibly causing fuel leaks. The susceptible elastomers are nitrile-rubber based (EPA, 2000a; Moses, Wilson, and Roets, 2003; Chevron, 2005; Dupont, undated), and fuel additives are being developed to improve seal performance (Graham et al., 2006). Additionally, a pure FT fuel would have reduced lubricity that may promote wear on engine components. Issues with fuel lubricity may also be addressed through the use of additives if required (Moses, Wilson, and Roets, 2003; DoD, 2006; Chevron, 2007).

Because of their paraffinic composition and low aromatic content, neat FT fuels have a specific energy that is approximately 2 percent higher and an energy density that is approximately 3 percent lower than that of typical Jet A (Moses, 2008). The increased specific energy means that less fuel weight would be required to fly a given distance. Considering the worldwide fleet of aircraft, commercial aircraft using neat FT jet fuel would, on average, consume about 0.3 percent less energy (Hileman and Donohoo, 2009). Since the weight required to fly a given distance would drop, the use of FT jet fuel could allow an aircraft to take off with a slightly larger payload without exceeding the maximum takeoff weight, with the result being less energy consumed per unit of payload carried.

The reduced energy density of neat FT jet fuel will shorten the maximum range of an aircraft. However, this is only a concern for the small percentage of actual flights that require full fuel tanks (Hileman and Donohoo, 2009). The decreased range is a consequence of less energy being contained within a given-size tank that is full of FT jet fuel than if it were full of Jet A.

Synthetic fuels produced via FT synthesis are currently used in aviation, and there is an ongoing effort to certify a generic synthetic fuel as a blendstock for Jet A. Since 1999, aircraft leaving O. R. Tambo International Airport in Johannesburg, South Africa, may receive a blend of up to 50 percent FT fuel. This is because synthetic fuels created at the Sasol facility in Secunda, South Africa, have been approved for use by the United Kingdom Ministry of Defence (2008), provided that the blended fuel has a minimum 8 percent aromatic content. The specification of 8 percent minimum aromatic content within Defence Standard 91-91, as the UK Ministry of Defence specification is commonly known, is based on a conservative estimate of the amount of aromatic compound that would be needed to ensure adequate swelling in certain seals (Moses, Wilson, and Roets, 2003). As of this writing, ASTM International, with assistance from the commercial aviation sector in the form of the Commercial Aviation Alternative Fuels Initiative (CAAFI) (FAA, 2008), is in the process of certifying blends of Jet A and a generic synthetic fuel, SPK,¹ by the end of 2009 (Haus, 2007b; “CAAFI Pools Aviation Industry Resources to Certify Synthetic Jet Fuel,” 2008; Rumizen, 2008).

To assist these efforts, a variety of fuel producers and users are testing alternative jet fuels. Qatar Airways, working with Airbus, Rolls-Royce, Shell, Qatar Fuel, and Qatar Petroleum, conducted a test flight of an Airbus A380 operating on a blend of 40 percent FT synthetic jet fuel on February 1, 2008 (Airbus, 2008). Within the past two years, the U.S. Air Force has flight tested a blend of 50 percent FT jet fuel in a number of aircraft, including the B-52H Stratofortress, C-17 Globemaster III, B-1B Lancer, and F-22 Raptor. Because of these flight tests and other work, the specification for JP-8 has been modified to allow up to 50-percent SPK blends with conventional jet fuel (DoD, 2008). The Air Force has a stated goal of being prepared to meet half of its 2016 U.S. fuel requirements for its continental U.S. operations using blends of synthetic and conventional fuels (Bates, 2008). Actually using this much fuel as a 50-percent FT blend would require the Air Force to consume approximately 20,000 bpd of unblended synthetic fuels (Bartis, Camm, and Ortiz, 2008).

Though compatibility issues associated with FT jet fuel have been identified, they are in the process of resolution. When used as a blend with Jet A, all compatibility issues appear to be resolved, and FT jet receives a neutral rating. If used unblended, lubricity issues and seal integrity may require that FT jet fuels have an enhanced fuel-additive package or be limited to use in aircraft without nitrile-rubber seals. For these reasons, FT jet fuel receives a rating of –.

Air-Quality Emissions

FT fuels have low aromatic content and are nearly sulfur free (Moses, 2008). For these reasons, they have the potential to reduce emissions that degrade air quality near airports. Recent tests show that large reductions in primary PM are possible using FT fuels. Corporan, DeWitt, Belovich, et al. (2007), Corporan, DeWitt, Klingshirn, et al. (2007) and Dewitt et al. (2008)

¹ The definition that is being suggested in a recent draft ballot by ASTM for SPK is a synthetic blending component that is comprised essentially of isoparaffins, normal paraffins, and cycloparaffins. Trace materials are permitted, provided that they are components that normally occur in hydroprocessed jet fuel, including but not limited to trace organics, nitrogen compounds, water, and dissolved air.

measured primary PM in the exhaust of older-technology, low-bypass ratio gas-turbine engines (TF33 engine, which is used in the B-52 aircraft) and turboshaft gas-turbine engines (T63 engine, which is used in some helicopters) when burning mixtures of conventional and synthetic fuels. The results, valid for both engine types, indicate that reductions in primary-PM mass are proportional to the percentage of FT fuel that was being consumed. Recent tests have investigated the emission characteristics of a CFM56, a modern, high-bypass ratio turbofan engine, when operating on synthetic fuels (Whitefield, 2008). The data from these tests demonstrate the primary-PM reductions that may be achieved with the use of low-sulfur, low-aromatic alternative fuels, such as those created from FT synthesis. These reductions also appear to be robust to the vintage and type of gas-turbine technology being used. Efforts to characterize the emissions of other fuels in in-service engines are continuing, being coordinated by CAAFI. FT fuel received a ++ rating for air quality, as the emissions of both primary PM and secondary PM from SO_x would be reduced by more than 10 percent as compared to the baseline fuel, Jet A.

Merit for Aviation Use

Because of their high cetane number (a measure of the fuel's ability to resist preignition) and near-zero sulfur content, FT fuels are attractive for automotive diesel applications. Cetane number is not a relevant fuel parameter for turbine engines, and aircraft engines are not equipped with catalytic converters that require the use of ULS fuels. Consequently, it is likely that FT diesel will carry a price premium over FT jet fuel in nations (such as the United States and the members of the European Union) with stringent fuel-quality standards for automotive fuels. This finding assumes that current regulations associated with air quality at airports are continued and that there are no mandated reductions of GHG emissions specifically targeted at commercial aviation.

FT fuels have several characteristics that make them attractive as a jet fuel. Their higher specific energy leads to a small reduction in the amount of energy required to fly a given distance with a given payload and could allow for increased payload capacity. FT fuels are clean burning, thus leading to increased combustor and turbine life, and their improved thermal stability should reduce deposits on engine components and fuel lines. Furthermore, the improved thermal stability of FT fuels may allow for fuel-system and engine design improvements to increase operating efficiency. However, the potential value of these characteristics has not yet been established. All of the testing conducted to date, which includes a variety of engine designs and vintages, suggests that the ultralow levels of sulfur and aromatic compounds of an FT fuel would lead to a substantial reduction in aviation's PM emissions.

If commercial aviation is required to reduce GHG emissions associated with aircraft operations, FT jet fuels derived from biomass or a combination of coal and biomass might carry a significant premium. As discussed in Chapter Eight, such FT jet fuels are one of the three near-term fuel options available if commercial aviation is required to significantly reduce GHG emissions. We note that shifting use of potential future FT fuels from automotive diesel to jet fuel would increase emissions of water vapor during cruise within the upper troposphere and lower stratosphere, which would likely increase aviation's contribution to global warming, although the magnitude of this effect remains highly uncertain.

In summary, we have some evidence that use of FT fuel in automotive applications is likely to provide greater societal benefits and demand a price premium over commercial aircraft operations. However, there remain uncertain issues that could raise the relative value

of FT fuel in aviation applications. These include the extent to which FT fuels will reduce engine maintenance and increase reliability, and whether and how commercial aviation will be required to improve airport air quality or to control GHG emissions. Considering these uncertainties, FT jet has a ○ rating for merit for aviation use.

Fischer-Tropsch Fuels from Natural Gas

When natural-gas deposits are in locations from which transportation by pipeline to large markets is difficult or impossible, these deposits are known as *stranded*. Stranded natural gas may be brought to market either through cryogenic conversion to liquefied natural gas (LNG) or through chemical conversion to liquid fuels.

The world's first commercial-scale gas-to-liquid (GTL) plant based on FT synthesis was built by Shell in Malaysia, began operating in 1993, and continues to produce approximately 15,000 bpd. Sasol recently converted a coal-to-liquid (CTL) facility to accept natural gas from Mozambique. In December 2006, Sasol commenced start-up operations at its Oryx GTL facility in Qatar. This facility has a design capacity of 34,000 barrels of diesel and naphtha per day. Shell, in collaboration with Qatar Petroleum, is currently building the Pearl GTL facility, which is an integrated natural-gas field-development and GTL plant. The plant is to consist of two 70,000-bpd trains and have a design capacity of 140,000 bpd of GTL fuels and products, including 12,000 bpd of GTL kerosene (Rahmim, 2008; GCC, 2008a). Construction began in February 2007. Start-up is anticipated to begin around the end of the decade.

Production Potential

As the world price of oil rose early in the decade, considerable commercial attention was directed at the potential of GTL facilities. This attention was captured in official forecasts, including the *World Energy Outlook* (IEA, 2006), which estimated that GTL production would rise from 0.1 million bpd in 2005 to 0.3 million bpd by 2015 and expand to 2.3 million bpd by 2030; EIA (2007a) expected world production of GTL to expand to 2.6 million bpd by 2030. A number of factors have led to proposed projects being scaled back (Rahmim, 2008). Based on current planned production in Malaysia, Qatar, and South Africa, we estimate that global production of GTL in 2017 will be between 200,000 and 300,000 bpd, of which up to one-quarter, 50,000 to 75,000 bpd, could be economically dedicated to jet-fuel production. The actual jet-fuel production fraction could be significantly lower. Because of the high value of, and growing demand for, natural gas in North America, production of GTL-derived jet fuel in commercial quantities there is highly unlikely. Including expected increases in global production capacity, GTL received a ○ rating for production potential.

Production Cost

A number of factors complicate estimating the production cost of GTL. These include proprietary information on capital costs and performance and the cost of the natural-gas feedstock. Based on an assessment of stated commercial interest in GTL, and the option of compressing and shipping the natural gas as LNG, we estimate production costs for GTL-based jet fuel to range from \$1.40 to \$2.50 per gallon (see Appendix A). This cost falls within the range of -/○.

Well-to-Wake Greenhouse-Gas Emissions

The production and combustion of GTL from natural gas result in estimated life-cycle GHG emissions of 101 g CO₂e/MJ, which is about 1.15 times greater than those of Jet A. This value is comparable to that of jet fuel from oil sands. The well-to-tank portion of the fuel life cycle is dominated by the conversion of natural gas to an FT fuel with emissions of 22 g CO₂e/MJ. As a result, jet fuel from natural gas receives a — rating.

For specific GTL production facilities, WTW GHG emissions are sensitive to the amount of CO₂ contained in the raw natural gas, to the method (partial oxidation or steam reforming) selected for preparing the synthesis gas, and to whether carbon capture and sequestration (CCS) is employed. GTL jet fuel produced from future facilities employing GHG management could have WTW GHG that would be slightly below conventional petroleum-derived fuels, thereby warranting a potential rating of +.

Readiness of Technology

As discussed above, GTL fuels have been in commercial production since 1993 in Malaysia, and there are additional plants in both the start-up and construction phases in Qatar. The technology is in commercial use; therefore, GTL received a +++ rating.

Fischer-Tropsch Fuels from Coal

Current CTL capacity is limited to South Africa, where Sasol operates two CTL facilities producing the energy equivalent of about 160,000 barrels of oil per day. The output is approximately 80 percent FT diesel and 20 percent FT naphtha, though the plants also produce a range of synthetic petroleum products (IEA, 2006). These plants have been in operation for several decades, and the type of gasifier used in these facilities would be considered obsolete for CTL production today (Bartis, Camm, and Ortiz, 2008). More relevant to the consideration of CTL today is the base of experience in coal gasification from integrated-gasification combined-cycle (IGCC) power plants, and FT synthesis from recent GTL facilities. With the increases in petroleum prices since 2003, there is renewed interest in producing FT liquids from coal in the United States (SSEB, 2005; Bartis, Camm, and Ortiz, 2008).

Production Potential

Taking into account coincident demonstrations of CCS and opportunities for cost reduction through experience-based learning, Bartis, Camm, and Ortiz (2008) estimate that a maximum production capacity of 200,000 bpd of coal-derived liquids in 2015, growing to 500,000 bpd in 2020, could be available in the United States, approximately one-quarter of which could be jet fuel. Assuming that 300,000 bpd of CTL production exists in 2017, approximately 75,000 bpd of FT jet fuel from coal could be available. Therefore, CTL receives a ○ rating for production potential.

Production Cost

Based on the analysis by Bartis, Camm, and Ortiz (2008), summarized in Appendix A, the estimated costs of production range is \$1.60 to \$1.92 per gallon (in 2005 dollars) of synthetic diesel fuel, on an energy-equivalent basis to Jet A. Given the range of potential production costs, synthetic FT fuels from coal receive a rating of ○ for cost.

Well-to-Wake Greenhouse-Gas Emissions

Based on analysis conducted by MIT as part of this study and prior research by the RAND Corporation and others, we report a fairly broad range for the mine-to-wake GHG emissions for jet fuel derived from coal (Wong, 2008; Bartis, Camm, and Ortiz, 2008; Williams, 2006). Without CCS, life-cycle GHG emissions for CTL jet fuel are estimated to be between 2.0 and 2.4 times greater than those of conventional jet fuel. More than half of these emissions (120 of 195 g CO₂e/MJ for the midpoint of the range) are associated with fuel production. The range in the estimate reflects variations in plant design, location, type of coal feedstock, and allocation of emissions among co-products. A major cause of variation is the allocation methodology and the extent to which the CTL plant receives a credit for electricity produced at the facility and exported to the grid. In general, the more electricity that is cogenerated and exported, the lower will be the GHG emissions assigned to CTL fuel production (see p. 93 in Appendix B for further discussion). CTL facilities built at low-altitude locations with abundant water supplies will, all other factors being equal, be more energy efficient and, therefore, have lower GHG emissions than plants that are at higher altitudes or designed to minimize water consumption. Variation in the emissions from coal extraction adds another layer of complexity. For example, bituminous coal production from some underground mines involves emissions of CH₄ that can add appreciably to the overall WTW GHG emissions.

Considering this range of values for WTW GHG emissions, CTL without CCS receives a rating of ——. CTL plants in which a credit is received for the naphtha co-product (i.e., if it is used as a petrochemical feedstock) may merit a rating of —. This case, however, was not examined quantitatively in our study.

The application of CCS can dramatically reduce the plant-site and life-cycle CO₂ emissions of the CTL pathway. Our research shows that mine-to-wake GHG emissions for CTL-derived jet fuel produced with CCS range from a factor of 0.8 to a factor of 1.3 times that of conventional jet fuel. This range assumes a carbon-capture efficiency of about 85 percent. The breadth of the range reflects potential variations in plant design, location, and coal feed, and how emissions are allocated to by-products and co-products, especially exported electricity. For additional detail, see p. 93 in Appendix B; see also GIACC (2009) and Bartis, Camm, and Ortiz (2008, Appendix B). Considering this range, jet fuel produced via CTL combined with CCS receives a —/++ rating.

Readiness of Technology

The technology base supporting production of FT fuels from coal has advanced considerably in the past 15 years (Bartis, Camm, and Ortiz, 2008). The two key components of the technology base have been demonstrated at commercial scale: coal gasification in the production of electricity at IGCC power plants and gas cleanup and FT synthesis at GTL facilities. Additionally, methods used to separate CO₂ from process streams, such as those at CTL facilities, have been in widespread commercial use for decades. Pipeline transportation of CO₂ is practiced today. Therefore, CTL technology is ready for initial commercial operations in the United States (Bartis, Camm, and Ortiz, 2008).

An established option for deposition of the captured CO₂ is in enhanced oil recovery (EOR) operations (Bartis, Camm, and Ortiz, 2008; Toman et al., 2008, Chapter 3). In a method known as *CO₂ flooding*, CO₂ is injected into an oil field at pressure, where it mixes with the oil, changing its flow properties and facilitating recovery. These methods have been practiced by the petroleum industry for many years and are well understood. In most instances,

natural reservoirs of CO₂ are used as sources for the process. In general, as much as possible of the CO₂ that is used in EOR operations is recovered from the site, repressurized, and reused, though it is possible to reinject the CO₂ and close the site, permanently storing the CO₂ (NETL, 2008a). The ongoing test in Weyburn, Saskatchewan, is investigating this approach (IPCC, 2007).

The second option for disposition of CO₂ from CTL facilities is geologic sequestration. Geologic sequestration avails itself of much of the same technology for transport and injection as EOR, and much of the current research is focused on assessing the capacity of particular geologies and specific regions (IPCC, 2005, Chapter 5; Bartis, Camm, and Ortiz, 2008). At present, there are three large-scale, ongoing tests of geologic sequestration: In Sleipner, Norway, CO₂ from gas processing is injected into a saline formation; in Weyburn, Canada, CO₂ from a gasification facility is used in an EOR project as a demonstration of geologic sequestration; and in In Salah, Algeria, CO₂ from gas processing is stored in a gas field. The storage potential of each of these sites is approximately 20 million tonnes, and the injection rate is 1 million to 2 million tonnes per year, about an order of magnitude less than the CO₂ that could be captured and prepared for storage at a moderately sized CTL facility. These demonstrations appear to be successful. Research continues on the development of methods for permanently disposing of CO₂ in geologic formations within the United States (NETL, 2007b). Recent studies considering geologic sequestration are optimistic regarding its prospects, but significant research, development, and demonstration remain to be performed (MIT, 2007).

The fuel readiness of CTL depends on the disposition of the plant-site CO₂, as summarized in Table 5.1.

CTL receives a -/+ rating for FRL to reflect both geological sequestration and EOR.

Fischer-Tropsch Fuels from Biomass and Coal

Biomass can be converted to liquid fuels via gasification and FT synthesis to produce a fuel that we call a biomass-to-liquid (BTL) fuel. This technology is currently in the demonstration phase. A German firm, CHOREN, is now constructing a small commercial BTL plant with a capacity of almost 300 bpd of liquid product that began start-up operations in 2008 (Kiener, 2008). Solena Group, in partnership with Rentech, has announced plans to develop and build a BTL facility that would produce 1,800 bpd of fuel (70 percent of which is JP-8 intended for the U.S. Air Force) from agricultural, forestry, and municipal waste from northern and central California; the facility is scheduled to begin construction in Gilroy, California, in 2009 (Environmental Protection Online, 2008).

Table 5.1
Fuel Readiness Levels of Coal to Liquids, Based on Disposition of Carbon Dioxide

| Disposition of CO ₂ | FRL Rating | FRL Description |
|--------------------------------|------------|--|
| Vented to atmosphere | ++ | All component systems have been deployed commercially and are ready for initial commercial application in the United States. |
| EOR | + | All component systems have been deployed commercially but at a smaller scale than would be needed. |
| Geologic sequestration | - | No commercial operations at scale. Many components remain to be developed and deployed. |

Many recent studies have investigated the potential to use a combination of coal and biomass as a feedstock for the production of coal-biomass-to-liquid (CBTL) fuels (NETL, 2007d, 2009; Bartis, Camm, and Ortiz, 2008; Boerrigter and van der Drift, 2004; Williams, 2006). Two potential benefits are motivating interest in CBTL plants: First, cofeeding biomass with coal allows for reduced life-cycle GHG emissions of the resulting products; and second, having a dedicated coal feed allows production plants to achieve greater economies of scale than would be possible if using biomass alone.

Successful tests of using a combination of coal and biomass in a gasifier have been carried out at an IGCC facility in the Netherlands (van Dongen and Kanaar, 2006). Beard Energy (Ohio River Clean Fuels, 2007) has announced plans to design a large-scale CTL facility that would also be capable of accepting up to 30 percent biomass if such feedstocks are available.

Production Potential

Because there are technical risks, albeit small, associated with designing commercial CBTL plants, only a fraction of the near-term production potential of CTL can be diverted to CBTL. NETL (2007d) estimates that the production potential of CBTL could reach 45,000 barrels (middle distillates and naphtha) per day by 2017 under an accelerated schedule; as in the case of CTL, the majority of this output would be FT diesel fuel. Assuming that one-quarter of the total production could be jet fuel, we estimate a maximum production potential of approximately 12,000 bpd of FT jet fuel coproduced from biomass and coal. In this time period, any constraints arising from the resource base of biomass is unlikely to be a significant concern. More information may be found in Appendix A. Given this potential production, CBTL receives a rating of —.

Production Cost

Using the analysis presented in Appendix A for a CBTL facility accepting 15 percent as-received biomass on a mass basis and producing 10,000 bpd of FT products, we estimate production costs ranging from \$1.99 to \$2.34 per gallon of jet fuel. However, it is important to note that the production costs of CBTL could span the entire range of costs for CTL and BTL: One option for CBTL is to cofire opportunistically in CTL facilities as biomass feedstocks become available, in which case the amount of biomass feed may be very low on average. It is likely that, in practice, the amount of biomass available to a facility would vary, from perhaps 10 to 30 percent by mass. Assuming that the plant analyzed in Appendix A is capable of this range in input feedstock, we estimate production costs ranging from \$1.97 to \$2.39 per gallon.² This range of estimated production costs receives a cost rating of -/○.

Fundamental uncertainty exists with respect to the production costs of BTL. Dedicated BTL facilities are likely to have higher unit production costs than those of CTL or CBTL plants because of lower thermal efficiencies associated with smaller plants and increased per-unit capital costs for gasification (NETL, 2009). CHOREN has claimed that its BTL fuel can be produced at costs competitive with prevailing retail prices for low-sulfur diesel, about \$5.80 per gallon at the time of CHOREN's statement. A recent NETL study estimates the production cost of diesel from a 5,000-bpd BTL facility to be in the range of \$6.00 per gallon (NETL, 2009). A production cost of approximately \$6.00 per gallon receives a cost rating of —.

² Because biomass contains less energy per unit mass than does coal, the range of biomass inputs of 10 to 30 percent corresponds to a range of energy inputs from biomass of 7 to 22 percent.

Well-to-Wake Greenhouse-Gas Emissions

The biomass feedstocks investigated in the BTL pathway in Appendix B include waste biomass (e.g., forest residue, agricultural residue) and nonfood energy crops (e.g., herbaceous biomass) assumed to be grown on land that did not contribute to emissions of CO₂ due to land-use change. The life-cycle GHG emissions of BTL are estimated to range from 0.08 to 0.17 times those of baseline conventional jet fuel. The low end of this range represents BTL produced from crop residues (i.e., corn stover), and the high end represents BTL produced from dedicated biomass crops (i.e., switchgrass). Complete results are presented in Appendix B. Overall, BTL receives a +++ rating.

As was observed for the life-cycle GHG emissions from CTL fuels, those from CBTL fuels depend on the methodology used for allocating emissions among fuel products and co-products. The analysis presented in Appendix B from GIACC (2009) assessed life-cycle GHG emissions from CBTL receiving 10 to 40 percent biomass on a mass basis and employing CCS. Emissions among products and co-products were allocated according to energy content. Other input parameters were also varied, including conversion efficiency, with the resulting life-cycle GHG emissions varying from 0.3 to 1.1 times those of conventional jet fuel. A rough estimate of the ratio of life-cycle GHG emissions from CBTL with CCS to those of conventional fuels is given by the relationship $R = 1.1 - 2.6F$, where F is the energy fraction of the biomass feed (Bartis, Camm, and Ortiz, 2008).³ Assuming a range of biomass feeds of 10 to 30 percent by as-received mass, or approximately 7 to 22 percent by energy, the life-cycle GHG emissions of CBTL are roughly 0.5 to 0.9 times those of conventional fuel. Higher biomass input ratios would result in lower GHG emissions, but production costs would increase. These considerations suggest that CBTL receive a mixed rating of — to +++ for WTW GHG emissions.

Readiness of Technology

The key technical barriers to the development of CBTL and BTL facilities are reliable methods for handling and feeding biomass into the gasifier and the effects of the biomass ash on the performance of the gasifiers. This is not a significant technological challenge, but it needs to be resolved before plants accepting significant fractions of biomass are constructed, delaying the readiness for initial commercial application of the technology by at least five years (Bartis, Camm, and Ortiz, 2008). Concurrent with technical issues with respect to production, there is a need to develop a biomass-supply industry capable of supplying the significant quantities of biomass needed to support a full-scale CBTL or BTL industry.

Because a pilot plant is under construction and some experience on cogasifying coal and biomass is available from the Netherlands, the CBTL and BTL fuel-creation process receives a + rating. Refer to Table 5.1 for FRLs of CBTL with CCS.

³ This equation assumes 90-percent capture of the plant-site CO₂ emissions and the upgrading of the naphtha co-product to automotive gasoline (see Bartis, Camm, and Ortiz, 2008, p. 39).

Fuels from Renewable Oils

Biodiesel and Biokerosene

Biodiesel is a fuel produced from plant oils and animal fats. Though biodiesel may be used unblended in conventional diesel engines, it is typically blended in low concentrations (below 20 percent) with conventional diesel fuel when marketed for retail sales. It is typically produced by chemically processing the fatty acid from the plant or animal source with methanol. A by-product of biodiesel production is glycerol, a feedstock for manufacturing soap. Biodiesel is sometimes referred to by its chemical composition and source: For example, soy-based biodiesel is also known as *soy methyl ester*. In general, biodiesels are often referred to as fatty acid methyl esters (FAMES).

There are two principal chemical differences between biodiesel and petroleum-derived diesel fuel: First, biodiesel contains oxygen, and second, the length of the carbon chains in biodiesel is inherited from the feedstock. These differences in chemical composition affect the fuel properties of biodiesel; some of these are critical to aviation—namely, freeze point, thermal stability, specific energy, and energy density.

Common feedstocks that are being used for the production of biodiesel include soybean oil in the United States, rapeseed (canola) oil in Europe, palm oil, coconut oil, animal fats, and waste products. Additional, nonedible feedstocks that could be used to make biodiesel include oils derived from jatropha, halophytes, and algae. Babassu, a species of palm tree indigenous to northeastern Brazil, produces an oil composed of carbon chains mostly of lengths 12 and 14. These are shorter than chains from most other plant-oil sources, which have lengths mostly of 16 and 18 carbon atoms.¹

Biokerosene generally refers to a biodiesel made from oils with shorter carbon chains, such as babassu, coconut, and palm-kernel oils. Because of the lower carbon-number range required for jet fuel (than for diesel), these feedstocks have been proposed as potential sources for alternative jet fuels (Daggett et al., 2008). In February 2008, Virgin Atlantic, in collaboration with Boeing, General Electric, and Imperium Renewables (a biodiesel producer from Washington state), conducted a flight test of a Boeing 747 with one engine operating on a 20-percent blend of a biodiesel made from babassu and coconut oils (GCC, 2008b).²

¹ Chevron (2007) provides an extensive list of renewable oils and the carbon numbers of the compounds that constitute them. The majority of renewable oils have carbon numbers between 16 and 18. This list includes canola, peanut, soybean, sunflower, palm, cocoa, jatropha, and animal fats. The exceptions are palm-kernel and coconut oils, which have carbon numbers between 12 and 14, and rapeseed, which has carbon numbers between 18 and 22.

² Between 1980 and 1984, the Brazilian government developed and tested a biokerosene called PROSENE. This fuel was used in an Embraer turboprop aircraft that flew from São José dos Campos to Brasília. Currently, the Brazilian corpora-

The analysis presented in this section is primarily based on an assumed 5-percent blend of biodiesel with Jet A. Where appropriate, analysis of a 20-percent biokerosene blend, similar to that used in the Virgin Atlantic flight test, is also presented. The relatively low blending concentrations were chosen such that the fuels could potentially meet the freeze-point requirements of Jet A.

Compatibility and Operability in Current Systems

There have been concerns with respect to the compatibility of straight biodiesel with diesel engines, including decomposition during storage and freezing at low temperatures. The Engine Manufacturers Association states that blends of up to 5 percent biodiesel should not cause engine or fuel-system problems for diesel engines (EMA, 2003). The relatively high freeze point of biodiesel requires that it be used in a blend when used for jet aircraft. A more serious issue is the potential for FAME to break down during engine operation. Further complications arise because of the reduced energy density of biodiesel, as compared to Jet A.

The pour point³ of pure biodiesel can vary from -3 to 12 degrees Celsius (Tyson, 2004), which is sufficiently high to freeze under normal aircraft cruise operating conditions. Corporan, Reich, et al. (2005) measured freeze points of -50 degrees Celsius and -27 degrees Celsius for biodiesel blends of 2 percent and 10 percent biodiesel and Jet A, respectively. Assuming that the freeze point scales linearly within this range of blending percentages, then a 5-percent biodiesel blend would have a freeze point of approximately -41 degrees Celsius and may meet the Jet A freeze-point specification of -40 degrees Celsius. However, other measurements indicate that blends containing only 1 percent biodiesel may not meet freeze-point requirements (Brook, Rickard, and Barratt, 2007).⁴

Jet fuel is an important medium for heat exchange within aircraft engines and systems, leading to thermal stresses that may cause biodiesel to decompose and leave deposits in fuel-system lines. These deposits can accrue over time and degrade system performance and safety. Testing indicates that some biodiesel blends, even when blended at just 1 percent, could lead to unacceptable thermal-stability degradation (Wilson, Thom, and Serino, 2007). Because of concerns about the thermal stability of jet fuel, biodiesel is currently not being transported in U.S. petroleum pipelines. The concern is that trace quantities of biodiesel will trail back to jet fuel that is traveling in the same pipeline and that this contamination will lead to an unacceptable degradation in the jet-fuel thermal stability. In Europe, biodiesel is currently being transported via pipeline as a blend with conventional diesel fuel, but there is ongoing research to determine the effect on jet-fuel quality and an acceptable level of biodiesel contamination

tion Tecbio is continuing the development of biokerosene. The biokerosene developed by Tecbio uses lower-carbon number vegetable-oil feedstocks (Parente, 2006).

³ Chevron (2007, p. 8), in its discussion on diesel fuel, provides the following in regard to cloud point:

As fuel is cooled, it reaches a temperature where it is no longer able to dissolve the waxy components that then begin to precipitate out of the solution. The temperature at which wax just begins to precipitate and the fuel becomes cloudy is the cloud point as measured by ASTM D 2500.

If the fuel is cooled below the cloud point, more wax precipitates. At approximately 3°C to 5°C (6°F to 10°F) below the cloud point (for fuels that do not contain a pour point depressant additive) the fuel becomes so thick it will no longer flow. This temperature is called the pour point or gel point as measured by ASTM D 97.

⁴ As demonstrated by the Virgin flight test, higher-blend percentages are possible with the use of lower-carbon number feedstocks, such as babassu and coconut oil.

of jet fuel (Viltart, 2007; JIG, 2007). Considering that this research is focused on determining a maximum FAME contamination, as measured in parts per million, it is highly uncertain whether any biodiesel or biokerosene blend can be certified for current jet-aircraft applications.

A 20-percent blend of biokerosene would have a 4-percent reduction in specific energy and a 3-percent reduction in energy density, both relative to conventional jet fuel. Such a fuel could meet freeze-point requirements, but its use would result in a 0.6-percent increase in aircraft energy use under normal operations (Hileman and Donohoo, 2009). The fuel would also have the same thermal-stability concerns as conventional biodiesel blends.

Biodiesel and biokerosene blends are assigned a — rating for compatibility because the potential problems with thermal stability could lead to the formation of deposits in fuel systems, even for blends with a fraction of a percent of the biomaterial. If the thermal-stability issue were to be overcome, there are also concerns regarding the maximum blending percentage for meeting freeze-point requirements. Specific energy considerations may also limit the blending percentage.

Merit for Aviation Use

A blend of 5 percent biodiesel is considered safe for general use in diesel engines, and a 20-percent blend of biokerosene was flight tested by Virgin Atlantic. However, there are continuing concerns regarding the freeze point, thermal stability, and specific energy of these fuels, especially in formulations that can be economically produced. It appears that biodiesel and biokerosene are better suited for ground-transportation applications, for which specific energy and freeze-point concerns are not as critical. Therefore, these fuels received a rating of –.

Because of the concerns regarding the safe use of biodiesel and biokerosene in gas turbine-powered aircraft, emissions, production potential, and cost were not evaluated for these fuels.

Hydroprocessed Renewable Jet Fuel

Plant oils, animal fats, or waste grease (renewable oils) may be processed to yield a fuel that has properties suitable for commercial aviation use. These fuels are created using a process that first uses hydrotreatment to deoxygenate the oil and then uses hydroisomerization to create normal and isoparaffinic hydrocarbons that fill the distillation range of Jet A. Because they are paraffinic, these fuels have properties similar to those of FT fuels (Marker, 2005; Rantanen et al., 2005; GCC, 2007b). Several companies either have developed or are developing hydroprocessing techniques to create paraffinic fuels that can substitute for conventional middle-distillate products:

- Neste Oil is producing a renewable diesel fuel termed NExBTL (next-generation BTL).
- Syntroleum is constructing a facility to use its Bio-Synfining™ process to produce renewable diesel (termed R-2) and renewable jet fuels (termed R-8).⁵
- UOP is licensing technologies that could be used to produce renewable diesel and renewable jet fuel.
- ConocoPhillips is creating renewable diesel fuel using refinery-based hydroprocessing.

⁵ Syntroleum refers to its FT fuels as S-2 (alternative to no. 2 diesel fuel), S-5 (alternative to JP-5), and S-8 (alternative to JP-8) (GCC, 2007b).

For the purposes of this report, an oxygen-free fuel that fills the distillation range of Jet A and is created from the hydroprocessing of plant oils or animal fats is termed HRJ; the diesel-fuel equivalent to HRJ is termed *hydroprocessed renewable diesel* (HRD). Syntroleum (Syntroleum, 2008b; GCC, 2007b) and UOP (2005) indicate that their HRJ fuels are suitable for use in jet aircraft.

Subsequent to the Virgin Atlantic flight test discussed at the beginning of this chapter, Boeing, in collaboration with multiple fuel and engine company partners, has conducted multiple flight tests using HRJ fuels. These tests are summarized in Table 6.1. Subsequent to its flight tests, Air New Zealand (2008a, 2008b) has also stated its intention “to use at least one million barrels of environmentally sustainable fuel annually, meeting at least 10% of its total annual needs” (1 million barrels per year is roughly equivalent to 2,700 bpd).

Other efforts are also under way to examine the viability of renewable fuels for aviation. These include a team comprised of Airbus, JetBlue Airways, UOP, and International Aero Engines (UOP, 2005); the alternative-fuel consortium led by Rolls-Royce and British Airways (Rolls-Royce, 2008); and the Sustainable Aviation Fuel Users Group, which is comprised of Boeing, UOP, World Wildlife Fund, Natural Resources Defense Council (NRDC), and several airlines, including Air France, Air New Zealand, All Nippon Airways, Cargolux, Gulf Air, Japan Airlines (JAL), KLM, Scandinavian Airlines (SAS), and Virgin Atlantic Airlines (Boeing, 2008c).

Compatibility and Operability in Current Systems

Because they are paraffinic fuels that fill the distillation range of Jet A, HRJ should behave similarly to an FT fuel, with similar compatibility concerns. As was noted for FT fuels (see Chapter Five), additives may have to be used to meet lubricity requirements; precautions will need to be made in regard to elastomers; and the difference in energy density between HRJ and Jet A will have positive consequences in terms of decreased energy usage but negative con-

Table 6.1
Recent Hydroprocessed Renewable Jet-Fuel Test Flights

| Airline | Air New Zealand ^{a,b} | Continental Airlines ^{b,c} | JAL ^{b,d} |
|----------------|---|--|--|
| Date | December 30, 2008 | January 7, 2009 | January 30, 2009 |
| Aircraft type | Boeing 747-400 | Boeing 737-800 | Boeing 747-300 |
| Engine type | Rolls-Royce RB211 | CFM56-7B | Pratt and Whitney JT9D |
| Oil supplier | Terasol Energy | Terasol Energy (jatropha) Sapphire Energy (algae) | Sustainable Oils (camelina) Terasol Energy (jatropha) Sapphire Energy (algae) |
| Fuel processor | UOP | UOP | Nikki-Universal/UOP |
| Fuel | Jatropha HRJ (50%) Conventional jet fuel (50%) | HRJ from jatropha (2.5%) and algae (47.5%) Conventional jet fuel (50%) | HRJ from camelina (42%), jatropha (< 8%), algae (< 1%) Conventional jet fuel (50%) |

^a Air New Zealand (undated).

^b Kinder and Rahmes (2009).

^c GCC (2009).

^d JAL (2009).

sequences in terms of decreased maximum range. For these reasons, HRJ receives a compatibility rating of –.

Production Potential

Facilities to hydroprocess renewable-oil products are being built worldwide. Neste Oil has five commercial processing plants (one in Austria, two in Finland, one in Singapore, and one in Rotterdam) that are either recently completed or under construction that will be capable of producing, collectively, 2.1 million tons per year (roughly 40,000 bpd) of diesel fuel from hydroprocessed-renewable-oil sources. The first Finnish facility became operational at the end of summer 2007, and the other facilities should be completed by 2011.

ConocoPhillips has been producing 1,000 bpd of HRD fuel at its Whitegate Refinery facility in Cork, Ireland, since December 2006 (GCC, 2006d). It has subsequently started a joint venture with Tyson Foods that will result in the production of 11,000 bpd of renewable diesel fuel from existing U.S. refineries by 2009 (GCC, 2007a). Syntroleum, also in a venture with Tyson Foods, is set to begin construction of a facility that will eventually produce 75 million gallons of renewable diesel fuel and jet fuel per year (4,900 bpd) from a feedstock of low-grade fats and greases. Commercial operation is set to begin in 2010 (Syntroleum, undated, 2008b).

If all of the aforementioned facilities achieve full-scale operations, the production capacity of HRD would be nearly 60,000 bpd. If successful and economic, additional plants could be constructed to increase production capacity. At present, almost all of the aforementioned production capacity is slated for HRD production, but this could change in the future. There are limits on near-term production capacity for hydroprocessed renewable fuels because of feedstock availability, especially since these facilities would be competing for the same feedstock as biodiesel producers. Therefore, for biodiesel, HRD, and HRJ, we estimate a combined production potential in the low hundreds of thousands of barrels per day. For these reasons, HRJ receives a supply production potential rating of –/+.

Production Cost

Publicly available information regarding capital and operating costs for HRJ-production facilities is not sufficient to allow a cost estimate for HRJ.

Well-to-Wake Greenhouse-Gas Emissions

Our research work investigated the life-cycle GHG emissions from the production and use of HRJ from soybean oil and palm oil. Ongoing research that is presented in GIACC (2009), which is also summarized in Appendix B, has also considered HRJ fuels from other feedstocks, such as jatropha and algae.

As soybeans and palm are both food crops requiring fertile land for cultivation, their use in the production of biofuels could potentially result in adverse land-use-change emissions of CO₂ (see Chapter One). These land-use-change emissions can dominate the overall GHG emissions of the pathway.

For example, Fargione et al. (2008) consider a variety of land types that could be converted to the production of ethanol feedstocks from corn, sugarcane, and biomass. They estimate that it would take up to 93 years to repay the carbon debt due to land-use-change emissions, depending on the type of feedstock grown and the type of land being converted for its cultivation. For example, growing lignocellulosic feedstocks on abandoned or marginal crop-

land would result in a land-use carbon debt that would take only one year to repay, while growing corn on land converted from central grassland in the United States would incur a carbon debt that takes 93 years to repay.

Recent studies have also highlighted the potentially large emissions that can result from indirect land-use change. Corn ethanol is often used as the example for how this could happen because of the possibility that extensive ethanol production could lead to a reduction in U.S. grain exports. If that were to happen, then other nations would increase their agricultural output to maintain a global balance of food supply and demand. The increased worldwide agricultural production would result in land-use change in some other parts of the world due to the conversion of noncroplands to croplands in these locations to replace food diverted to biofuel production. Searchinger et al. (2008) examine a case in which U.S. corn ethanol production was increased to 30 billion gallons annually by 2016 (twice that required by the 2007 Energy Independence and Security Act, Pub. L. No. 110-140). In this hypothetical case, indirect land-use changes would result in a 93-percent increase in GHG emissions as compared to gasoline use (Searchinger et al., 2008).⁶ This large increase is the result of 104 g CO₂e/MJ being added to the life-cycle GHG inventory to account for worldwide land-use changes that would be needed to replace the nutritional value of the corn that was used for ethanol production.⁷

Further, if the production of biofuels involves direct land-use changes that result in net CO₂ emissions, the life-cycle GHG emissions of these biofuels will increase. The level of increase depends on the type of land being converted for biofuel production,⁸ with little or no increase for idle or degraded land, moderate increases for grasslands, and dramatic increases for tropical rainforest and peatland rainforest (Fargione et al., 2008).⁹

In the case of HRJ from soy oil, excluding the impact of land-use–change emissions, the life-cycle GHG emissions are about 0.4 to 0.8 times those of baseline conventional jet fuel. This variation is due to variation in soybean yield, N₂O emissions from fertilizer, liming emissions, and hydrogen requirements in the hydroprocessing step, among others (see Appendix B for more details). When land-use–change emissions were included in the analysis, the life-cycle GHG emissions of the pathway increased. In the case of Cerrado grassland conversion to cropland with a high soybean yield, life-cycle GHG emissions increased to 1.3 times those of conventional jet fuel; in the case of tropical rainforest conversion and a low soybean yield, life-cycle GHG emissions increased to 8 times those of conventional jet fuel (see Appendix B

⁶ In the scenario modeled by Searchinger et al. (2008), the ethanol production level appears to be significantly higher than the legal mandate and expected trends in U.S. corn ethanol production. Though critics have pointed out that this scenario might not be entirely realistic (Wang, 2008), a sensitivity study (provided in the same paper) that assumed a much smaller increase in ethanol production of about 8 billion gallons above projected levels in 2016 showed a reduction in average GHG emissions from land-use changes of only about 2 percent (343 tonnes CO₂e per hectare [ha]) compared to the original scenario (351 tonnes CO₂e/ha). This shows that land-use–change emissions arising from ethanol production at the range examined in the paper (an 8-billion to 15-billion gallon increase) do not vary significantly with the scale of production. Nonetheless, it is unclear how their magnitude would change for far larger or far smaller levels of production.

⁷ These emissions are amortized over 30 years.

⁸ The type of crop grown also affects the extent of CO₂ emissions from land-use changes. For example, the growth of prairie biomass results in less CO₂ emission from land-use changes than does the growth of corn (Fargione et al., 2008). This is because prairie biomass stores more carbon from the atmosphere in the form of root and soil carbon than does corn.

⁹ Such land-use–change impacts could arise when the biofuel production directly results in the conversion of noncropland to cropland for the production of biomass feedstocks or causes the diversion of current food crops to biofuel production that indirectly results in conversion of land elsewhere to replace these diverted crops.

for a complete summary of results). The analysis allocates emissions from land-use changes to the fuel over a 30-year period after land conversion.

For the production of HRJ from palm oil and palm-kernel oil (collectively called *palm oils*) without the effect of land-use-change emissions, the life-cycle GHG emissions are about 0.3 to 0.4 times those of conventional jet fuel. This range is due to variation in input parameters, such as palm fresh-fruit bunch yield per acre, farming energy, methane emissions from palm oil-mill effluent treatment, processing hydrogen requirements, and hydroprocessing fuel yield. However, when land-use-change emissions are included, the ratio of life-cycle GHG emissions of HRJ to conventional fuel ranges from 0.4 (assuming previously logged-over forest and a high yield of palm fresh-fruit bunches) to 8 times (assuming conversion of peatland rain-forest and a low yield of palm fresh-fruit bunches) those of conventional jet fuel. As in the previous case, the emissions from land-use change are allocated to the fuel over a 30-year period (see Appendix B for complete results).

Given the wide range of possible emissions from these two pathways, HRJ was given a rating of ---/+++ . This rating demonstrates the importance of tracking the source of the renewable-oil feedstock that is used to create the fuel. The feedstock source will determine whether the HRJ results in reduced or greater net emissions of GHG than conventional jet fuel.

Air-Quality Emissions

Given the similarity in HRJ fuel properties to those of FT fuels, the impacts of HRJ combustion on aircraft landing and takeoff emissions should be similar to those from FT fuels (see “Common Characteristics” in Chapter Five). HRJ received a ++ rating for air quality, as the emissions of both primary PM and secondary PM from SO_x are expected to be reduced by more than 10 percent with FT fuel combustion, as compared to the baseline fuel, Jet A.

Readiness of Technology

Refineries are currently hydroprocessing vegetable oil to create alternative diesel fuels. Moreover, a pilot plant is currently under development to create HRJ from waste animal fats. These activities suggested that the HRJ fuel-creation process warrants a ++ rating for technical readiness.

Merit for Aviation Use

Given their chemical similarity to FT fuels, HRJ fuels have similar environmental and performance trade-offs, as considered in Chapter Five. Based on the arguments in that section, HRJ has been given a neutral (○) rating for merit for aviation use.

Alcohols

Ethanol

Ethanol is a simple, two-carbon alcohol typically made by fermenting sugar. Production of ethanol in this manner for human consumption in alcoholic beverages dates back thousands of years. Although the interest in alternative fuels for aviation is relatively recent, ethanol is not new to ground transport. Henry Ford used ethanol in a car in the 1880s, and, in the 1930s, more than 2,000 service stations in the midwestern United States sold corn-based ethanol (Kovarik, 1998).

In the United States today, corn grain is used as the principal feedstock for fuel-alcohol production. Research is under way to produce alcohol fuels from cellulosic feedstocks. In general, research emphasis is on pretreatment methods that break down the cellulose, making the sugar available for fermentation. In February 2007, the U.S. Department of Energy (DOE) announced federal funding of up to \$385 million for commercial demonstration of six initial cellulosic-ethanol plants (DOE, 2007). The six demonstration facilities are to be constructed between 2007 and 2011 and have target capacities ranging from 440 to 2,040 bpd of ethanol. The processes underlying the proposed facilities have been demonstrated at the pilot scale (on the order of 0.01 the proposed capacities). Four of these facilities incorporate approaches that involve fermentation. Two of the processes being demonstrated are based on gasification of biomass followed by catalytic conversion of the resultant gas to a blend of ethanol and other alcohols.

Compatibility and Operability in Current Systems

The chemical composition and properties of ethanol differ substantially from those of conventional Jet A. Ethanol has higher volatility (boiling point of 78 degrees Celsius); propensity to attract water, which freezes at cruising altitude; low specific energy and energy density; low flash point; corrosion; and elastomeric decomposition. The chemical and property differences between ethanol and Jet A could lead to problems when blended (Chevron, 2006); as such, the analysis in this report assumes pure ethanol.

The most serious problem with ethanol as a jet fuel is its low flash point, since this poses a serious risk to both crew and passengers. High volatility could also pose a problem during cruise operation due to evaporative losses or fuel-system vapor lock (Chevron, 2006). While technical means are available to reduce these risks during normal aircraft operations, significant costs would be associated with retrofitting existing aircraft to accept ethanol.

In addition, the use of ethanol would result in reduced operational capabilities and a reduction in the energy efficiency of aircraft operations. The specific energy and energy density

of ethanol are each about 40 percent lower than the energy density of Jet A. As discussed in Hileman and Donohoo (2009), using ethanol as a fuel in jet aircraft would result in a substantial loss in operational capabilities due to low energy density. Depending on the aircraft type, between 5 and 55 percent of the operations that were possible with Jet A would have reduced payload and range capability with ethanol use because the tank volume would not be able to hold sufficient fuel to fly the required distance with the desired payload. For the aircraft types considered in their analysis, Hileman and Donohoo (2009) estimated that the Embraer 145-LR, a regional jet, would have 17 percent of its flights affected; single-aisle aircraft, such as the Boeing 737 and 757, would have from 5 to 25 percent of their flights affected; and larger, twin-aisle aircraft, such as the Boeing 767, 777, and 747, would have between 28 and 55 percent of their flights affected. Ignoring for the moment the limitation on operability, if all aircraft were able to use ethanol, the worldwide fleet would require 78 percent more fuel by volume and 9 percent more energy delivered to the tank than if it used all Jet A.

Ethanol received a --- rating for compatibility because its low energy density would limit operations of existing jet aircraft, its volatility could cause problems with existing jet-aircraft fuel systems, it is not allowed in the existing pipeline system, and its low flash point could pose a safety hazard.

Readiness of Technology

Ethanol from sugarcane and corn is currently in widespread production, while lignocellulosic ethanol is still in a phase of research and development. Based on the readiness of sugarcane and corn ethanol, the FRL is +++.

Merit for Aviation Use

Ethanol use would limit jet-aircraft operability, and considerably more ethanol would be required on an energy basis than any of the other fuels that have been considered in Chapters Three, Four, Five, or Six. Because of the increased energy use and the increased amounts of water vapor that would be emitted to the upper atmosphere during ethanol combustion in jet aircraft, the GHG benefits of ethanol production would be compromised by its use in jet aircraft relative to its use in ground transportation. Ethanol is desirable within the ground-transportation market due to its high octane rating. On top of these other concerns, the use of ethanol in jet aircraft would compromise safety due to its vapor pressure and flash-point characteristics. Because of these concerns, ethanol is more attractive for use in spark-ignition, internal-combustion engines for ground transportation (than jet aircraft), and it received a rating of – in this category.

Because ethanol cannot be safely used in gas turbine-powered aircraft and because of the inherently greater benefits of its use in ground transportation relative to aviation, this report does not address emissions, production potential, or production costs.

Butanol

Butanol is a simple, four-carbon, straight-chain alcohol that can also be made by fermentation of sugars. Like ethanol, butanol (also referred to as *biobutanol* in the literature and press) has the potential to be produced from lignocellulosic feedstocks.

Compatibility and Operability in Current Systems

Like ethanol, butanol has higher volatility, lower energy content, and a lower flash point than Jet A. However, the differences between butanol and Jet A are smaller than those between ethanol and Jet A. As was the case for pure ethanol, pure butanol was the subject of the analysis in this report. Although blending of butanol in Jet A may be possible, there are considerable chemical and physical differences between the two fuels.

The specific energy and energy density of butanol are both 23 percent lower than those of Jet A. Similar to ethanol, using butanol as a jet fuel would result in a reduction in operational capabilities. Depending on the aircraft type, up to 36 percent of operations would have to sacrifice payload or range if they were operating on butanol. If all aircraft were able to operate on butanol (ignoring the previous observation on operational limitations), then the worldwide fleet would require 4 percent more energy when using butanol than it would when using Jet A (Hileman and Donohoo, 2009).

Butanol suffers from the same compatibility concerns as ethanol: Low energy density would limit operations of existing jet aircraft, its volatility could cause problems with existing jet-aircraft fuel systems, and its low flash point could pose a safety hazard. However, these concerns are not as strong for butanol as they are for ethanol, because butanol's physical and chemical properties are closer to those of Jet A than are ethanol's. Based on these considerations, butanol's rating for compatibility is —.

Readiness of Technology

The original acetone-butanol-ethanol (ABE) fermentation process developed in 1915 results in a 15- to 25-percent by-weight yield of butanol with a number of byproducts, including hydrogen gas; acetic, lactic, and propionic acids; acetone; isopropanol; and ethanol. The ABE fermentation process was in widespread commercial use prior to 1950, when a cheaper petrochemical process gradually replaced it. A newer technique using a two-step fermentation process has increased the butanol yield to 42 percent with two by-products of hydrogen and butyric acid (Ramey and Yang, 2005). The increased efficiency doubles the potential yield of butanol from a bushel of corn from 1.3 to 2.5 gallons per bushel (GCC, 2005). However, there is still a question of what to do with the large quantities of butyric acid that would result from such a process.

In 2006, BP and DuPont announced that they were working with British Sugar to create butanol in the UK's first ethanol fuel-fermentation plant. The collaboration was to have two phases, with the first being the use of existing technology to convert sugar beets into 30,000 tons, or 9 million gallons, of butanol annually (590 bpd) at a facility in Wisington, England. The second phase would be to genetically engineer yeast with improved yields (Chase, 2006). In a March 2007 interview, Philip New, president of BP Biofuels, stated, "This (butanol) is absolutely in a testing phase, and we're looking to how we can move it into a pilot [plant] phase. We'll be dealing with some trial quantities soon" (Bullis, 2007, p. 2). There are no public data on yields or costs of the product. Based on the maturity of the BP and DuPont project, the FRL rating for butanol was set as +.

Merit for Aviation Use

Used in its pure form, butanol carries an energy penalty and is not attractive for use in aircraft that are operating on routes that require taking off with fuel tanks that would be more than 75 percent full using Jet A. Significant compatibility issues remain unresolved, and use of

butanol may require modifications to both aircraft and airport fuel-delivery systems. There is also the issue of whether and how butanol could be used as a blend with Jet A.

However, aviation is not the only application for butanol. Butanol is an attractive blend stock for gasoline, especially when compared with ethanol. It can be blended at refineries rather than being trucked prior to blending. Unlike ethanol-blended gasoline, butanol-blended gasoline is compatible with existing petroleum pipelines. The octane number of butanol is relatively high, and physical and chemical properties, including a low vapor pressure, are compatible with the properties of gasoline. It can be used at high blend ratios in unmodified engines.

If butanol were available, would it have higher commercial value as an automotive fuel or an aviation fuel? Our analysis suggests that butanol will carry a premium when used as a blend stock for gasoline as opposed to its use as an aviation fuel. First, butanol is an octane booster. This gives it extra value when used in gasoline engines, but octane number is an irrelevant specification for gas-turbine engines. Second, when used in aircraft, butanol results in a performance penalty due to its low energy density and specific energy.

So long as butanol supplies are limited, as they surely will be for the next two decades, these considerations imply that, on strictly economic grounds, automotive users should be able to outbid aircraft operators for butanol. Likewise, any diversion of butanol from the automotive sector to the aviation sector will result in higher GHG emissions.

As we see from these considerations, butanol is better suited for use in ground transportation and has a rating of – for this metric.

Because of the concerns regarding the safe use of butanol in gas turbine–powered aircraft and the benefits of its use in ground transportation relative to aviation, we did not evaluate emissions, production potential, or production cost.

Findings and Recommendations

Key Findings

Table 8.1 summarizes the seven metrics and the associated ratings, as developed and reviewed in Chapter Two, devised to rate alternative jet fuels. Table 8.2 illustrates the results of applying these metrics to the 13 alternative jet fuels examined by the MIT-RAND research team. This table supports a number of our key findings regarding the prospects of alternative fuels for aviation for the next ten to 15 years. Figure 8.1 presents the ratio of the life-cycle GHG emissions for each of the feedstock-to-fuel pathways presented in the main text and the life-cycle GHG emissions for jet fuel from conventional crude. The uncertainty bars represent the range of this ratio as given by the low- and high-emission cases.

In the Next Decade, Up to Three Alternative Jet Fuels May Be Available in Commercial Quantities

The alternative aviation fuels not derived from conventional petroleum that have the greatest production potential for the next decade are (1) Jet A derived from Canadian oil sands and Venezuela's VHOs; (2) FT jet fuel produced from coal, a combination of coal and biomass, or NG; and (3) HRJ produced by hydroprocessing renewable oils. All three are or can easily and inexpensively be made fully compatible with current aircraft and fuel-delivery systems.

Current and planned development of Canadian oil sands and Venezuelan VHOs should yield a few hundred thousand barrels per day of Jet A. Additional production increases after 2020 are likely. Production of jet fuel from these resources results in roughly 10 percent to 25 percent higher life-cycle GHG emissions over conventional Jet A, depending on extraction technique. Approaches are available to reduce these emissions to levels that are no worse than conventional petroleum, but application of these approaches (such as nuclear power or CCS) might increase production costs beyond the range shown in Table 8.2).

Continued increases in the development of Canadian oil sands and the VHOs of Venezuela require world crude oil prices to be in or above the range of \$50 to \$60 per barrel (2009 dollars).

The prospects for FT fuel production in the United States prior to 2020 depends crucially on beginning construction on a few pioneer commercial plants in the next few years. With early production experience, gasification of coal or a combination of coal and biomass followed by FT synthesis could yield as much as 75,000 bpd of a Jet A substitute by 2017. At most, about 12,000 bpd might be produced from facilities gasifying both coal and biomass.

Table 8.1
Rating-System Definitions

| Ranking | Compatibility in Current Systems | FRL Ranking | Production Potential (% of 2017 Jet A demand) | Production Cost (2005 \$ per gallon) | WTW GHG Emissions (% of conventional Jet A) | Air Quality (net reduction or increase in primary PM, SO _x , NO _x) | Merit for Aviation Use (versus automotive use) |
|---------|--------------------------------------|--|---|--------------------------------------|---|---|--|
| +++ | | The fuel is in large-scale, commercial production using fuel-creation process. | ~100 | | < 50 | Net reduction in 3 | |
| ++ | | The fuel is in limited commercial production using fuel-creation process. | ~50 | < 0.90 | 50–90 | Net reduction in 2 | |
| + | | Commercial pilot plant is under construction or in operation. | ~10 | 0.90–1.40 | 90–98 | Net reduction in 1 | Jet use more attractive |
| ○ | Fully compatible | All relevant technologies that are necessary for fuel production have been proven. | ~5 | 1.40–2.10 | ~100 | No net change | Uncertain or near equal utility to both |
| - | Yes, with fuel additives or blending | Fuel-creation process is undergoing advanced R&D. | ~1 | 2.10–3.50 | 102–110 | Net increase in 1 | Automotive use more attractive |
| -- | No, infrastructure changes needed | Fuel-creation process is undergoing intermediate R&D to prove viability of individual components. | ~0.5 | > 3.50 | 110–150 | Net increase in 2 | |
| --- | No, complete system overhaul needed | Fuel-creation process is undergoing fundamental R&D at laboratory scale to prove viability of fuel-creation concept. | ~0.1 | | > 150 | Net increase in 3 | |

NOTE: Metrics are fully described in the second section of Chapter Two, “Metrics for Comparing Alternative Fuels.” Jet A implies Jet A from conventional petroleum. The production-potential metric is based on estimated U.S. 2017 jet-fuel demand of 2 million bpd. Production costs are for an amount of fuel having the energy equivalent of 1 gallon of Jet A. Costs do not include subsidies or fuel taxes and pertain to a gallon of the pure fuel and not a blended fuel product. The air-quality metric is based on how many sources of PM (primary PM and secondary PM precursor gases of SO_x and NO_x) would have more than 10 percent reduction compared to conventional petroleum-based jet fuel.

Table 8.2
Near-Term Alternative Jet-Fuel Comparison Matrix

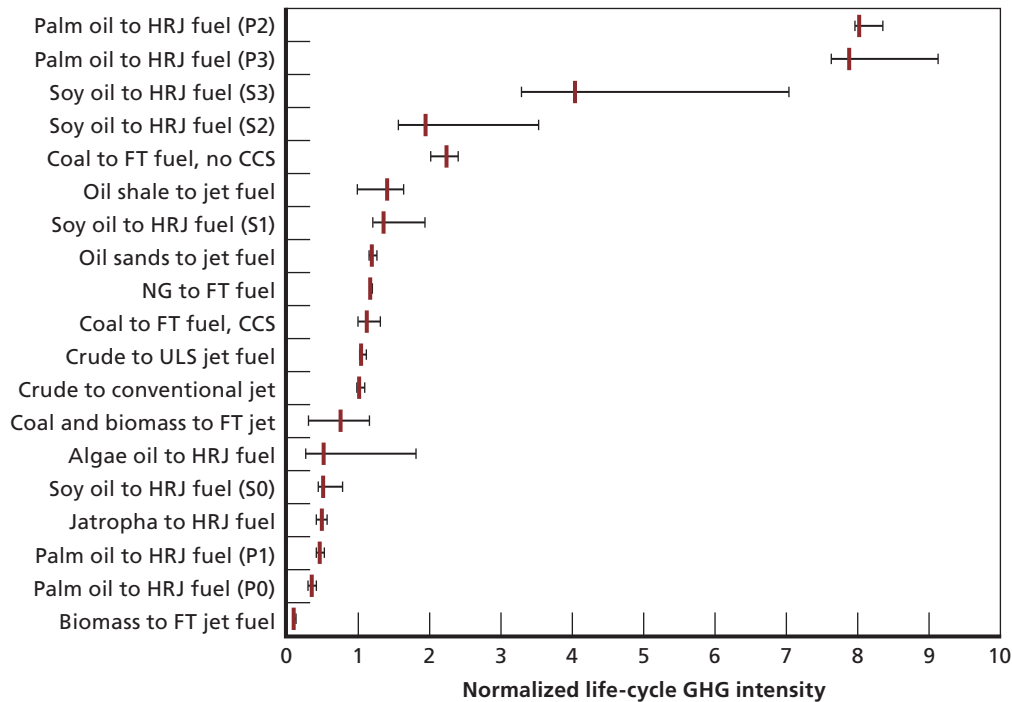
| Fuel | Compatibility | FRL | 2017 Production Potential | Production Cost | WTW GHG Emissions | Air Quality | Merit for Aviation Use |
|--|---------------|-----|---------------------------------|--------------------|----------------------|-------------|---------------------------|
| ULS Jet A from conventional petroleum | - | +++ | +++ | ○ | - | ++ | ○ |
| Jet A from oil sands or VHOs | ○ | +++ | + | ○/+ | -- | ○ | ○ |
| Jet A from oil shale | -/○ | -- | --- | --/○ | ---/○ | +/** | ○ |
| FT fuel from coal | - | ++ | ○ | ○ | --- | ++ | ○ |
| FT fuel from coal with CCS | - | -/+ | ○ | ○ | --/** | ++ | ○ |
| FT fuel from biomass and coal with CCS | - | -/+ | -- | -/○ | --/** | ++ | ○ |
| FT fuel from NG | - | +++ | ○ | -/○ | -- | ++ | ○ |
| FT fuel from biomass | - | + | --- | --- | +++ | ++ | ○ |
| Biodiesel | --- | +++ | No estimate | No estimate | No estimate | No estimate | - |
| Biokerosene | --- | +++ | No estimate | No estimate | No estimate | No estimate | - |
| HRJ (100%) | - | ++ | -/+ | No estimate | ---/** | ++ | ○ |
| Ethanol (100%) | --- | +++ | No estimate | No estimate | No estimate | No estimate | - |
| Butanol (100%) | -- | + | No estimate | No estimate | No estimate | No estimate | - |

NOTE: Definitions for the fuel ratings are given in Table 8.1. For oil sands and VHOs, the production potential applies to resources located in Canada and Venezuela, respectively. The range of FRL ratings for FT fuel from coal with CCS is based on geological sequestration, -, and EOR, +.

However, major uncertainties surround the development of coal-derived liquids. These uncertainties include the future course of world oil prices, FT production costs, and regulatory and technical issues associated with managing the large amounts of CO₂ that would be released during production. If these issues are favorably resolved, large increases in FT jet-fuel production might occur after 2017. For nearer-term production, our best estimate is that private funding of CTL production requires that investors be confident that oil prices remain in or above the range of \$60 to \$70 per barrel over the operating life of the production facility.

Jet fuel produced at a CTL facility employing CCS will have life-cycle GHG emissions that are comparable to those of conventional Jet A; without CCS, the life-cycle GHG emissions would be approximately twice those of conventional Jet A. Depending on the amount of biomass that is used and whether CCS is employed, fuel produced from a combination of coal

Figure 8.1
Normalized Life-Cycle Greenhouse-Gas Emissions for the Low-, Baseline, and High-Emission Cases for Jet-Fuel Pathways



NOTES: Land-use-change scenarios are defined in Table B.2 in Appendix B.

RAND TR554-B.1

and biomass at a production facility employing CCS could have life-cycle GHG emissions that are less than 50 percent of those of conventional Jet A.

HRJ is derived from the same renewable oil resources that are or can be used to produce biodiesel fuels for ground-based applications, such as automotive transport and heating. By 2017, global production of fuels from renewable oils has the potential to reach beyond 300,000 bpd, of which about 20 percent could be located in the United States. Beyond 2017, larger amounts of fuels might be produced from renewable oils, but developing an estimate of the longer-term production potential is complicated by major uncertainties associated with the environmental and economic impacts of the major land-use changes required to sustain production levels beyond the near-term maxima.

Life-cycle GHG emissions and production costs of HRJ depend strongly on the source of the underlying renewable oil. For HRJ produced from waste oils or from crops grown without land-use changes (direct or indirect) that would release large amounts of soil carbon as CO₂ when converted to agricultural use, life-cycle GHG emissions would be well below those associated with Jet A from conventional petroleum. These criteria would apply to a small fraction of the maximum production level estimated in the preceding paragraph. Life-cycle GHG emissions could be comparable to or significantly exceed those of conventional Jet A for situations in which the cultivation of crops for renewable-oil production results in large releases of CO₂ due to either direct or indirect land-use changes.

In the absence of government subsidies, HRJ produced from soybeans would be competitive with conventional Jet A at crude-oil prices in the range of \$80 to \$110 per barrel. This

range reflects uncertainties regarding the future price of soybean oil, especially when food and energy applications are competing for the product. Production costs for HRJ produced from waste oils could be considerably less. We did not examine production costs associated with other oils.

In the Next Decade, Alternative Fuels to Reduce Aviation's Impact on Climate Will Be Available, Although Supplies Are Limited

Certain HRJ and FT fuels are able to reduce the GHG emissions from aviation. For HRJ to be effective in reducing GHG emissions, it must be produced from oils that do not incur land-use changes, either directly or indirectly, that cause a large release of other GHGs. This constraint places a severe limit on the amount of climate-friendly HRJ that can be produced within the next decade.

For FT jet fuels to be effective agents for GHG reduction, they must be produced from biomass or a combination of coal and biomass. In the former case, the fuels will be very expensive and demand extensive cultivation of biomass for inputs. In the latter case, capture and sequestration of plant-site carbon emissions would be required, but overall costs would be much less, as would biomass consumption. In either case, the provision of biomass must not incur land-use changes, either directly or indirectly, that cause a large release of GHGs. For FT-derived fuels, as opposed to HRJ, this is a less restrictive constraint, since the gasification process accepts a broad range of biomass feedstocks.

Provided that sufficient renewable feedstocks are available and that they are grown without incurring CO₂ emissions from land-use changes, these alternative fuels have the potential to reduce life-cycle GHG emissions by up to 90 percent relative to conventional Jet A. However, increasing production of biofuels is leading to changes in the agricultural industry, and this may lead to unintended consequences, such as indirect land-use changes. The large-scale production of these fuels would require that considerable tracts of land be converted from alternative uses, incurring direct land-use changes. If the production of the biofuel feedstock results in either direct or indirect land-use changes, then the life-cycle GHG emissions could increase dramatically.

Within the next decade, the North American resource base of plant and animal oils and biomass can support only limited production of HRJ. The near-term growth of FT-type jet fuel from production facilities based on the gasification of biomass or a combination of coal and BTL via FT technology is limited by lack of commercial experience in operating such plants and in sequestering CO₂. Considering both HRJ and FT jet fuels that yield low GHG emissions, production of aviation fuel will be limited to a few thousand barrels per day. If the time horizon for the use of alternative jet fuels is extended beyond the ten-year limit applied to this study, much larger amounts of these fuels could be produced without stressing biomass-production systems significantly. In particular, producing 3 million bpd of transportation fuels using BTL FT requires that about 500 million tons per year of biomass be delivered to production facilities. Using a 30/70 biomass/coal mixture (by energy) with CCS would allow the same amount of alternative-fuel production and a WTW GHG reduction of more than 60 percent but would require the use of roughly 150 million tons of biomass per year.¹

¹ This assumes 85 percent carbon capture and no GHG credit for coproduced electricity; see GIACC (2009). If the capture efficiency were 90 percent and a GHG credit were given for coproduced electricity, the reduction would be nearly 70 percent (Bartis, Camm, and Ortiz, 2008, p. 40).

Potential worldwide renewable oil sources for HRJ could include such crops as jatropha, babassu, camelina, rapeseed (canola), halophytes, and algae grown specifically for energy applications in controlled environments. Likewise, the combination of coal and biomass resources is available in numerous nations, especially Russia, China, India, and Australia.

Drop-In Fuels Have Considerable Advantages over Other Alternatives

In the foreseeable future, air transportation is likely to continue to rely heavily on petroleum-derived kerosene jet fuel. Most of the alternative fuels we examined scored well regarding their compatibility with current systems. As these fuels become available, they can gradually enter the fuel supply chain serving aviation. Four of the alternative fuels we examined—biodiesel, biokerosene, ethanol, and butanol—scored poorly on compatibility with current systems. Further research may show approaches by which the safety problems associated with aviation use of one or more of these fuels might be overcome. However, none of these fuels offers sufficient benefits, considering production costs, environmental performance, and production potential, to warrant a large investment either in research or in the infrastructure modifications that would likely be required to accommodate such fuels. Additional fundamental issues argue against using alcohol and biodiesel/kerosene fuels, as further reviewed later in this chapter.

In a longer time frame, it is possible that an alternative jet fuel could be developed that would provide sufficient benefits to aviation and that would be available in sufficient quantities to warrant major modifications to the infrastructure (aircraft plus fuel delivery and handling). However, no alternative fuel that can be available in large quantities offers sufficient price or environmental benefits to aviation to warrant major changes in infrastructure for at least the next decade.

Some Fuel Feedstocks May Provide Greater Benefits If Used for Purposes Other Than Alternative Jet Fuels

The significant public and political pressures faced by aviation to reduce its impact on the environment are a strong driver behind the active pursuit of alternative jet fuels. As an example, global climate change has been cited as a reason for rejecting multiple airport-expansion projects in airports near London, UK. However, all of the alternative fuels considered in this study, regardless of feedstock, could be used by ground transportation either in pure form or as a blending stock with conventional petroleum-based fuels. Because they are fungible with ground-transportation fuels, the relative merit of a fuel for use as an aviation fuel has been noted to take into account that the fuels and markets for aviation and ground transportation are related. Similarly, the same biomass feedstock could be used to generate electricity, heat, fuels for ground transportation, or fuels for aviation.

For example, FT fuels and HRJ are attractive aviation fuels because they have specific energies that are slightly greater than current petroleum-derived jet fuel; however, these fuels are also high-performance fuels for ground transportation based on their high cetane number. Under current U.S. and European regulations for automotive fuels, the exceptionally low sulfur and aromatic content of these fuels yields a higher price premium for ground applications. So long as the specification for jet fuel allows sulfur content of the order of 100 ppm or higher, it is unlikely that aviation uses of ULS alternative fuels will be cost competitive with automotive applications.

In the next decade, if not longer, the potential supplies of all of the alternative fuels, other than ULS Jet A, examined in this study will be limited. Forcing certain of these fuels into one

or another application (e.g., aviation versus automotive) may result in severe diseconomies and reduce progress toward reducing overall GHG emissions and increasing energy security.

Alcohols Do Not Offer Direct Benefits to Aviation

Ethanol, as a ground-transportation fuel, is technologically mature and has a resource base capable of supporting significant production. It offers no direct benefit to aviation: The high vapor pressure of ethanol poses problems for high-altitude flight and safe handling. Ethanol is not suitable for use in current aviation-fueling infrastructure. Butanol suffers similar challenges. Because of the reduced energy density, aircraft operating on either ethanol or butanol, as opposed to petroleum-based Jet A, would have substantially reduced operating capabilities and would be less energy efficient.

Depending on the aircraft type, the aircraft's range with a full tank² would be reduced by 52 to 66 percent when using ethanol, and it would be reduced by 33 to 54 percent when using butanol (Hileman and Donohoo, 2009). In addition, aircraft operating on alcohols require more energy to travel any distance than they would need if Jet A were in the tank. This is because the reduced specific energy of alcohol fuels requires that additional fuel be carried, which increases the weight of the loaded aircraft and degrades performance. If it were possible to deploy ethanol throughout the global commercial aviation fleet, 9 percent more energy would be required than if conventional, kerosene-based Jet A were used. Butanol, if it were commercially available, would require 4 percent more energy. This effect is not present in ground transportation: Cars operating on alcohol- and petroleum-derived gasoline require comparable amounts of energy to travel a given distance because they can refill as needed, compensating for the reduced energy being carried in their fuel tanks. Aircraft, however, must carry enough energy to travel between two fixed points without refilling en route. Therefore, because biomass-based alcohols are a limited resource, society receives a larger GHG benefit when biomass-based alcohols are used in ground transportation. Fuels that have specific energy lower than that of conventional Jet A will, in general, suffer a similar energy and GHG penalty when they are considered for aviation use relative to ground-transportation use.

Because of their reduced energy density, their impacts on aircraft range, the handling and operational considerations involved in their safe use, and the limited supply of biomass to create them, alcohol fuels are clearly better suited for ground-based transportation applications.

Biodiesel and Biokerosene Are Not Appropriate for Use in Aviation

Biodiesel and biokerosene are produced through the chemical conversion of plant oils and animal fats to methyl esters and are collectively known as FAMES. These compounds, and impurities derived from the source oils and fats, break down and leave deposits when subjected to the high temperatures of aircraft fuel systems. This thermal instability constitutes a significant safety issues when using these fuels in aircraft. Additionally, FAME fuels have freeze points higher than those of petroleum-based jet fuel, potentially leading to other problems in fuel systems. Finally, FAME fuels may break down during storage. It is for these reasons that most recent aviation tests of fuels derived from plant oils have used HRJ.

² This is the range with full tanks and maximum takeoff weight, which is denoted as *R2* in Hileman and Donohoo (2009).

The Economic Benefits of Producing Alternative Transportation Fuels Extend to All Petroleum Users

The major societal economic benefit of producing alternative fuels is a reduction in the demand for conventional petroleum, which would cause world oil prices to be lower than they would otherwise be. This lowering of world oil prices is independent of whether the alternative-fuel production and use occurs in the United States or in some other country. This effect is also independent of whether the alternative fuel is used in aircraft or in some other application in which conventional petroleum is used, such as ground transportation, building heating, and industrial process heating. Further, it is independent of whether the reduction in demand is due to additional supply or to conservation. The world oil-price reduction stemming from each additional 1 million barrels of alternative-fuel supply is estimated to be 0.6 to 1.6 percent of the oil price that would otherwise prevail.³

Alternative-Fuel Production Yields Large Benefits to Commercial Aviation, Whether or Not Those Fuels Are Used in Aviation

In the next decade, large amounts of alcohol-based fuels and fuels derived from oil sands and VHOs will likely enter the world oil market. For example, these sources dominate the unconventional category in EIA's 2009 projection of future supplies of liquid fuels, which show unconventional sources yielding about 7.5 million bpd in 2017.⁴ According to prior RAND analyses, this level of production would cause long-term world oil prices to be between 5 and 12 percent lower than what they would be in the absence of such production. For world crude oil prices in the range of \$100 per barrel, this amounts to a price impact of roughly \$5 to \$13 per barrel.

These calculations suggest that the existence of 7.5 million barrels of alternative-liquid fuel production in 2017 will save the aviation community between \$5 and \$13 per purchased barrel of jet fuel. In 2017, jet-fuel consumption in the United States (commercial aviation plus military) is projected to be about 1.6 million bpd (EIA, 2009a). Applying the per-barrel savings to this consumption yields net annual jet-fuel cost savings of between \$2.7 billion and \$7 billion. For each million barrels per day of alternative-fuel production added or subtracted, jet-fuel cost savings in the United States would increase or decrease by roughly \$0.4 billion to \$0.9 billion per year.

The preceding calculations are based on crude oil prices of \$100 per barrel. Net savings are roughly linear with crude prices, so if crude oil is selling in the \$50-per-barrel range, the net savings would be reduced by half.

The Ability of Alternative Jet Fuels to Reduce Price Volatility Is Limited

A mature alternative-fuel industry could improve the resilience of the fuel-supply chain in the United States, since there could be a greater diversity in the geographic locations at which finished fuels, including jet fuel, are produced. For example, alternative-fuel production from coal, oil shale, or biomass would likely result in a smaller fraction of fuels being produced in U.S. Gulf Coast refineries that are vulnerable to operational disruptions from hurricanes and

³ The wide range in the estimate is due to uncertainties in the behavior of OPEC and the price elasticities of petroleum.

⁴ Within EIA's projection for 2017 are a few hundred thousand barrels per day of alternative liquid fuels from coal, natural gas, oil shale, and biomass (other than alcohol). Note that the production metric in Tables 8.1 and 8.2 is based on maximum potential and does not include consideration of price or competing fuels.

other adverse weather events. To the extent that operational disruptions are smaller than they would otherwise be, price volatility of conventional fuels, and likewise of substitutes, will be dampened.

When the cause of price volatility is fluctuations in supply and demand, the existence of a commercial alternative-fuel industry will not dampen price fluctuations, at least in the next few decades. During this time frame, finished fuel prices will be determined by the world price of conventional petroleum, which will be supplying the bulk of global liquid-fuel demand. Consumers willing to sign long-term contracts with alternative-fuel producers should be able to lower their susceptibility to price variations; however, this same type of protection is also available for purchases of conventional-petroleum products.

An Ultralow-Sulfur Specification for Jet A Would Reduce Aviation's Impact on Air Quality

By changing how it is refined from conventional petroleum, jet fuel could be produced with very low sulfur levels (e.g., between 10 and 100 ppm). Fuel sulfur leads to the formation of both primary and secondary PM; both of these contribute to ambient levels of PM_{2.5}, an EPA criterion air pollutant that affects human health.

In recent years, the United States and other nations have moved to desulfurize ground-transport and maritime fuels. ULS jet fuel would virtually eliminate secondary PM due to SO_x emissions while also reducing primary-PM emissions. Desulfurization would also alter aviation's impact on global climate change. Increased hydroprocessing during refining could result in an increase in life-cycle GHG emissions of about 2 percent, and use of a ULS jet fuel would eliminate sulfur aerosols, which have a short-term cooling effect.

As seen in experiences from the diesel industry and based on the potential need to include lubricity additives, the production of a ULS (15 ppm) jet fuel could add \$0.04 to \$0.07 per gallon to the fuel price (EPA, 2000a, 2006; EIA, 2001) and result in an approximately 1-percent increase in the fuel volume consumed (because of a change in fuel energy density that accompanies the hydrodesulfurization process). A ULS specification for jet fuel could potentially improve refinery scheduling and operations and reduce multiuse pipeline issues stemming from the transport of fuels with varied sulfur specifications. At present, the relatively high sulfur content of Jet A necessitates special handling requirements to avoid sulfur contamination of ULS diesel.

Many of the alternative fuels considered in this study, such as synthetic paraffinic fuels and possibly fuels derived from shale oil, meet a potential ULS standard (i.e., less than 15 ppm). These fuels have been shown to reduce primary-PM emissions, and their use could result in further air-quality benefits relative to jet fuel.

Recommendations

From its findings, the research team makes the following recommendations.

Measures Designed to Lower Greenhouse-Gas Emissions Should Not Treat Commercial Aviation Separately from Other Sectors

In particular, national laws and regulations aimed at lowering GHG emissions should place commercial aviation under a multisector umbrella or cap. At a minimum, that umbrella or cap should include other transportation sectors. Our findings on alternative fuels in the near

term show that the opportunities that are available to reduce WTW GHG emissions during aviation operations are costly and potentially counterproductive. For at least the next decade, the feedstocks (and associated land requirements) used to produce low-GHG alternatives to Jet A (such as FT jet fuel via CBTL or HRJ) are limited in supply. These same feedstocks can also be used to make low-GHG automotive fuels or be used for other energy needs. Rather than legislating or regulating the sector to which these feedstocks should be directed, we suggest broader-based mechanisms that place a price on GHG emissions and allow economically efficient choices to be made across multiple sectors. Examples of these approaches include cap-and-trade systems and carbon-tax-and-rebate systems.

Any Measures Designed to Promote Alternative-Fuel Use in Aviation Should Consider the Potentially Large Greenhouse-Gas Releases Associated with Land-Use Changes Required for Cultivating Crops for Producing Biomass or Renewable Oils

Although the magnitude of the GHG releases associated with land-use changes remains a topic of research, sufficient information is available to warrant a precautionary approach. This is a special concern for any fuel produced from energy crops grown in carbon-rich soils, such as palm oils. The potential magnitude of GHG release is sufficiently large that we recommend that no GHG credit be given to any biofuel production from deforested areas until EPA establishes criteria for accounting for direct and indirect land-use changes. As directed by the Energy Independence and Security Act of 2007, the EPA is in the process of establishing these criteria (EPA, 2009).

Establish a Standard Methodology for Assessing Life-Cycle Greenhouse-Gas–Emission Inventories and Impacts

At present, uncertainties associated with the treatment of fuel production and in-flight GHG emissions allow for a broad range of emission estimates and impacts for alternative jet fuels. To better prepare commercial aviation for potential regulation of GHG emissions, a standard methodology for estimating life-cycle GHG-emission inventories and impacts is required.

With regard to fuel production, the important issues are also common to other sectors dependent on liquid fuels. One common issue is establishing a baseline emission for conventional-petroleum fuels, taking into account key inputs, including crude-oil properties, refining efficiency, and the allocation of production (extraction, crude delivery, and refining) emissions to the various final products (e.g., gasoline, diesel, jet fuel, petroleum coke). For alternative-fuel production, the key issues include allocating production emissions or emission credits to multiple final products (including electricity) and establishing standards for estimating emissions associated with direct and indirect land-use changes.

With regard to flight-related emissions, a standard methodology and metric are needed to allow proper accounting of high-altitude non-CO₂ combustion emissions and the formation of contrails and contrail-cirrus clouds.

Further research is required to resolve some of the uncertainties mentioned here—in particular, those regarding engine-combustion emissions at cruise and emissions resulting from land-use changes. Recognizing that resolving these issues through research will take some years and that decisions regarding the control of GHG emissions may be sooner rather than later, tentative standards for assessment methodology could be appropriate.

For Improved Air Quality, Consider the Adoption of a Reduced-Sulfur Standard or an Ultralow-Sulfur Jet Fuel

Given the human-health impact of aviation emissions of PM and gaseous PM precursors during takeoff, landing, and ground operations, the aviation community should consider the adoption of a ULS jet fuel. ULS jet fuel would virtually eliminate secondary PM due to SO_x emissions (greater than a 97-percent reduction) while also reducing primary-PM emissions due to sulfur (by about 15 percent).

A ULS specification for jet fuel could have the effect of bringing aviation to a similar specification to that of highway diesel fuel, potentially improving refinery scheduling and operations and multiuse pipeline operations. The introduction of a ULS jet-fuel specification would act to ease the introduction of FT synthetic fuels and HRJ into commercial aviation, as they pose similar concerns in terms of infrastructure compatibility of lubricity and effect on seals due to their low sulfur and reduced aromatic content. Finally, unlike new aircraft and engine technologies, which take some time to diffuse into the fleet, the air-quality benefits of sulfur elimination could be realized as soon as ULS jet fuel were introduced.

Adverse consequences of a ULS jet fuel would be higher fuel prices (by about \$0.05 per gallon), a slight increase (about 1 percent) in the fuel volume purchased and consumed, a slight reduction (about 1 percent) in the aircraft range with full fuel tanks, a small increase (by about 2 percent) in life-cycle (i.e., WTW) GHG emissions, and the near elimination of the climate-cooling effect of aviation-based sulfate aerosols. The benefits of ULS jet-fuel use in reducing air-quality impact need to be balanced against these potential positive and negative impacts on global climate change and economics. PARTNER, as part of Project 27, is currently examining the environmental costs and benefits of significantly reducing the current jet-fuel sulfur standard.

Utilize Emission Measurements from Alternative Jet Fuels to Understand the Influence of Fuel Composition on Emissions

As part of the SPK certification process, FAA, U.S. Air Force, National Aeronautics and Space Administration (NASA), and some international organizations are currently funding research to measure the emissions from alternative jet fuels. Continuing emission measurements are essential to assess accurately the impact of alternative-fuel combustion on both air quality and climate change. These ground-based tests are often being augmented with emission measurements. Additional testing of alternative jet fuels is anticipated due to the continued strong interest within the aviation community.

Considering that SPK fuels are compositionally similar to jet fuel, with the important exceptions that they are free of sulfur and they are comprised solely of paraffinic compounds, opportunities exist to blend SPK fuels with conventional jet fuel to better understand how changes in fuel composition in terms of fuel-sulfur content and fuel–aromatic compound content affect engine PM emissions. These results could then be used to develop improved relationships between fuel properties (e.g., total aromatic content, naphthalene content, hydrogen-carbon ratio) and PM emissions as well as directing aviation toward changes in the fuel specification that could result in reduced PM emissions.

Support Long-Term Fundamental Research on the Creation of Middle-Distillate Fuels for Use in Ground Transportation and Aviation

Middle distillates represent about 30 percent of the petroleum products used in the United States. They are essential not only to commercial aviation but also to the movement of freight by land, river, or sea. Moreover, middle distillates power the aircraft, ships, and fighting vehicles of the armed forces. At present, the technical options to provide these applications with low-GHG emission fuels are severely limited. Certain FT and hydroprocessed fuels offer lower GHG emissions and reduced engine emissions that degrade surface-air quality. Sustainable production of either of these fuel types requires sustainable sources of renewable feedstocks. This is especially the case for fuels produced from vegetable oils. The extensive use of first-generation feedstocks, such as soy, jatropha, and palm, will incur large land-use changes that will cause a large increase in GHG emissions. Next-generation feedstocks are needed that do not compete with food production and that consume less water.

Conclusions

Alternative sources of fuel for aviation could be used to expand and diversify supplies of jet fuels. To the extent that such alternative fuel supplies reduce world demand for crude oil, world oil prices would be reduced, to the benefit of commercial aviation as well as all other users of petroleum. The same economic benefits to aviation occur through energy conservation (a barrel saved has the same effect as a barrel displaced by alternative fuels) and by expanding use of alternative fuels in ground transportation (a barrel displaced in ground transportation has the same effect as a barrel displaced in aviation). Even though some alternative fuels can be produced at costs that are well below current world oil prices, the prevailing prices will be those associated with petroleum-derived fuels.

If the goal of the commercial aviation community is to moderate the long-term trend of increasing petroleum prices, the preferred strategy consists of promoting efficiency in the use of petroleum in all end-use sectors (including aviation, of course) and promoting alternative-fuel production and use in all end-use sectors that are dependent on petroleum.

Alternative jet fuels that can meet this goal in the short term include the oil sands, VHOs, the FT jet fuels, and HRJ. In the slightly longer term, oil shale might yield commercial quantities of jet fuel at reasonable costs.

If the goal is to moderate cost increases and keep GHG-emission levels on a par with conventional petroleum-derived jet fuel, CCS must be employed with all of the fossil energy-based alternative jet fuels—namely, oil sands, VHOs, FT jet fuels from coal or NG, and oil shale. These jet fuels can be produced at GHG-emission levels that are comparable to or below those of conventional petroleum. In the absence of measures to capture and sequester CO₂, HRJ from certain feedstocks is the only alternative-fuel option available to aviation at reasonable costs.

In the absence of CCS, our research shows that, for oil sands, VHOs, and GTL, life-cycle GHG emissions would increase by 10 to 25 percent, relative to conventional Jet A. For CTL, life-cycle GHG emissions would roughly double.

To achieve GHG-emission levels that are significantly below those of current aviation operations, there exist only two options at reasonable costs: HRJ from certain feedstocks or FT jet fuel produced from a combination of biomass and coal in a production scheme employ-

ing CCS. The technology base for creating commercial quantities of HRJ or FT jet fuel from a mix of biomass and coal is available for initial commercial operations. The use of CO₂ for EOR is also commercially demonstrated, although further research is required to allow confident prediction of long-term CO₂ retention. Demonstration of the commercial viability of geologic sequestration will require at least a decade, to allow for large-scale, long-term testing and evaluation.

The use of HRJ or FT jet fuel would also significantly reduce aviation impacts on local air quality. Efforts are ongoing to certify these fuels for aviation use. Should low-cost feedstocks become available, there would be a ready market for the fuels. If these feedstocks do not require the use of arable land that would otherwise be used for food production, GHG-emission reductions could be significant.

A substantial reduction in the environmental impacts of aviation on air quality could be achieved by removing sulfur from the existing fuel supply. This approach could be fully implemented within five to ten years. The main environmental benefit would be a reduction in PM emissions that degrade air quality. Implementation of a ULS standard for jet fuel, however, would be accompanied by a small (i.e., ~2 percent) increase in life-cycle CO₂e emissions and the elimination of sulfur aerosols from aviation, both of which would increase aviation's impact on global climate change.

Resource Base, Production Potential, and Estimated Production Costs

This appendix documents the analysis of production potential and production costs of certain alternative jet fuels through 2017. This analysis applies to the following resources or fuels: low-sulfur jet fuel, oil sands, VHO, GTL, CTL, CBTL, and certain renewable oils. In general, the resources and fuels considered are North American in origin, but other worldwide resources and fuels are reported when they exist or are produced principally outside North America. These estimates are compared to cases of future jet-fuel demand and price as published by EIA.

The production potential of the fuels is the estimated amount of jet fuel that can be produced from the identified resources in 2017. Several of the resources are already part of the world petroleum supply—Canadian oil sands and Venezuelan VHO—and are being refined into a slate of products, including jet fuel. Other fuels currently constitute a very small part of the world supply of jet fuel—for example, the FT liquids that are produced for aviation use in South Africa. Finally, others currently provide no source of jet fuel (e.g., renewable oils), complicating estimation of future potentially available supply. The production potential is reported in order-of-magnitude estimates.

The production costs reported in this appendix are taken from the literature or estimated using standard methodologies. The cost estimates for CTL, CBTL, and biodiesel are derived from existing low-definition engineering studies available in the literature using a cash-flow analysis model developed for related RAND research (Bartis, Camm, and Ortiz, 2008, Appendix A). Similar assumptions are applied to derive all cost estimates. In these cases, the cost estimates that we report are those for diesel fuel or a fuel that is a potential substitute for diesel fuel. Since jet fuel and diesel fuel are closely related, we assume that the cost of producing a diesel fuel should be close to the cost of producing a jet fuel.

Projections of U.S. Jet-Fuel Consumption and Price

Due to uncertainties regarding the future supply and demand for petroleum-derived fuels, it is not possible to provide confident estimates of the future price of jet fuels. Critical issues affecting future prices include global economic conditions, uncertainties regarding the response of demand and non-OPEC petroleum supply to prices, and uncertainty regarding how OPEC might respond to these factors. Recognizing this problem, most credible projections of global and domestic energy supply and demand are based on one or more assumed world crude-oil price trajectories. Specifically, a future trajectory of crude-oil prices is assumed, and econometric modeling provides estimates of the future supply and demand for various fuels.

For example, EIA generally uses three oil-price trajectories: a reference case and cases representing low and high crude-oil prices (EIA, 2008a). Table A.1 summarizes EIA's three cases, as used in its 2008 projection.

In all three oil-price cases, consumption of kerosene-type jet fuel in the United States is expected to rise from 1.6 million bpd in 2005 to 1.9 million bpd in 2017. Note that EIA's projections assume that domestic demand for jet fuel is unresponsive to prices. Given EIA's range of world crude prices in 2017, the expected price of jet fuel ranges from \$1.20 per gallon to \$2.57 per gallon (2005 dollars).¹

Resource Base and Production Potential

Table A.2 summarizes the results of the assessment of production potential in 2017. The production potential listed in the table represents the order of magnitude of the maximum amount of aircraft-appropriate fuel that could be produced by the resources described in this section. It does not represent a prediction of the amount of fuel that will be available for aviation use. The latter is a function of many factors, including future world crude-oil prices, general economic conditions, government policies, availability of appropriate fuel-distribution networks, and the willingness of investors to accept the risks inherent in building pioneer commercial plants. For example, if EIA's low-oil price trajectory holds, we anticipate negligible production of jet fuels from coal and biomass in the absence of major government incentives that would promote, or mandates that would require, investments in alternative-fuel production.

Ultralow-Sulfur Jet Fuel

Producing sufficient low-sulfur jet fuel to satisfy projected demand for jet fuel would require additional desulfurization capacity at U.S. refineries and abroad. U.S. refineries made a

Table A.1
Current and Projected Consumption and Price of Crude Oil and Jet Fuel in the United States

| Factor | 2005 Actual | 2017 Case | | |
|--|-------------|-----------|----------------|---------------|
| | | Reference | High Oil Price | Low Oil Price |
| World crude-oil price (\$ per barrel of low-sulfur, light crude oil) | | 55.37 | 92.72 | 37.48 |
| Jet-fuel consumption (million bpd) | 1.6 | 1.9 | 1.9 | 1.9 |
| Jet-fuel price (\$/gallon) | 1.74 | 1.68 | 2.57 | 1.20 |
| Jet-fuel share of total transportation-fuel consumption (%) | 12 | 13 | 14 | 13 |
| Jet-fuel share of total petroleum consumption (%) | 8 | 9 | 10 | 9 |

SOURCES: EIA (2008b, Tables 5.13c, 5.22, and D.1); EIA (2008a).

NOTE: Includes military use of jet fuel. All prices are in 2005 dollars. Jet-fuel prices include federal and state taxes (EIA, 2008b, Table 5.22). Consumption shares are calculated on equivalent energy basis to account for the different energy densities of finished petroleum products.

¹ All adjustments for dollar years are made using the implicit gross domestic product (GDP) deflator (BEA, 2008).

Table A.2
Alternative-Fuel Production Potential to Meet U.S. 2017 Jet-Fuel Demand

| Fuel | Potentially Available Production of Aircraft-Compatible Fuel (bpd) | Notes |
|---------------------------------|--|--|
| ULS jet fuel | 2 million | Requires sufficient lead time to allow refinery conversion and infrastructure modifications. |
| Jet fuel from oil sands and VHO | 300,000–400,000 | A portion of this production is already part of current oil and jet-fuel supply. |
| Jet fuel from oil shale | 5,000–10,000 | Production from several pioneer facilities. |
| Jet fuel from NG | 50,000–75,000 | Represents non-U.S. production capacity. Potential to reach U.S. jet-fuel market is low. |
| Jet fuel from coal | | Maximum estimates that assume early construction of proposed U.S. production facilities. |
| Overall | 75,000 | |
| Portion from coal and biomass | 12,000 | |
| Jet fuel from renewable oils | | Both biodiesel and HRJ are produced from the same feedstocks. |
| U.S. | 65,000 | |
| Worldwide | 300,000–400,000 | |

similar—and larger—transition in meeting the ULS highway diesel requirement. The key issues center on how quickly a low-sulfur rule for jet fuel could be phased in and what the impact would be on jet fuel prices. Resolving these issues requires consideration of aircraft and jet-fuel distribution-system compatibility issues and an analysis of the marginal costs (and benefits) of alternative sulfur standards for jet fuels. Lessons learned from the ongoing process of phasing in ULS highway diesel should be valuable—see, for example, EPA (2000a). Based on that experience, an eight-year lead time (2009–2017) should be adequate for rule making, refinery conversion, and infrastructure modifications, supporting an estimated production potential of about 2 million bpd of ULS jet fuel.

Jet Fuel from Canadian Oil Sands

Presently, Canadian oil sands yield the crude-oil equivalent of approximately 1.5 million bpd. The majority of Canada's oil sands are located in the province of Alberta, with reserves of remaining recoverable bitumen estimated to be 173 billion barrels.² Of this amount, 31 billion are suitable for recovery via surface mining, and the remaining 142 billion barrels will likely have to be recovered by an in situ extraction approach (ERCB, 2008).³ Most production of Canadian oil sands through 2006 has been through mining (3.7 billion barrels versus 1.8 billion barrels for in situ extraction).

² For comparison, Saudi Arabia has 264 billion barrels of proven reserves of conventional petroleum, 21.9 percent of the world's total and almost twice the reserves of the next leading country (Iran) (BP, 2007).

³ In in situ extraction, steam is pumped into the oil-sand deposit, heating and thinning the bitumen so it can flow to wells and be recovered. In 2005, about 65 percent of Alberta's bitumen production was recovered by surface mining (NEB, 2006).

From current production levels and projects under active development, we anticipate that oil-sand production in 2017 will be at least 2 million bpd by 2017. A number of estimates for future production of oil sands have been published. Estimates from Canadian sources suggest an upper bound for production in 2017 of roughly 3 million bpd (Toman et al., 2008). Where in this range actual levels of production will fall will be determined by the future course of world oil prices and the resolution of major socioeconomic and environmental issues associated with oil-sand production. These include the following:

- the ongoing effects of oil-sand operations in the Canadian boreal forest, including air quality and groundwater pollution, and the extent and success of reclamation activities
- the requirements for water in the extraction and processing of oil sands and potential limits on water resources from the Athabasca River
- the price and availability of NG, which is used to produce steam and hydrogen for extraction and upgrading operations, and the development of potential substitutes
- the availability of both skilled and unskilled labor and infrastructure in the lightly developed oil-sand regions.

Assuming that production of Canadian oil sands rises to between 2 million and 3 million bpd of synthetic crude oil and bitumen in 2017, and that 10 percent of this production is refined into jet fuel (an amount consistent with the amount of crude oil refined into jet fuel as in Table A.1), Canadian oil sands may contribute 200,000 to 300,000 bpd to jet-fuel supplies.

Jet Fuel from U.S. Oil Sands

U.S. resources of bitumen have not been exploited and are not characterized as thoroughly as the resources in Canada. Major deposits of bitumen in the United States (larger than 100 million barrels) can be found in Alabama, Alaska, California, Kentucky, New Mexico, Oklahoma, Texas, Utah, and Wyoming (USGS, 2006). Utah contains the largest volume of resources. The total U.S. oil-sand resource is estimated at 54 billion barrels in the form of bitumen, of which 22 billion are considered to be *measured*, and 32 billion are considered *speculative* (University of Utah, 2007).⁴ The estimates of resources in place do not indicate how much of that resource may be recoverable or at what cost.

U.S. oil sands are different in character from their Canadian counterparts. For example, U.S. oil sands are hydrocarbon wetted, whereas Canadian oil sands are water wetted. As such, the methods used to produce Canadian oil sands may be less productive when applied to the resources located in the United States. Moreover, the geology of U.S. oil-sand deposits and the rugged terrain where they exist will likely make extraction of bitumen more difficult in the United States than it is in Canada (BLM, 2008a). Therefore, though U.S. oil-sand resources are large, within the next several decades, they are not likely to add appreciable liquid-fuel capacity to the United States (Bartis, Camm, and Ortiz, 2008) and are not included in Table A.2. This finding is supported by the apparent low-level of commercial interest in developing oil-sand resources located in the United States.

⁴ Speculative resource estimates are highly uncertain because they are typically the result of extrapolating observations of surface resources below the surface (USGS, 2006).

Jet Fuel from Venezuelan Very Heavy Oil

VHO is a significant worldwide resource. In 2003, the estimated amount of technically recoverable VHO was 434 billion barrels (Meyer and Attanasi, 2003). More than 60 percent of the world's VHO resources are in South America, which is estimated to hold 266 billion barrels of recoverable heavy oil and VHO. Venezuela holds an estimated 1.2 trillion barrels of VHO resources in place, of which an estimated 200 billion barrels are technically recoverable VHO. Venezuela's proven oil reserves, which include conventional, heavy, and very heavy oil, are estimated to be 80 billion barrels (EIA, 2007a).

Production of VHO from Venezuela is expected to grow. Estimated production of VHO was 600,000 bpd in 2005 (EIA, 2008a). In the EIA reference case, production is expected to rise to 900,000 bpd in 2015 and 1.0 million bpd in 2020, and in the high-oil price case, production is expected to rise to 1.1 million bpd in 2015 and 1.5 million bpd in 2020. How much of this production will actually occur is uncertain. Venezuela has recently nationalized its oil sector, and production has fallen (Romero, 2007). Assuming that production of VHO is approximately 1 million bpd in 2017 and that 10 percent of this is refined into jet fuel (consistent again with the average amount of crude oil refined into jet fuel, per Table A.1), then VHO may add approximately 100,000 bpd of jet fuel to supplies. Combining this production potential with the 200,000- to 300,000-bpd estimate for Canadian oil sands yields the total estimate in Table A.2—namely, a combined total aviation-appropriate fuel production of 300,000 to 400,000 bpd.

Jet Fuel from Oil Shale

U.S. oil-shale resources are very large, estimated to be from 1.5 trillion to 1.8 trillion barrels in several basins throughout the Green River Formation in Colorado, Utah, and Wyoming. Total potentially recoverable resources are estimated at between 500 billion and 1.1 trillion barrels. The midpoint of this range, 800 billion barrels, is more than triple the total conventional-petroleum reserves of Saudi Arabia (Bartis, LaTourrette, et al., 2005). Extracting oil from oil shale is intrinsically more complicated than conventional-oil recovery. In particular, the solid shale must be heated to a high temperature in the absence of oxygen, and the resultant liquid must be separated, collected, and upgraded.

There is presently no commercial production of oil shale in the United States. Extensive efforts were undertaken during the 1970s and 1980s for the purpose of developing commercially viable oil-shale technologies. Most past efforts focused on approaches that involved mining the shale, crushing it, and heating it in large, aboveground vessels called retorts. Aided by federal subsidies, the Union Oil Company (later Unocal and now part of Chevron) built a pioneer commercial plant that produced a few thousand barrels of liquids per day. But this plant, as was the case with all other commercial plants for oil shale, was far from competitive with conventional oil selling at the low prices prevailing during the latter half of the 1980s and the 1990s.

The much higher oil prices that have prevailed since 2003 have renewed interest in oil-shale development. In particular, a number of firms are developing technical approaches based on in situ retorting and extraction, in which the oil-shale deposit is heated, perhaps for several years, and the resource recovered via producing wells. The recovered resource may be refined to meet specifications for transportation fuels. In December 2006, BLM issued small lease tracts in Colorado to Shell, Chevron, and EGL Resources. The purpose of the leases was to conduct RD&D of in situ methods for producing fuels from oil shale. In April 2007, BLM awarded an

additional RD&D lease in Utah to Oil Shale Exploration, which seeks to mine and surface-retort oil shale.

Ultimately, oil shale within the United States might be capable of supplying between 2 million and 4 million bpd of transportation fuels. But reaching these high levels of production will take decades. For example, a production level of 1 million bpd is, at best, about 20 years into the future (Bartis, LaTourrette, et al., 2005). This time lag is caused by the need to scale up and verify the economic and environmental viability of advanced technologies and the time required to address substantial barriers to a full-scale industrial development. These barriers are large and include high water consumption (in an arid region), limited availability of labor and community facilities and services (in a sparsely settled region), environmental constraints (especially land-use issues, GHG emissions, air-quality controls, and groundwater protection), and cost uncertainties.

By 2017, we anticipate that, at most, a few pioneer commercial oil-shale projects will be undergoing their initial start-up. In total, liquid production will likely be no more than 50,000 bpd. This level of production would be sufficient to support the production of between 5,000 and 10,000 bpd of jet fuel.

Jet Fuel from Natural Gas

World reserves of NG are equal in energy content to 1.14 trillion barrels of oil—a reserve that compares to world petroleum reserves of 1.37 trillion barrels of oil (BP, 2008). Converting NG to liquid fuels or shipping it as LNG are attractive options when the NG is *stranded*, meaning that the resource is located far from significant centers of demand and without pipeline capacity to transport it. Qatar, for example, possesses NG reserves of 160 billion barrels of oil equivalent and has been constructing both LNG facilities and GTL facilities employing FT synthesis.

As oil prices rose earlier in this decade, considerable commercial attention was directed at the potential of GTL facilities. Early projections anticipated that a few million barrels per day of production could be in place by 2030 (see, for example, IEA, 2006). More recently, these estimates have been scaled back, in light of continued political turmoil in Nigeria and Qatar's decision to reevaluate additional construction beyond the current Sasol and planned Shell facilities. Considering current and planned GTL production in South Africa, Malaysia, and Qatar, we estimate that 2017 global GTL production will be between 200,000 and 300,000 barrels (diesel-oil equivalent) per day.⁵ At most, one-quarter of this production, 50,000 to 75,000 bpd, could be economically dedicated to jet-fuel production. This amount of jet fuel could be delivered to the United States, but a more likely outcome is that GTL middle distillates will meet diesel and jet-fuel demands in the Middle East, Europe, and Asia.

Because of the high value of, and growing demand for, NG in the United States, domestic production of jet fuel via GTL approaches is highly unlikely.

Jet Fuel from Coal

The United States possesses vast resources of coal. Estimates of proven coal reserves are about 270 billion tons (EIA, 2006b; Task Force on Strategic Unconventional Fuels, 2007). In 2005, the United States mined slightly more than 1.1 billion tons of coal. The vast majority of this

⁵ Note that this estimate is fully compatible with EIA's latest estimate for GTL production—namely, 200,000 bpd by 2015 and 300,000 bpd by 2020 (EIA, 2008a).

coal, more than 1.0 billion tons, was used to produce electricity in coal-fired power stations. Dedicating 15 percent of these reserves to liquid-fuel production would yield approximately 100 billion barrels of synthetic fuels, which is sufficient to sustain 3 million bpd of production for more than 90 years. Alternatively stated, a CTL industry producing 3 million bpd of coal-derived liquids would require the mining of 550 million tons per year of coal for that purpose alone (Bartis, Camm, and Ortiz, 2008). Depending on future government actions to control GHG emissions, mining coal for the purpose of producing liquid fuels may or may not increase overall coal production significantly beyond current levels.

There is significant development activity worldwide in CTL. Existing capacity in South Africa is approximately 150,000 bpd, of which a portion is used as a blend stock for jet fuel. China is constructing at least two plants with stated capacities ranging from 20,000 to 80,000 bpd. In the United States, four CTL and CBTL facilities have been publicly announced and appear to have progressed to the front-end engineering design (FEED) phase (Toman et al., 2008) (see Table A.3). The FEED phase is the beginning of site-specific engineering design of a facility at a sufficient level of detail to estimate system construction and operating costs and environmental emissions and water requirements. Three of these proposed facilities will employ FT synthesis; one will produce gasoline via the methanol-to-gasoline approach.⁶

Given the development status of a CTL industry in the United States, within the time frame of this study, the availability in the United States of FT jet fuel produced from coal is likely to be limited. Bartis, Camm, and Ortiz (2008) derive an estimate of the maximum production capacity of CTL in the United States, taking into account opportunities for experience-based learning and cost reduction, and demonstration of CCS. Their estimate for 2015 is a maximum production capacity of approximately 200,000 bpd, growing to 500,000 bpd by 2020 (Bartis, Camm, and Ortiz, 2008, Table 3.1). This growing CTL industry would produce

Table A.3
Coal-to-Liquid and Coal Biomass-to-Liquid Facilities That Have Advanced to the Front-End Engineering Design Phase

| Firm | Location | Capacity (bpd) | Feedstock | Notes |
|---------------|--------------------|--------------------------------------|----------------------|--|
| Rentech, Inc. | Natchez, Miss. | 1,600 (phase 1); 28,000 (phase 2) | Coal, petroleum coke | Phase 1, demonstration; phase 2, full capacity |
| Baard Energy | Wellsville, Ohio | 50,000 | Coal, biomass | First phase would be at reduced capacity |
| WMPI | Frackville, Pa. | 5,000 | Waste anthracite | |
| DKRW Energy | Medicine Bow, Wyo. | 15,000–20,000 | Coal | To employ the methanol-to-gasoline process |

SOURCES: Toman et al. (2008, Table 5.1); CONSOL Energy and Synthesis Energy Systems (2008).

NOTE: The FEED for the CONSOL Energy and Synthesis Energy Systems plant, not shown in the table, was canceled in October 2008.

⁶ The methanol-to-gasoline process does not produce jet fuel. For more information on the methanol-to-gasoline process, see Bartis, Camm, and Ortiz (2008).

a slate of products, including diesel fuel, gasoline, naphtha, and jet fuel.⁷ If one-fourth of the production were jet fuel, then U.S. CTL capacity could supply approximately 75,000 bpd in 2017.

Jet Fuel from Gasification of Coal and Biomass

Unlike coal and other fossil resources, the availability of biomass resources for energy applications is not well quantified. Estimating biomass resources requires careful consideration of agricultural, geographic, and economic factors, including alternative land uses, road transportation networks, equipment lifetimes, and variations in yield due to soil quality and weather, among others. Here, we provide an overview of the nongrain-biomass resource base in the United States and indicate key constraints on production and implications for the production of liquid fuels. Nongrain biomass is suitable for conversion to liquid fuels via FT synthesis.

There are two general categories of nongrain biomass. The first is dedicated energy crops, which are crops that are grown for the purpose of producing energy, including electricity in conventional boilers. Examples of dedicated energy crops include switchgrass and poplar or willow trees bred to maximize mass yield. Another potential energy crop in this category is mixed prairie grasses, which are mixtures of indigenous grasses that require few agricultural inputs (Tilman, Hill, and Lehman, 2006). The second broad category of biomass resources is residues. These include agricultural residues, such as corn stover, wheat straw, and manure; limbs and other tree parts left over from logging operations; forest thinnings; and waste, such as municipal wood waste and yard trimmings, and sewage sludge (Bartis, Camm, and Ortiz, 2008).

Several recent analyses have investigated the potential biomass resource that exists and could exist in the United States. A study by Oak Ridge National Laboratory (Perlack et al., 2005) estimated that approximately 330 million dry tons per year of forest residue and thinnings, urban wood waste, and agricultural residue are available annually in the United States, assuming current land use and observed agricultural yields. With more-intensive collection efforts, significantly improved agricultural yields, land-use changes, and inclusion of bioenergy crops, such as switchgrass, Oak Ridge estimates that a biomass industry could produce 1.4 billion dry tons annually. This estimate is based solely on land availability and does not consider the cost of collecting and delivering this biomass. The National Renewable Energy Laboratory (Milbrandt, 2005) estimated that 360 million dry tons per year of such biomass resources could exist, assuming some cultivation on idle farmland. If 700 million tons of biomass were available annually (one-half of the high Oak Ridge estimate), these resources could support a production of approximately 3 million barrels of FT liquids per day. However, actual production may be limited by a number of factors, including current annual per-acre yields of potential biomass crops and the availability of land in the vicinity of a plant for the production of biomass (Bartis, Camm, and Ortiz, 2008).

A promising option with respect to the use of biomass to produce liquid fuels that is considered in several recent studies is to cogasify coal and biomass (NETL, 2007d, 2009; Wil-

⁷ Many current analyses of CTL propose to maximize production of FT diesel fuel. For example, the plants considered in SSEB (2005) and NETL (2007b) yield a product slate of approximately 70 percent diesel and 30 percent naphtha. Jet fuel could constitute a portion of the output from these plants. NETL (2007b) estimated that the same process could be tuned to produce a product slate of approximately 60 percent jet fuel and 40 percent naphtha but did not analyze such a case nor estimate the additional costs involved.

liams, 2006; Bartis, Camm, and Ortiz, 2008). Cogasification helps to achieve several ends. First, the biomass provides a carbon credit, reducing the life-cycle GHG emissions of the FT products. When combined with CCS, fuels produced through cogasification of coal and biomass may have negative life-cycle carbon emissions. Second, a supply of coal can fill in variation in supply that might occur from year to year in the cultivation of the biomass. Third, including both feedstocks allows a plant to achieve economies of scale not available with biomass alone: A plant accepting only biomass would be limited by the amount of biomass economically collectable in the area surrounding it, which, in practical terms, would limit output to approximately 5,000 bpd of FT liquids (Bartis, Camm, and Ortiz, 2008).⁸

The challenges to producing liquid fuels from coal and biomass are technical, and resolving these challenges is the principal constraint in the near-term availability of CBTL. Biomass has different bulk handling and chemical properties than coal. Engineering development is required to demonstrate a reliable processing for feeding the biomass at high pressures into a gasifier and to ensure reliable long-term operation. Notable tests of cogasification of biomass and coal at ratios up to 30 percent biomass have occurred at the IGCC power plant in Buggenum, the Netherlands (Hannemann et al., 2002; van Dongen and Kanaar, 2006). Beard Energy plans to design its facility along the Ohio River to accept up to 30 percent biomass, though initial plans call for a dedicated coal feed (see Table A.3 and Ohio River Clean Fuels, 2007). A joint National Energy Technology Laboratory and U.S. Air Force Study (2007d) estimated that the production potential of CBTL could reach 45,000 bpd by 2017 under an accelerated development schedule. Taking this estimate as the near-term production potential and assuming once again that approximately one-quarter of the total production is jet fuel, there could be 12,000 bpd of FT liquids coproduced from coal and biomass in 2017.

Jet Fuel from Renewable Oils

In this section, we provide a rough estimate of the production potential of jet fuel from plant oils in the next decade. Given the near-term perspective of our efforts, we consider conventional feedstocks, which primarily are plant oils, though relatively small amounts of animal fats are also available. Unconventional feedstocks, which include genetically engineered algae, for example, are not considered.

There are two approaches for using renewable oils in jet aircraft. First, conventional jet fuel can be blended with a small quantity of biodiesel. Equipment for the production of biodiesel is simple, technologically mature, and relatively inexpensive at industrial scales, and the process for producing biodiesel has a very high product yield. The second approach consists of subjecting plant oils to petroleum-refining processes that yield a fuel with chemical and physical properties that are close to those of ULS jet fuel. We refer to this fuel as HRJ.

Feedstock cost and availability are the primary constraints on the near-term production of biodiesel or HRJ. The cost and availability of appropriate feedstocks are dependent on a number of uncertain factors, including but not limited to yield per acre; costs of cultivation, harvest, storage, delivery and drying; the global market for alternative uses, especially food production; land availability; biofuel subsidies and requirements for the use of renewable fuels; and the prices of petroleum-derived fuels. Further, it is uncertain how much of the production

⁸ Considering gasification and FT technology available in the next decade, this low an output makes FT gasification of biomass infeasible. Through 2020, we anticipate that jet fuel will not be produced from biomass using gasification unless production occurs in a CBTL facility.

of fuels derived from plant oils and animal fats would be available for aviation use, given potential compatibility issues and competition with the ground-transportation market.

In the United States, the dominant feedstock for the production of biodiesel is soybean oil (U.S. Interagency Agricultural Projections Committee and U.S. Department of Agriculture, 2008). Other conventional feedstocks for biodiesel production include sunflower oil, rapeseed (canola) oil, beef tallow and other animal fats, and waste cooking grease. In 2007, biodiesel production in the United States averaged approximately 32,000 bpd (EIA, 2008b, Table 10.3). Alternatively stated, if the entire U.S. production of biodiesel in 2007 had been devoted to aviation use, it would have offset almost seven days of U.S. jet-fuel use. EISA mandates that biomass-based diesel use increase to 65,000 bpd. Taking into account the requirements of the EISA, EIA projects that biodiesel use from domestic sources will grow to between 65,000 and 78,000 bpd in 2017, with the lower estimate representing legislated targets corresponding to the low-oil price case (EIA, 2008a).

In analysis completed prior to the passage of the EISA, the U.S. Department of Agriculture (USDA) estimated that 12.5 percent of the 2017 U.S. soybean crop would be used to produce approximately 39,000 barrels of biodiesel per day (U.S. Interagency Agricultural Projections Committee and U.S. Department of Agriculture, 2008). The USDA predicts that meeting the requirements of the EISA will cause soybean production and prices to increase and exports to decrease. According to the National Biodiesel Board (2009), U.S. production capacity for biodiesel is 2.69 billion gallons per year, or approximately 175,000 bpd; expansions of an additional 430 million gallons per year, approximately 28,000 bpd, of capacity are reportedly under way.⁹

In Europe, rapeseed is the principal feedstock for the production of biodiesel (Körbitz, 1999; Venendaal, Jorgensen, and Foster, 1997). The European Biodiesel Board (EBB) reports average production in the EU in 2007 to have been approximately 112,000 bpd. This is an increase of 17 percent over 2006 production and a 79-percent increase over 2005 production. The EBB claims that subsidized biodiesel imports from the United States have stalled growth of European production (“EU Biodiesel Capacity Seen Rising 55 Pct in 2008,” 2008). Like in the United States, European production capacity is significantly greater than actual production. Production capacity in 2007 was approximately 200,000 bpd. The EBB estimates 2008 production capacity at just over 310,000 bpd. According to the EBB, approximately 60,000 bpd of capacity is idle. The amount of growth of European biodiesel production is uncertain. Proposals in the European Union would require biofuels to be produced sustainably, meaning that they would have to result in verifiable reduction in life-cycle carbon emissions and could not be produced in areas that are currently forested or environmentally sensitive (“Proposed European Ban to Affect Crops Worldwide,” 2008).

Biodiesel is produced throughout the world from locally available feedstocks. Malaysia is in the process of expanding its production of biodiesel based on palm oil, by which it expects to offset regional demand for transportation fuels (IEA, 2006). A widely cited emerging source of plant oil that may be grown in tropical, subtropical, and arid climates is *Jatropha curcas*, a shrub native to Central America whose inedible seeds contain a high quantity of oil; data regarding yield of *jatropha* are limited, but current yield data from mature plantations suggest an oil yield of approximately 170 gallons per acre (King et al., 2009; Tiwari, Kumar, and

⁹ This mismatch between production capacity and annual production may reflect seasonal variations in the availability of oil-producing feedstocks.

Raheman, 1997). This is slightly less than three times the oil yield of soybeans as reported for the 2006–2007 growing season in the United States (Interagency Agricultural Projections Committee and U.S. Department of Agriculture, 2008). BP and D1 Oils, a British biodiesel producer, have announced a joint venture to produce biodiesel from jatropha on plantations throughout Southeast Asia, Africa, and Central and South America, with a total output of approximately 39,000 bpd¹⁰ targeted at the regional and European markets for road diesel (BP, 2007). Production of biodiesel is expected to increase in Brazil, where it is mandated to provide 5 percent of diesel-fuel supplies by 2013 (EIA, 2008a).

Research is currently being directed at developing oil-rich strains of algae or halophytes suitable for low-cost production of biodiesel or biokerosene in confined production facilities. However, these research efforts remain at the fundamental stage and will not yield commercial quantities of fuels within the time frame of our study.

A recent analysis estimated worldwide biodiesel production potential from internationally traded oils and fats at 813,000 bpd (Johnston and Holloway, 2007). Such a large diversion of oils and fats from current uses, however, is highly unlikely, since it would have a profound effect on food prices, even if additional acreage is devoted to oil crops.

Let us provide a rough estimate for potential production of fuels derived from renewable oils in the next decade. If the United States is able to meet legislated targets for production (65,000 bpd) and the European Union doubles production, then production of biodiesel there will be approximately 300,000 bpd on average. Production of feedstocks and biodiesel in the rest of the world has the potential to augment this production somewhat. Therefore, world supplies of biodiesel may be between 300,000 and 400,000 bpd.

Cost Estimates

Cost estimates for the production of alternative jet fuels are derived for FT fuels from coal and biomass and for fuels from renewable oils. There remains considerable uncertainty with respect to capital and feedstock costs for these fuels, so a range of estimates based on alternative assumptions is provided. We present cost estimates from the literature for oil sands. The estimates of production cost provided in this section are not indicative of the retail price of the fuel.

Table A.4 summarizes the results for this section and compares them to current and projected prices of jet fuel.

Jet Fuel from Oil Sands and Very Heavy Oil

Production costs for jet fuel from oil sands depend on two factors: the cost of producing a synthetic crude oil and the cost of converting that crude oil to final products. Using the most recent cost evaluation by the Canadian National Energy Board (NEB, 2006), a RAND analysis (Toman et al., 2008) estimates production costs for surface mining and upgrading facilities of \$34 per barrel and for in situ extraction and upgrading of \$37 per barrel of synthetic crude oil. Both estimates are in 2005 dollars, and both apply to new production facilities. In

¹⁰ This estimate is based on a biodiesel yield of 1 gallon per 7.35 pounds of oil, which is the value used for the conversion of soybean oil to biodiesel by the U.S. Interagency Agricultural Projections Committee and the U.S. Department of Agriculture (2007).

Table A.4
Current and Projected Prices of Jet Fuel and Cost Estimates for the Production of Alternative Jet Fuels

| Fuel | Price or Cost (\$/gallon) | |
|--|---------------------------|------|
| | Low | High |
| Annual Energy Outlook 2008 reference and high-oil price cases for 2017 | 1.20 | 2.57 |
| Jet fuel from oil sands | 1.19 | 1.55 |
| Jet fuel from NG | 1.40 | 2.50 |
| Jet fuel from coal | 1.60 | 1.92 |
| Jet fuel from coal and biomass | 1.97 | 2.39 |

SOURCES: EIA (2008a); Bartis, Camm, and Ortiz (2008); SSEB (2005); Haas et al. (2006)

NOTE: All costs have been adjusted on a net energy basis according to the data in Table B.5 in Appendix B to be comparable to jet fuel. All prices and costs are presented in 2005 dollars.

the past few years, there has been extensive cost escalation associated with the construction of new oil-sand projects in Alberta. This persistent cost escalation indicates that the marginal costs of oil-sand production may be somewhat higher, although likely under \$50 per barrel (Toman et al., 2008). For costing purposes, we assume that synthetic crude oil from oil sands is competitive with low-sulfur light crude, such as WTI, selling at between \$40 and \$50 per barrel (2005 dollars).

According to the Air Transport Association (2008), the margin charged by refiners to produce jet fuel from crude oil has increased dramatically in recent years as excess refining capacity has decreased. Current margins, about \$18 per barrel in 2007, are likely a better reflection of marginal refining costs. For this reason, we assume marginal refining costs of \$10 to \$15 per barrel and calculate a production cost of jet fuel that ranges from \$50 to \$65 per barrel, or equivalently, from \$1.19 to \$1.55 per gallon.

Independent estimates of the production cost of Venezuelan VHO are not available. Given the nature of the Venezuelan VHO deposits, production costs should be similar to those for Canadian oil sands.

Jet Fuel from Natural Gas

Insufficient cost information is available to allow development of an estimate of GTL jet-fuel production costs via application of standard cost-analysis methods. Instead, we develop a rough estimate based on observed decisionmaking by investors in GTL plants.

When oil prices were in the mid-\$20s-per-barrel range in 2001–2003, considerable industrial interest was directed at the commercial prospects of GTL approaches based on stranded NG. Adjusting for inflation and allowing for modest cost escalation, we assume that GTL facilities begin to be competitive at crude-oil prices of \$30 per barrel (2005 dollars). This edge of competitiveness likely involves a minimal charge (e.g., \$0.50 per million British thermal units, or Btu) for NG. Such a low charge for the stranded gas, however, may not be acceptable, since the cryogenic liquefaction of NG to produce LNG is also an option in most locations where a GTL plant can be constructed. Considering the competing option of LNG production, a more reasonable assumption is that stranded gas has a value of between \$2.00 and \$6.00 per million Btu. Since roughly 9 million Btu of NG is required to produce a barrel of GTL product, each

\$1.00 increase in the cost of NG translates into a \$9.00-per-barrel increase in the cost of GTL products. For these reasons, we anticipate that, in the next ten to 15 years, GTL production from new plants will be competitive at crude-oil costs ranging from \$44 to \$80 per barrel. This range corresponds roughly to a jet-fuel production cost between \$1.40 and \$2.50 per gallon. Note that the upper bound of this range applies to situations only in which delivered LNG would have a fairly high wholesale value—namely, about \$6.00 per million Btu.

Jet Fuel from Coal

Cost estimates for CTL are taken from a related RAND report (Bartis, Camm, and Ortiz, 2008, Appendix A) and considered in other analyses (Toman et al., 2008). In Bartis, Camm, and Ortiz (2008), a required selling price of FT diesel is derived using standard cash-flow analysis techniques. That analysis derived a required selling price for FT diesel ranging from \$1.67 to \$2.00 per gallon. If we adjust the cost estimates to compare on a net energy basis with Jet A (see Table B.5), the prices rise to \$1.70 to \$2.04 per gallon. The foregoing costs are in first-quarter 2007 dollars. Converting to 2005 dollars using the general GDP deflator, which is 1.064 (BEA, 2008) yields Jet A–equivalent costs of \$1.60 to \$1.92. These are refinery-gate prices that exclude distribution and marketing costs.

Jet Fuel from Gasification of Coal and Biomass

For developing a cost estimate, we assume that coal and biomass are cogasified, which is the approach taken in several recent studies (NETL, 2007d; Williams, 2006). Our cost estimate is based on a low-definition plant design (NETL 2007d, pp. 28–46), which is a 10,000-bpd CBTL facility with 15 percent of the as-received feedstock by mass being woody biomass—specifically, farmed poplar, though forest residues could be substituted. Ten megawatts of electricity are produced for export. The facility consumes 4,430 tons per day of coal and 782 tons per day of poplar (590 tons per day on a dry-mass basis). About 88 percent of the CO₂ that would be released at the CBTL facility is captured and compressed so that it is ready for pipeline transport to a location for sequestration. This combination of cofiring biomass and carbon capture should yield life-cycle (coal mine to vehicle exhaust) GHG emissions that are about 20 percent below those of conventional petroleum (NETL, 2007d; Bartis, Camm, and Ortiz, 2008).

We estimate that the total capital requirement for this plant would be between \$110,000 and \$140,000 (2005 dollars) per barrel of daily production capacity, on a diesel value–equivalent (DVE) basis.¹¹ The low end of this range is derived from the NETL estimate by replacing the 15-percent project contingency with a 25-percent contingency. Our judgment is that this level of contingency is the minimum required in light of the level of design definition associated with the publicly available conceptual studies. The high end of the range reflects raising the project contingency by an additional 25 percent, which may be more realistic. These project contingencies are in addition to the 33-percent process contingency on the gasification plant, which is already incorporated into the design.

We assume a cost for the biomass of \$55 per dry ton (\$41 per dry ton as received with 25-percent moisture content), which is consistent with some current experience in sourcing

¹¹ The DVE production is calculated by assuming that a barrel of the naphtha produced by the CBTL plant has a value that is 71 percent of the value of a barrel of the plant's diesel product (Bartis, Camm, and Ortiz, 2008).

forest residues.¹² Coal costs are assumed to be \$30 per ton, which requires that the CBTL plant be built very close to its coal source.

For operating costs, our low estimate is identical to that presented in the NETL design analysis. For an upper bound, we raise fixed operating costs by a third, as was done in the RAND analysis of CTL costs (Bartis, Camm, and Ortiz, 2008).

Table A.5 summarizes the key parameters for the CBTL cost estimates. Applying the methodology described in Appendix A of Bartis, Camm, and Ortiz (2008), we estimate

Table A.5
Parameters Used to Estimate Production Costs of Fischer-Tropsch Liquids from Coal and Biomass

| Parameter | Value |
|--|-------------|
| Capital investment (\$ millions) | 1,128–1,354 |
| Total depreciable plant costs (\$) | 976–1,202 |
| Coal use (tons/day) | 4,430 |
| Coal cost (\$/ton) | 30 |
| Biomass use | |
| Tons/day | 782 |
| Tons/day (dry basis) | 590 |
| Biomass cost | |
| \$/ton | 41 |
| \$/ton (dry basis) | 55 |
| Other variable costs (\$/barrel diesel value equivalent) | 3.65 |
| Annual fixed operating costs (\$ millions) | 54.0–71.8 |
| Plant outputs | |
| Total liquids (DVE barrels/day) | 10,000 |
| Electricity for export (MW) | 10 |
| Minimum required selling prices | |
| FT diesel (2005 \$/gallon) | 1.96–2.31 |
| Jet-fuel energy equivalent (2005 \$/gallon) | 1.99–2.34 |

SOURCES: Bartis, Camm, and Ortiz (2008); SSEB (2005, Table C.2).

NOTE: All figures in 2005 dollars. For more information on DVE, see Bartis, Camm, and Ortiz (2008).

¹² The supply of biomass to the Joseph C. McNeil Generating Station in Burlington, Vermont, is a useful example of commercial-scale use and cost of biomass. McNeil has agreements with approximately 50 individual suppliers that specify size and cleanliness of the delivered wood chips, most of which are residues from forestry operations, though the generating station also receives municipal and household wood waste (Irving, 2007). Recent average prices for wood chips at McNeil have been \$30 per green ton (\$50 to \$55 per dry ton) delivered. McNeil receives wood chips by offering to suppliers a price for the delivered wood chips and raising the price until suppliers meet demand.

production costs for FT diesel for this hypothetical plant to range from \$1.96 to \$2.31 per gallon (in 2005 dollars). On an equivalent-energy basis to jet fuel, the production costs for CBTL range from \$1.99 to \$2.34 per gallon.

These production costs do not include any revenues that might be received if the CO₂ captured at the CBTL production facility were to be sold. These costs also reflect per-unit production-cost increases that are associated with building a plant with a liquid output of only 10,000 bpd. Considering that the biomass input is only 15 percent, building a much larger plant (i.e., more than 20,000 bpd) should be possible without significantly raising biomass collection costs.

The preceding analysis reflects a single option of using 15 percent (as received) biomass. Production costs from plants using a lower amount would be less, while production costs from plants using a higher amount would be higher. NETL, for example, has recently examined a broad range of biomass inputs to CBTL plants (NETL, 2009). Assuming that the plant we consider here could handle ranges of biomass inputs from 10 to 30 percent as received by mass, this plant may be able to offer jet fuel at production costs ranging from \$1.97 to \$2.39 per gallon.

Jet Fuel from Gasification of Biomass

A plant producing FT liquid fuels only from biomass would have much higher production costs. Operating costs would increase because the total costs of bringing biomass to a central facility are higher than the costs of mining and delivering coal. Also, the practical upper bound for the output of a biomass-only production facility is about 5,000 bpd.¹³ Building a plant of this size would result in per-unit production-cost increases because of the small scale of the plant.

Because of these cost increases, we do not judge biomass via gasification a practical option unless it is used in conjunction with coal. For example, a recent NETL (2009) study estimates the production cost of diesel from a 5,000-bpd BTL facility to be in the range of \$6.00 per gallon.

Hydroprocessed Renewable Jet Fuel

Analytic estimates of the costs of refining jet fuel from plant and animal oils are not publicly available. Neste Oil (2006) has stated that its facility for producing diesel fuel from vegetable oil would cost approximately \$135 million and have a production capacity of 3,800 bpd. This plant is being constructed at an existing oil refinery, presumably to take advantage of existing utilities for electricity and the production of hydrogen. These data imply capital costs of approximately \$36,000 per daily barrel of production and a feedstock input rate of 555 tons of vegetable oil per day. These data are insufficient to produce a reliable estimate of production costs, although they suggest production costs of roughly \$3.00 per gallon.¹⁴ In particular, at prices for soybean oil ranging between \$610 and \$800 per ton, feedstock costs alone would be between \$2.12 and \$2.78 per gallon of diesel fuel.

¹³ This upper bound is based on consideration of current per-acre yields for energy-relevant biomass (less than 10 tons per acre) and the costs of delivering biomass to a central facility.

¹⁴ This rough estimate assumes a 10-percent cost of capital over a 30-year operating life of the facility and an 85-percent capacity factor.

Well-to-Wake Greenhouse-Gas Emissions

This appendix reports the results of the GHG life-cycle analysis of alternative aviation fuels. These results have been published and presented publicly by MIT as GIACC (2009).¹ This appendix provides complete documentation of the methodology for determining baseline, low, and high life-cycle GHG emissions from the alternative aviation fuels considered in this study. Additionally, this appendix compares the MIT estimates of the life-cycle GHG emissions and those in a recent RAND publication (Bartis, Camm, and Ortiz, 2008).

Jet-Fuel Pathways Considered

Table B.1 lists the fuel pathways analyzed in GIACC (2009).

The results presented in GIACC (2009) are presented in terms of CO₂-equivalent emissions from CO₂, N₂O, and CH₄ based on the 100-year global-warming potential estimates of these gases of the Intergovernmental Panel on Climate Change (IPCC) (2007). The life-cycle GHG emissions for each fuel pathway are the mass of GHGs per unit of energy on a lower heating value (LHV) basis: g CO₂e/MJ LHV jet fuel.²

Overview of Analytical Procedure Used to Estimate Life-Cycle Greenhouse-Gas Emissions for Alternative Jet Fuels

The life-cycle GHG analyses in GIACC (2009) apply the GREET framework (ANL, 2007), but with jet-specific data that represent the latest information in the open literature. For those pathways in Table B.1 that are not available in GREET, new pathways were developed based on inputs gathered from the open literature. GIACC (2009) augmented or updated the underlying data driving the GREET model in most cases. The general process for estimating the GHG emissions for each fuel pathway using the GREET framework is well documented in ANL (2007).

The GREET method is a top-down method in which individual process steps are often characterized with a single conversion efficiency. GREET uses data for how much of each

¹ As part of the PARTNER Project 28, researchers at MIT are expanding the GIACC analysis to include halophytes and additional means of algae production. At the time of this writing, a report on the life-cycle GHG emissions from these fuels and those within the GIACC analysis was being prepared. Please see PARTNER (2009) to obtain a copy of the final report.

² LHV is sometimes referred to as the net heat of combustion.

Table B.1
Fuel Pathways Investigated

| Source | Feedstock | Recovery | Processing | Final Product |
|------------------|--|---|--|----------------------|
| Petroleum | Conventional crude ^a | Crude extraction | Crude refining | Jet fuel |
| | Canadian oil sands | Bitumen mining/ extraction and upgrading | Syncrude refining | Jet fuel |
| | Oil shale | In situ conversion | Shale-oil refining | Jet fuel |
| NG | NG | NG extraction and processing | Gasification, FT reaction, and upgrading | FT jet fuel (GTL) |
| Coal | Coal | Coal mining | Gasification, FT reaction, and upgrading (with and without CCS) | FT jet fuel (CTL) |
| Coal and biomass | Coal and biomass | Coal mining and biomass cultivation | Gasification, FT reaction, and upgrading (with CCS) | FT jet fuel (CBTL) |
| Biomass | Biomass | Biomass cultivation | Gasification, FT reaction, and upgrading | FT jet fuel (BTL) |
| | Renewable oil (soybean oil) | Cultivation and extraction of soy oils | Hydroprocessing | HRJ fuel |
| | Renewable oil (palm oil from Southeast Asia) | Cultivation and extraction of palm oils | Hydroprocessing | HRJ fuel |
| | Algae oil | Cultivation and extraction of algae oils | Hydroprocessing | HRJ fuel |
| | Jatropha oil | Cultivation and extraction of jatropha oils | Hydroprocessing | HRJ fuel |

SOURCE: GIACC (2009).

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

type of process energy is needed per unit energy of feedstock to calculate a single conversion efficiency. The source of the GREET data is based on industry averages as well as simulation of specific scenarios. For each process step within the pathways considered by GIACC (2009), multiple bottom-up studies were considered in addition to the GREET default values to determine a range of likely efficiencies and process flows. In general, new data were not collected for these studies; instead, the existing data were thoroughly considered and evaluated.

Within the analysis of GIACC (2009), scenarios were examined using the GREET framework with data ranges from the literature. Three scenarios for life-cycle GHG emissions for each pathway were evaluated: a baseline, or nominal, scenario that indicates representative life-cycle GHG emissions resulting from the fuel pathway; a low-emission scenario, which represents the effect of improvements in the efficiency of key production steps, scale economies, agricultural yields, or other factors on the life-cycle GHG emissions; and a high-

emission scenario, which represents the failure to achieve desired plant efficiencies, lower agricultural yields, and other factors that degrade performance and would likely lead to increased GHG emissions. The scenario analysis does not represent a statistical distribution of life-cycle GHG emissions that result from the fuel pathways.

Changes in land use, both direct and indirect, may affect life-cycle GHG emissions from biofuels. Soil may store significant amounts of carbon. When land is converted to farming, either for the cultivation of biomass-energy crops, or as a result of agricultural land elsewhere being cultivated for biomass-energy crops, some of the carbon in the soil may be released as CO₂ into the atmosphere. In some cases, additional carbon may be sequestered by the soil. The magnitude of land-use-change emissions depends primarily on the type of land being converted to producing energy crops and the type of crops being grown. The cases for direct and indirect land-use-change emissions considered in the analysis of GIACC (2009) are listed in Table B.2. Land-use-change emissions as a result of surface mining of coal or bitumen (oil sands) are not considered in the analysis of Wong (2008), as these are insignificant compared to the case of biofuels when amortized on a per-unit energy-output basis.

Results

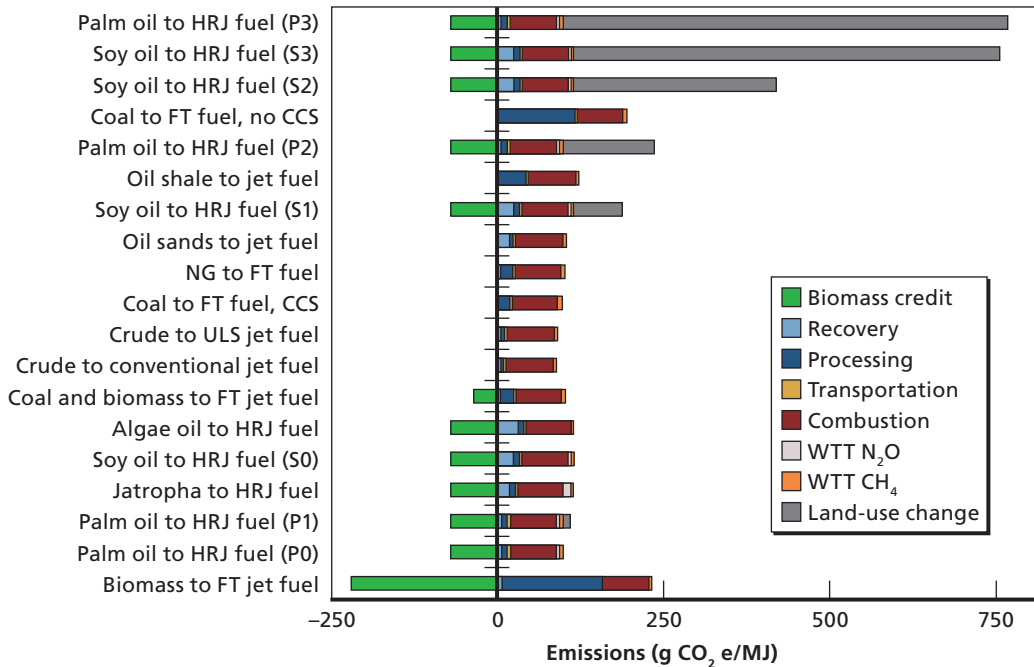
Figure B.1 presents the life-cycle GHG emissions from a wide range of potential alternative jet fuels. It is important to note that this plot does not show a cumulative total but rather displays the emission contributions from each step in the fuel life cycle. The impact of the land-use-change scenarios, summarized in Table B.2, is included in the form of four pathways for both soy-oil and palm-oil HRJ. These results highlight the need to avoid land-use changes that result in GHG emissions. This method of presentation displays the biomass credits that are given to biofuels because of the CO₂ that is absorbed during biomass growth; these credits are largely the reason that these fuels offer the potential for reduced GHG emissions. With the exception of BTL and CBTL, the biofuel pathways all have similar biomass credits, and the magnitude of these credits is equal in magnitude to the combustion emissions. The biomass

Table B.2
Land-Use-Change Scenarios Explored for Hydroprocessed Renewable Jet-Fuel Pathways

| Pathway | Scenario | Description |
|-----------------|----------|---|
| Soy oil to HRJ | S0 | No land-use change |
| | S1 | Grassland conversion to soybean field |
| | S2 | Worldwide conversion of noncropland |
| | S3 | Tropical rainforest conversion to soybean field |
| Palm oil to HRJ | P0 | No land-use change |
| | P1 | Logged-over forest conversion to palm-plantation field |
| | P2 | Tropical rainforest conversion to palm-plantation field |
| | P3 | Peatland rainforest conversion to palm-plantation field |

SOURCE: GIACC (2009).

Figure B.1
Baseline Life-Cycle Greenhouse-Gas Emissions for Jet-Fuel Pathways



SOURCE: GIACC (2009).

NOTE: Scenarios are described in Table B.2.

RAND TR554-B.1

credit for CBTL is smaller because the fuel is created from a combination of coal and biomass. The biomass credit for BTL is larger because biomass is being used to power the entire fuel-production process.

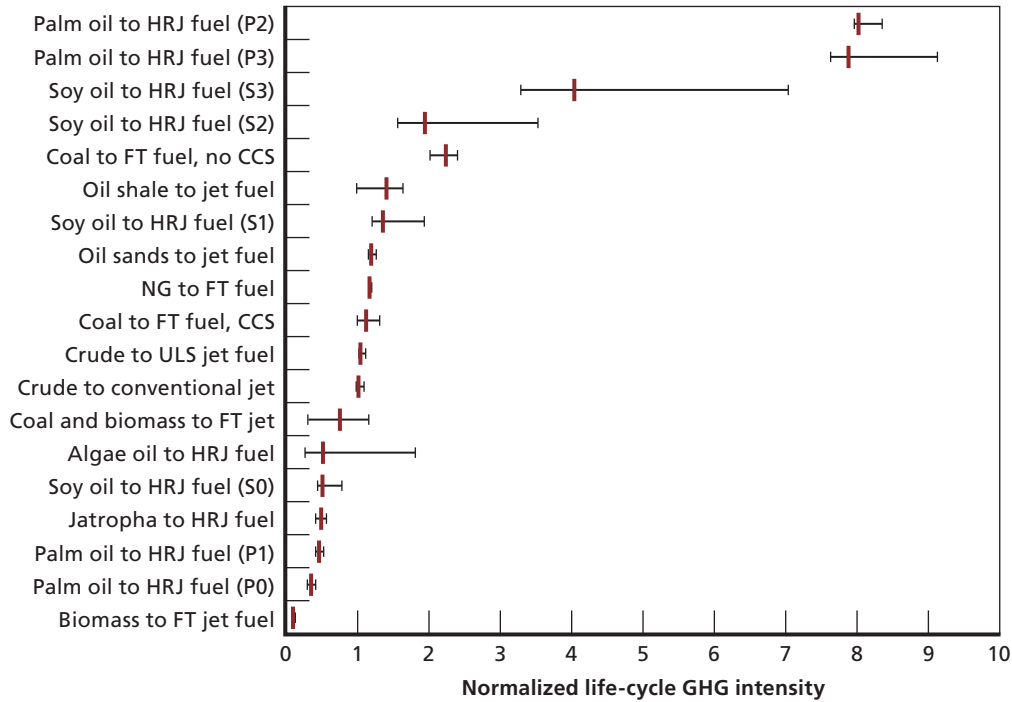
Figure B.2 gives the cumulative totals for each of the pathways presented in Figure B.1, normalized by the life-cycle GHG emissions for jet fuel from conventional crude. The uncertainty bars represent the range of emissions as given by the low- and high-emission cases. Both CBTL and algal HRJ have baseline life-cycle GHG emissions that are lower than those of conventional jet fuel but have the potential to have GHG emissions that are higher than those of conventional jet fuel. The estimates of life-cycle GHG emissions from jatropha-based HRJ have a much narrower range than either CBTL or algae and have an upper bound that is only 54 percent of the GHG emissions from conventional jet fuel. For this reason, it is essential not to simply assume that biofuels are beneficial for the environment without knowing the specifics of how the fuel is produced.

Comparison of Results of GIACC Study to Recent RAND Results

A recent RAND report (Bartis, Camm, and Ortiz, 2008) examined the life-cycle GHG emissions of CTL. The methodology, data, and assumptions of Bartis, Camm, and Ortiz (2008) differ from those of GIACC (2009), but the resulting life-cycle GHG emissions are comparable.

Appendix B of Bartis, Camm, and Ortiz (2008) derives an estimate of life-cycle GHG emissions from two first-of-a-kind CTL facilities nominally producing 30,000 bpd of diesel fuel and naphtha. The facilities considered in their analysis are cases 3 and 8 of SSEB (2005).

Figure B.2
Normalized Life-Cycle Greenhouse-Gas Emissions for the Low-, Baseline, and High-Emission Cases for Jet-Fuel Pathways



SOURCE: GIACC (2009).

NOTE: Land-use-change scenarios are defined in Table B.2.

RAND TR554-B.2

One facility receives bituminous coal, and the other receives subbituminous coal. Additionally, Bartis, Camm, and Ortiz (2008) assume that the naphtha is upgraded to reformulated gasoline. Two cases are considered: a no-CCS case, in which the captured CO₂ is vented to the atmosphere, and a CCS case, in which the captured CO₂ is dehydrated and compressed in preparation for pipeline transportation. In the CCS case, 90 percent of plant-site CO₂ emissions are captured. For each CCS case, alternative cases are considered in which the exported electricity receives and does not receive a credit for displaced CO₂. The results of Bartis, Camm, and Ortiz (2008) are compared to those from GIACC (2009) in Table B.3.

The methodology and assumptions of Bartis, Camm, and Ortiz (2008) differ from those of GIACC (2009) in that the former analysis is focused on the emissions from an individual, first-of-its-kind FT facility, while the latter considers a developed industry and is concerned about the average GHG emissions from the industry. Bartis, Camm, and Ortiz (2008) base their analysis on two alternative low-definition plant designs accepting particular types of coal. They then explore alternative options for providing a CO₂ credit for exported electricity. The baseline case of GIACC (2009) is intended to represent the average emissions that would result from U.S.-based CTL facilities using typical coal inputs. Rather than considering a particular plant, GIACC (2009) assume an average conversion efficiency (LHV basis) from coal to all products (liquid fuels) of 50 percent for the no-CCS case and 48.7 percent for the CCS case (assuming that 85 percent of plant-site CO₂ emissions are captured). The properties of the input coal, and the emissions associated with mining it, are based on average industry values. GIACC (2009) assumes that the plant is designed to maximize liquid-fuel production and

Table B.3
Life-Cycle Greenhouse-Gas Emissions of Fischer-Tropsch Liquid Fuels from Coal (g CO₂ e/MJ LHV)

| Life-cycle Step | Bituminous | | Subbituminous | | GIACC (2009) | |
|---------------------------------------|------------|------------|---------------|-----------|--------------|------|
| | No CCS | CCS | No CCS | CCS | No CCS | CCS |
| Recovery (coal extraction/ mining) | 17.4 | 17.4 | 4.3 | 4.3 | 3.7 | 3.7 |
| Production and upgrading | 142.3 | 14.2 | 139.2 | 13.9 | 120.1 | 22.1 |
| Credit for exported electricity | -25.5 | -25.4-0 | -20.0 | -18.7-0 | 0 | 0 |
| Product transportation | 0.5 | 0.5 | 0.5 | 0.5 | 0.7 | 0.7 |
| Product combustion | 71.8 | 71.8 | 71.8 | 71.8 | 70.4 | 70.4 |
| Total | 206.4 | 77.5-103.9 | 195.8 | 71.8-90.5 | 194.8 | 96.9 |

SOURCES: Bartis, Camm, and Ortiz (2008); GIACC (2009).

NOTE: Results from Bartis, Camm, and Ortiz (2008) have been converted to an LHV basis to facilitate comparison with the results of GIACC (2009). Due to rounding, numbers may not add precisely.

that little or no net electricity is produced. The energy-allocation method is used to apportion plant-site CO₂ emissions among the liquid fuels produced. This is unlike the Bartis, Camm, and Ortiz (2008) approach, which uses the displacement method to account for the electricity and naphtha co-products in the process. As discussed in GIACC (2009), the choice of allocation method can have a considerable impact on the reported life-cycle GHG emissions.

Despite the differences in the two analyses and the allocation methods used, the results presented in Table B.3 from Bartis, Camm, and Ortiz (2008) and those from GIACC (2009) shown in Table B.2 are similar. For the no-CCS case, the life-cycle GHG-emission estimates in Bartis, Camm, and Ortiz (2008) are slightly higher than those of GIACC (2009). In the cases with CCS, the life-cycle GHG estimates that include a credit for exported electricity from Bartis, Camm, and Ortiz (2008) are less than the estimate in GIACC (2009). The life-cycle GHG emissions in Bartis, Camm, and Ortiz (2008) for the cases that do not include a credit for exported electricity are slightly higher in the bituminous case and slightly lower in the subbituminous case than the estimates that appear in GIACC (2009).

Summary of General Feedstock and Fuel Properties

The properties of the main feedstocks and fuels used in this analysis are given in Table B.4.

Table B.4
Feedstock and Fuel Properties

| Feedstock or Fuel | LHV (MJ/kg) | Density (kg/L) | Carbon Content (wt %) | Sulfur Content (wt ppm) | Source |
|----------------------------------|-------------------|--------------------|-----------------------|-------------------------|----------------------------|
| Crude oil or syncrude | 41.3 ^a | 0.872 ^b | 84.6 ^a | 13,400 ^b | EIA (2009b) |
| Conventional Jet A | 43.2 | 0.802 | 86.2 | 700 | Hileman and Donohoo (2009) |
| ULS Jet A | 43.3 | 0.792 | 86.0 | 15 | Hileman and Donohoo (2009) |
| FT jet fuel/HRJ | 44.1 | 0.757 | 84.7 | 0 | Hileman and Donohoo (2009) |
| Renewable diesel ^c | 44.0 | 0.780 | 87.1 | 0 | ANL (2008) |
| Coal (U.S. average) ^d | 22.7 | — | 59.0 | 11,100 | ANL (2007), EIA (2006b) |
| Bituminous coal | 26.4 | — | 64.8 | 29,400 | SSEB (2005) |
| Subbituminous coal | 18.4 | — | 49.2 | 3,500 | SSEB (2005) |
| Petroleum coke ^e | 33.2 | — | 92.3 | 68,000 | EIA (2006c), ANL (2008) |
| Biomass (forest residue) | 15.4 | — | 51.7 | 0 | ANL (2007) |
| Biomass (corn stover) | 16.3 | — | 44.5 | 0 | ANL (2007) |
| Biomass (switchgrass) | 17.6 | — | 47.0 | 900 | NREL database ^f |
| NG | 47.1 | 0.00078 | 72.4 | 6 | ANL (2007) |
| Hydrogen | 120.0 | 0.00009 | 0 | 0 | ANL (2007) |

^a Energy content of crude oil assumed to be 5.8 million Btu per barrel (higher heating value, or HHV); carbon content calculated from formula: % carbon = 76.99 + (10.19 × specific gravity) + (-0.76 × sulfur content) (EIA, 1999).

^b Density and sulfur content derived using historical data (1995–2007) provided in EIA (2009b).

^c Used as surrogate for HRJ in estimation of energy and emissions in hydrotreating of renewable oils to synthetic paraffinic fuels.

^d U.S. average coal is assumed to be the energy source for electricity generation. LHV and sulfur content from ANL (2007); carbon content derived from coal HHV and U.S. average coal-carbon emission factor of 26.0 million tonnes per quadrillion Btu for the electric-power sector in 2004 (EIA, 2006c).

^e Used as a source of process energy in the refining of jet fuel. LHV and carbon content from EIA (2006c); sulfur content from ANL (2008).

^f Accessible from DOE (2004).

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