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# Alternative Fuels
## for Military Applications

**James T. Bartis | Lawrence Van Bibber**

Prepared for the Office of the Secretary of Defense

Approved for public release; distribution unlimited

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*Cover photo by Tom Reynolds: X-35A Joint Strike Fighter being refueled by a KC-135 tanker.*

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# Preface

Over the past few years, the U.S. Department of Defense has spent hundreds of millions of dollars on the development, testing, and certification of alternative fuels that can substitute for petroleum-derived fuels used by the Army, Navy and Marine Corps, and Air Force in their tactical weapon systems. This monograph summarizes research directed at understanding key policy, management, and technical issues associated with these efforts. This document is called for in the Duncan Hunter National Defense Authorization Act for Fiscal Year 2009 (P.L. 110-417). As called for in the act, this monograph includes a review of alternative approaches for reducing lifecycle greenhouse gas emissions; an examination of the military utility of mobile, in-theater synthetic fuel processes; and a review of the goals and progress of the military departments in the research, testing, and certification of alternative fuels.

This monograph is intended for delivery to the Secretary of Defense and the congressional defense committees. Beyond federal officials who have responsibility for research and policymaking affecting transportation fuels, this monograph should be of interest to potential investors in alternative fuel technologies and production facilities.

This research was sponsored by the Defense Logistics Agency Energy, and conducted within the Acquisition and Technology Policy Center of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community. The RAND research reported herein began in May 2009 and was completed in early 2010.

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# Summary

The U.S. Army, Navy, Marine Corps, and Air Force have all expressed a clear interest in being early users of alternative fuels in their tactical weapon systems. Doing so would supplement the services' current use of gasohol and biodiesel in administrative and other nondeployable vehicles. Congress has, as yet, not required the U.S. Department of Defense to use alternative fuels in tactical weapon systems. Nor has the Secretary of Defense issued any directives to this end. Rather, the interest in pursuing alternative fuels centers primarily on the services.

Each of the services has established programs geared toward reducing dependence on the use of fossil fuels in tactical weapon systems, such as aircraft, combat ships and vehicles, and supporting equipment. Since at least 2000, the Air Force has played the lead role in Department of Defense efforts to evaluate and test alternative fuels for military applications. It aims for the Air Force to *be prepared* by 2016 to acquire amounts of alternative fuel blends sufficient to meet 50 percent of its domestic requirements for aviation fuel. Air Force policy clearly specifies that this must be done in a manner that is cost-competitive and emits fewer greenhouse gases than fuels produced from conventional petroleum. Moreover, the alternative fuel component of the blend must be derived from domestic sources.

In October 2009, Navy Secretary Ray Mabus committed the Navy and Marine Corps to "creating a *Green Strike Group* composed of nuclear vessels and ships powered by biofuels" by 2012 and deploying it by 2016. By 2020, at least 50 percent of the energy the Navy consumes is to come from alternative sources.

With regard to the Army, it is participating with the other services in developing a fuel qualification process for the Department of Defense. It is also evaluating the performance of alternative fuels in combat vehicles and tactical power generators. The Army has not yet formally established goals for the use of alternative fuels in its combat systems.

If the services are indeed to use alternative fuels in tactical weapon systems, these fuels must be able to substitute for one or more of the three petroleum-based distillate fuels that currently support the majority of military operations: the two military jet fuels, JP-8 and JP-5 ("JP" stands for "jet propellant"), and naval distillate (F-76). From the perspective of *technical* viability, a number of alternative fuels can meet this requirement. But uncertainties remain regarding their *commercial* viability—namely, how much these fuels will cost and what impact they may have on the environment, particularly in terms of greenhouse gas emissions. Despite these unknowns, the Department of Defense is currently directing substantial resources—both dollars and personnel—to testing and certifying alternative fuels for use in tactical systems. The services, the Defense Advanced Research Projects Agency (DARPA), and the Defense Logistics Agency Energy (DLA Energy) are also sponsoring and conducting technology-development activities aimed at identifying advanced methods of producing alternative fuels.

In this context, the Duncan Hunter National Defense Authorization Act for Fiscal Year 2009 (P.L. 110-417, Sec. 334) contains provisions (see Appendix A) calling for the Secretary of Defense to select a federally funded research and development center (FFRDC) to conduct a study on the use of alternative fuels in military vehicles and aircraft. This study was to examine several specific topics:

- Opportunities to produce alternative fuels in a way that reduces lifecycle greenhouse gas emissions, including the use of clean energy alternatives such as nuclear, solar, and wind energies for powering the conversion processes.
- The military utility of concepts for production of alternative fuels in or close to the theater of military operations compared to domestic production.
- The goals and progress of research, testing, and certification efforts by the Department of Defense related to the use of alternative fuels in military vehicles and aircraft.
- The prospects for commercial production of nonpetroleum military fuels.

Responding to Congress, the Department of Defense asked the RAND National Defense Research Institute, an FFRDC, to conduct an examination of alternative fuels for military applications. To answer the specific topics raised by Congress, RAND researchers focused on alternative fuels that might be candidates for military applications within ten years, with emphasis on those that either have been or are currently the focus of research, testing, and certification within the department. The RAND team examined economic viability, technical readiness for commercial production, lifecycle greenhouse gas emissions, and approaches that could be used to reduce those emissions. This examination benefited from recent studies completed by RAND and the National Academy of Sciences.

For its review of concepts for producing alternative fuels in theater, the RAND team drew on the experience of RAND defense analysts and active-duty military officers working as RAND fellows. To analyze the Defense Department's and private sector's efforts in the area of alternative fuels, team members reviewed available documentation and technical reports; contacted key firms; and conducted in-depth interviews with representatives of DARPA, DLA Energy, and relevant organizations in each of the services.

The findings and recommendations presented in this report are those of the research team. In some cases, these findings conflict with views held and actions taken by the Department of Defense organizations involved in alternative fuel research, testing, and certification.

## Opportunities to Produce Alternative Fuels with Lower Greenhouse Gas Emissions

**Fischer-Tropsch fuels are the most promising near-term options for meeting the Department of Defense's needs cleanly and affordably.** The Fischer-Tropsch (FT) method was invented in Germany in the 1920s. It can produce alternative liquid fuels that can substitute for petroleum-derived civilian and military fuels, including JP-8, JP-5, and naval distillate. The method accepts a variety of feedstocks. For example, a commercial facility operating in South Africa uses coal, one operating in Qatar uses natural gas, and a small facility starting up in Germany will use biomass.

Blends of up to 50 percent FT-derived jet fuel and petroleum-derived jet fuel have been certified for use in commercial aircraft. Ongoing work by the services strongly suggests that appropriately formulated FT fuel blends can be safely used in tactical military systems as well.

Both coal and biomass are abundant in the United States. Together, they are sufficient to support a multimillion-barrel-per-day alternative fuel industry based on FT fuels. But if FT fuel production is to occur without compromising national goals to control greenhouse gas emissions, the following must hold:

- For **biomass-derived FT fuels**, the biomass feedstock must be produced in a sustainable manner; specifically, its production should not be based on practices that lead to sizable emissions due to direct or indirect changes in land use. If this is achieved, lifecycle greenhouse gas emissions can be near zero.
- For **coal-derived FT fuels**, carbon dioxide emissions at the FT fuel production facility must be captured and sequestered. If this is achieved, lifecycle emissions can be in line with those of petroleum-derived fuels.
- For **FT fuels derived from a mixture of coal and biomass**, carbon dioxide capture and sequestration must be implemented. The biomass must also be produced in a sustainable manner. If this is achieved, lifecycle emissions can be less than half those of petroleum-derived fuels. In particular, a feedstock consisting of a 60/40 coal/biomass blend (by energy) should yield alternative fuels with lifecycle greenhouse gas emissions that are close to zero.

The above approaches can result in FT fuels with lifecycle greenhouse gas emissions that are less than or equal to those of their petroleum-derived counterparts, and thereby fuels that are eligible for government purchase per the provisions of Section 526 of the Energy Independence and Security Act of 2007.

Considering economics, technical readiness, greenhouse gas emissions, and general environmental concerns, FT fuels derived from a mixture of coal and biomass represent the most promising approach to producing amounts of alternative fuels that can meet military, as well as appreciable levels of civilian, needs by 2030. But whether this technology will reach its potential depends crucially on gaining early production experience—including production with carbon capture and sequestration—in the United States. At present, no agency of the U.S. government has announced plans to promote early commercial use of FT fuels derived from a mixture of coal and biomass.

**It is highly uncertain whether appreciable amounts of hydrotreated renewable oils can be affordably and cleanly produced within the United States or abroad.** Hydrotreated renewable oils are produced by processing animal fats or vegetable oils (from seed-bearing plants such as soybeans, jatropha, or camelina) with hydrogen. Various types of algae have high oil content and are another possible source of oil for hydrotreatment. Fifty-fifty blends of hydrotreated oils have already been successfully demonstrated in flight tests sponsored by the commercial aviation industry. Laboratory analyses and testing strongly suggest that hydrotreated renewable oils can also be formulated for use in the Department of Defense's tactical weapon systems. Technical viability is not an issue.

The problem lies in uncertainties regarding production potential and commercial viability, especially affordability and lifecycle greenhouse gas emissions. Animal fats and other waste oils may offer an affordable low-greenhouse-gas route to hydrotreated renewable oils. But these fats and waste oils are also traditionally used in other nonfuel applications. Because the supply of these feedstocks is limited, substitutes would need to be found for use in these other applications. These substitutes may cause additional greenhouse gas emissions. Production potential is also a clear issue with animal fats and waste oils: The available supply of these feedstocks will likely limit production to no more than 30,000 barrels per day.

With regard to feedstock vegetable oils, to keep lifecycle greenhouse gas emissions at levels lower than those of petroleum-derived fuels, these oils must be derived from crops that do not compete with food production and minimize nonbeneficial direct and indirect changes in land use. Jatropha and camelina are often mentioned as ideal plants to meet these requirements, but there exists little evidence to back these claims. Even if low-greenhouse-gas approaches can be established and verified, total fuel production is likely to be limited. Producing just 200,000 barrels per day (about 1 percent of U.S. petroleum consumption) would require an area equal to about 10 percent of the croplands currently under cultivation in the United States.

Advanced approaches, such as those using algae as a feedstock, may yield hydrotreated renewable oils without the limitations and adverse land-use changes associated with seed oils. But all of these advanced approaches are in the early stages of the development cycle. Large investments in research and development (R&D) will be required before confident estimates can be made regarding production costs and environmental impacts.

Considering (1) the very limited production potential for fuels derived from animal fats and waste oils, (2) the highly uncertain prospects for affordable, low-greenhouse-gas fuels derived from seed crops, and (3) the early development status of algae-based concepts, hydrotreated renewable oils do not constitute a credible, climate-friendly option for meeting an appreciable fraction of military fuel needs over the next decade. Because of limited production potential, fuels derived from animal fats, waste oils, and seed oils will never have a significant role in the larger domestic commercial marketplace. Algae-derived fuels might, but technology development challenges suggest that algae-derived fuels will not constitute an important fraction of the commercial fuel market until well beyond the next decade.

**Nuclear, solar, and wind energy technologies may offer important benefits in the production of military, as well as civilian, alternative fuels.** Nuclear, wind, and solar energy offer electric power without emitting appreciable amounts of greenhouse gases. For the near- and mid-term alternative fuel options (i.e., hydrotreated oil from animal fats and vegetable oils, and FT liquids), electric power is not an important input to the production process. Electric power, however, can be used to produce hydrogen via electrolysis of water, and hydrogen *is* an important input. For example, hydrogen produced from nuclear or renewable power can be used to hydrotreat renewable oils produced from seed crops. If sufficient hydrogen is available, nearly all of the carbon in the coal or biomass feedstock to a Fischer-Tropsch plant would end up in the fuel products and not in the air, eliminating the need to capture and sequester carbon dioxide. In addition, the use of hydrogen in an FT plant could nearly triple yields of liquid fuels.

For hydrotreated oil from algae, a longer-term option, climate-friendly sources of electric power could be used directly in the processes of cultivating the algae and extracting the oil, because electricity is required for mixing, circulation, and management of water and nutrients.

**But the beneficial hydrogen derived from nuclear, solar, and wind energy technologies is not an economically viable option over the near- to mid-term.** The trade-off is cost: Producing hydrogen from clean sources in capacities large enough to gain the benefits described above requires very large amounts of generating capacity and would significantly increase the costs of producing liquid fuels. Considering the importance of reducing greenhouse gas emissions during the process of generating electric power for traditional uses, investments in climate-friendly power generation are already likely to be very high over the coming decades. In this context, the additional investment required to construct large amounts of generating capacity dedicated to producing alternative fuels is probably not feasible. For at least the next two decades, it is highly unlikely that hydrogen from nuclear or renewable electric-generating technologies will be a commercially viable option for producing alternative fuels.

## The Military Utility of Forward-Based Alternative Fuel Production

**Concepts for forward-based alternative fuel production do not offer a military advantage.** Concepts have been proposed for alternative fuel production systems that could be deployed in forward operating bases or within a theater of operations. Any scheme for the production of military fuels requires a source of carbon, which can be supplied from locally available feedstocks or from military wastes. One approach would be to build an alternative fuel plant on a large barge that could be towed to a location near or within a theater of operations and connected to an undersea natural gas deposit. But this and similar floating concepts would suffer operational problems—such as securing a feedstock supply and starting up the process—that would limit their utility to long-duration deployments. In certain cases, they would require a dedicated defense. Finally, there is no evidence that a floating production plant would be less expensive than using either Navy oilers or commercial tankers to deliver finished fuel products to a forward-based oil depot.

A second set of concepts would have small-scale alternative fuel production units co-located with tactical units. From a strictly technical perspective, a number of the concepts currently being supported by Defense Department funds may be viable. But from a military utility perspective, any concepts that require delivery of a carbon-containing feedstock appear to place a logistical and operational burden on forward-based tactical units that would be well beyond that associated with delivery of finished fuels. The alternative of obtaining carbon from low-concentration sources such as the carbon dioxide in air or water would be technically daunting and prohibitively expensive.

Compact fuel production systems that would use carbonaceous military wastes are now being developed. These systems could meet a small fraction of the energy needs of a forward-based unit. They do not offer a compelling military benefit but may be a cost-effective approach to managing wastes. However, considering the complexity of equipment required to produce liquid fuels meeting military specifications in this way, these small waste-to-energy concepts are better suited for use in appropriately modified tactical power generators, as opposed to producing fuels such as JP-8 for high-performance weapon systems.

In short, traditional systems, in which fuel is produced outside the theater and then shipped in, continue to be the most practical in terms of military utility.

## Goals and Progress of the Military Departments

**Defense Department goals for alternative fuels in tactical weapon systems should be based on potential national benefits, since the use of alternative, rather than petroleum-derived, fuels offers no direct military benefits.** While Fischer-Tropsch fuels and hydrotreated renewable fuels are no less able than conventional fuels to meet the Defense Department's needs, they offer no particular military benefit over their petroleum-derived counterparts. For example, even if alternative fuels can be produced at costs below the prevailing costs for conventional fuels, they will be priced at market rates. Also, we are unable to find any credible evidence that sources to produce jet or naval distillate fuel will run out in the foreseeable future. If conflict or a natural disaster were to abruptly disrupt global oil supplies, the U.S. military would not suffer a physical shortage. Rather, the resulting sharp increase in world prices would cause consumers around the world to curb use of petroleum products. Less usage would ensure that supplies remained available. As long as the military is willing to pay higher prices, it is unlikely to have a problem getting the fuel it requires. If problems do arise, the Defense Production Act of 1950 (P.L. 81-774) contains provisions for performance on a priority basis of contracts for the production, refining, and delivery of petroleum products to the Defense Department and its contractors.

Nevertheless, despite the absence of a specific military benefit, there are nationally important benefits to be gained from the use of alternative fuels. If the Department of Defense were to encourage early production experience, government decisionmakers, technology developers, and investors would obtain important information about the technical, financial, and environmental performance of various alternative fuel options. If favorable, that information could lead to a commercial alternative-fuels industry producing strategically significant amounts of fuel in the United States. Once established, a large, commercially competitive alternative fuel industry in the United States and abroad would weaken the ability of the Organization of the Petroleum Exporting Countries to assert its cartel power. Lower world oil prices would yield economic benefits to all fuel users—civilian and military alike. Lower prices would also decrease the incomes of "rogue" oil producers, and thereby likely decrease financial support to large terrorist organizations such as Hamas and Hizballah.

Because alternative fuel production would probably occur in diverse locations throughout the United States, a domestic alternative fuel industry would additionally improve the resilience of the petroleum supply chain, especially against natural disasters such as hurricanes.

Certain alternative fuels that can have military applications can be produced in ways that yield greatly reduced greenhouse gas emissions, in comparison with their petroleum-derived counterparts. If climate-friendly alternative fuels were available, the Department of Defense could reduce the greenhouse gas emissions from the operation of its tactical vehicles, aircraft, and supporting equipment. However, fuel use in tactical systems represents less than 1 percent of U.S. energy-related emissions of greenhouse gases. The greater benefit, again, would result if early use of alternative fuels by the Defense Department were to accelerate the use of alternative fuels in the much larger civilian marketplace.

**Current efforts by the services to test and certify alternative fuels are far outpacing commercial development.** With the intention of increasing their usage of alternative fuels in the coming years, the services have a range of efforts underway to test and certify FT liquids and hydrotreated renewable oils for use in tactical systems. Yet, given where industry is in the process of developing these fuels, some of these efforts—at least at the current levels of funding and personnel—may be premature.

*Testing and certification of Fischer-Tropsch fuels.* Commercial production of FT fuels is well established in South Africa, Qatar, and Malaysia. By 2012, global production is scheduled to be more than 350,000 barrels per day. In the United States, five plants are in the advanced stages of planning; three would use waste biomass and two would use a combination of coal and biomass. If these plants are constructed, they will be able to produce about 60,000 barrels per day of FT liquids that could be blended with military jet fuel and naval distillate. Developers of all five projects claim that they will be able to keep lifecycle greenhouse gas emissions below those of petroleum-derived fuels. But as of November 2009, none of these plants have begun final design, and most have not begun front-end engineering design.

Considering that commercial aircraft are now certified to use 50/50 blends of FT fuels, that substantial FT production is currently taking place abroad, and that the services have already undertaken extensive certification efforts, it makes sense for the Department of Defense to finish certifying the use of 50/50 blends. Completing this effort will provide additional flexibility in purchasing jet fuel in certain locations. But given the extremely small quantity of FT fuels available on the global market, there is no reason to extend this work to blends with a higher FT fuel content.

*Testing and certification of hydrotreated renewable oils.* Algae-derived fuel is a research topic, not an emerging option that the military can use to supply its operations, and cultivating seed oils affordably without adverse effects on climate change has yet to be demonstrated. Because the prospects for appreciable domestic production of hydrotreated oils over the next decade are so uncertain, the Department of Defense should discontinue large-scale testing and certification efforts (other than laboratory R&D). Given the growing market for these fuels in commercial vehicles and aircraft, there is no benefit to the department or the nation in proving that they can be formulated to fuel the high-performance engines in military tactical systems. If, after a few years, uncertainties regarding algae-derived fuels or seed oils are resolved, a military certification program for an alternative fuel blend may be appropriate, but at fuel blend limits that are consistent with anticipated commercial blend levels, which are highly likely to be well below 50 percent over at least the next decade.

**If the Department of Defense continues to support the development of technology to produce alternative fuels, it should consider consolidating and strengthening management and shifting support to longer-term goals.** Much of the Defense Department's work to develop alternative fuel production technologies is based on the unfounded assumption that the military will gain a direct benefit from having access to alternative fuels that can substitute for military fuels. Consequently, the department and Congress need to decide whether defense appropriations should continue to support activities focused on developing technology to produce alternative fuels. If Defense Department funding is phased down, consideration should be given to providing the Department of Energy with adequate resources to continue support for the more meritorious projects within the current Defense Department portfolio.

If the decision is made to continue to use defense funds for R&D of alternative fuels, the roles of the Departments of Defense and Energy should be clarified. With regard to developing technology for alternative transportation fuels, advanced technology that works for the large civilian markets for diesel and jet fuel will also work for the much smaller demand for military jet and naval fuels. For this reason, Defense Department efforts need to be integrated with the overall national energy R&D program for transportation fuels.

*The Defense Department's current R&D efforts are overly focused on short-term gains, foregoing the work required for long-term progress.* For the most part, the Defense Department's efforts to develop the technology to produce alternative fuels consists of a collection of independent projects, each focused on demonstrating the technical viability of a single concept for producing military fuels. Demonstrating technical viability is easy; consider the history of photovoltaic power and fuel cells. But demonstrating affordable and environmentally sound production—i.e., commercial viability—is difficult, requiring investments in exploratory and applied research dedicated to understanding fundamental problems and developing sound solutions. If the Department of Energy is unwilling to provide adequate support to applied and fundamental research in program areas in which DARPA and the services are investing, the Department of Defense should restructure or expand its efforts to create a proper balance between shorter-term engineering development projects and research directed at long-term progress.

*Improved management of the alternative fuel R&D program is key to success.* Alternative fuel production generally involves numerous process steps, many of which are highly complex. The construction costs for a single commercial facility can range from hundreds of millions to billions of dollars. But currently, none of the Department of Defense organizations conducting or supporting alternative fuel R&D have put in place the critical mass of expertise required to cover the broad range of technical disciplines (including experience in thermochemical or biochemical process development and process scale-up) needed for a successful technology-development program in alternative fuels.

To remedy the situation, the Department of Defense could opt to make a single organization—either in the department or one of the services—responsible for funding and managing the entirety of the department's efforts to develop alternative fuel technology. It would then be critical to staff that organization with a group of program managers whose combined technical expertise spans the scientific and engineering knowledge base critical to program success. The ability to conduct independent engineering analyses would be another essential capability.

Alternatively, the Department of Defense could assign management of its alternative fuel portfolio to one or two of the Department of Energy's national laboratories that already have the required expertise and capabilities in engineering analysis.

**To cost-effectively promote early industrial production of alternative fuels, the Department of Defense needs extended contracting authority for fuel purchases.** If the services are to promote early industrial experience in the production of alternative fuels, the Defense Department must obtain legislative approval to proffer longer-duration and higher-value contracts for fuel purchases. Long-term fixed-price fuel contracts should be avoided in favor of a combination of low-price guarantees and income sharing.

## The Prospects for Commercial Production

**Within the United States, the prospects for commercial production of alternative fuels that have military applications remain highly uncertain, especially over the next decade.** Uncertainties regarding (1) the future course of world oil prices, (2) the costs of building commercial-scale facilities in the United States, and (3) the management (technical and regulatory) of greenhouse gases are impeding the large investments required to build FT production facilities. Those very small facilities that are moving forward are doing so with significant financial support from the government. It is highly unlikely that early industrial experience in the production of FT fuels, using a combination of coal and biomass and capturing greenhouse gases, will occur without government subsidies that reduce the risks to investors.

For hydrotreated renewable oils, the prospects for commercial production depend on the feedstock. For fuels derived from waste oils and animal fats, a small amount of commercial production directed at the civilian diesel fuel market is scheduled to come on line in 2010. But overall production potential in the next decade is unlikely to exceed 25,000 barrels per day.

For fuels derived from seed oils, existing federal subsidies have promoted production and use of biodiesel, which is not a hydrocarbon but rather a fatty acid methyl ester (FAME) unsuitable for military applications. Competition in the marketplace requires that customers be willing to pay a premium for hydrotreated renewable jet fuels above the going price for FAME-type biodiesel. Otherwise, renewable oil production for fuels will continue to be directed at this type of biodiesel rather than hydrotreated jet fuel, which is more costly to produce than a FAME-type biodiesel. Additionally, there is the overriding issue of whether appreciable levels of production can occur without raising food prices and causing the release of greenhouse gases through direct and indirect changes in land use.

For algae-derived hydrotreated oil produced via photosynthesis or fermentation of cellulosic materials, the scale of the technical challenge and the early development status of the enabling technology strongly suggest that appreciable amounts of commercial production are highly unlikely through 2020.

## A Few Words in Conclusion

The RAND investigation was limited to alternative fuels, as opposed to the whole of energy use across the Department of Defense. But this study can be placed within the broader context of an overall energy strategy for the U.S. military. The RAND team's finding that the use of alternative fuels offers the armed services no direct military benefit is consistent with top-level findings of recent studies on military energy issues by the Defense Science Board and the JASON Defense Advisory Group: In short, the military is best served by efforts directed at using energy *more efficiently* in weapon systems and at military installations. In this regard, the services' energy programs are clearly, and appropriately, placing the greatest emphasis on measures that would increase the efficiency of energy use.

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# Abbreviations

| | |
|---|---|
| bpd | barrels per day |
| Btu | British thermal unit (roughly, the amount of energy required to raise the temperature of one pound of water one degree Fahrenheit) |
| CAAFI | Commercial Aviation Alternative Fuels Initiative |
| CDE | carbon dioxide equivalent |
| DARPA | Defense Advanced Research Projects Agency |
| DLA Energy | Defense Logistics Agency Energy |
| DoD | U.S. Department of Defense |
| FAA | Federal Aviation Administration |
| FAME | fatty acid methyl ester |
| FT | Fischer-Tropsch |
| FY | fiscal year |
| ISBL | inside battery limit |
| Navy Fuels Team | Naval Fuels and Lubricants Cross-Functional Team |
| NETL | National Energy Technology Laboratory |
| R&D | research and development |

CHAPTER ONE

# Introduction

Addressing energy use and security within the U.S. Department of Defense (DoD) has been a growing concern of the U.S. Congress and national defense decisionmakers. The military services are highly dependent on petroleum-derived fuels for maintaining readiness and executing their missions. The unanticipated surges in world oil prices over the past few years overwhelmed DoD's budgeting system, leaving the military services with inadequate funding to meet fuel costs without cutting programmed spending elsewhere. Historically high petroleum prices in 2007 and 2008 also raised issues regarding the long-term availability of affordable fuels suitable for military operations.

Reflecting these concerns, Congress explicitly addressed energy security in the Duncan Hunter National Defense Authorization Act for Fiscal Year 2009 (P.L. 110-417). Among the energy security topics addressed by the act, Section 334 (presented in Appendix A) calls for the Secretary of Defense to select a federally funded research and development center (FFRDC) to conduct a study on alternative and synthetic fuels. The RAND Corporation has performed the required study, the results of which are presented in this monograph. The DoD sponsor and manager of this study is the Defense Logistics Agency Energy (DLA Energy), formerly the Defense Energy Support Center.

## Imported Oil and U.S. National Security

The United States' consumption of liquid fuels is about 19 million barrels per day (bpd). Meeting this demand requires importing about 10 million bpd of petroleum, mostly in the form of crude oil. In a world that consumes about 85 million bpd of petroleum products, the United States holds first place in consumption and the magnitude of its imports. As of fall 2009, the average price of crude oil imports was about $70 per barrel. At this price, oil imports would cost U.S. oil consumers about $250 billion per year.

The national security consequences of the dependence of the United States, and its allies and trading partners, on imported oil are well documented (Crane et al., 2009). All oil consumers are vulnerable to increased payments for oil when oil exporters are able to reduce supplies on the world oil market. Most serious would be the economic impact of a large and extended disruption in global oil supplies as a result of conflict or natural disaster.

The governing regimes of some oil-exporting nations, such as Iran, pursue policies that run counter to the national security interests of the United States and its allies. When oil prices are high, these nations have more funds to invest in purchasing armaments and building their own industrial bases for manufacturing munitions. High oil prices also provide more funds that may eventually find their way to Hamas and Hizballah (Crane et al., 2009).

Alternative fuels are already being produced in many countries. Examples include corn-derived ethanol in the United States, sugar-derived ethanol in Brazil, synthetic crude from oil sands in Canada, coal-to-liquids production in South Africa, natural-gas-to-liquids production in Qatar and Malaysia, and small amounts of biodiesel production in the United States and Europe. Expanding alternative fuel production beyond these initial efforts might offer economic and national security benefits to the United States. Because it provides a substitute for products refined from crude oil, increased production of alternative fuels will reduce demand for crude oil, resulting in lower world oil prices, to the direct benefit of all oil consumers. Lower world oil prices and greater supply diversity also mitigate the adverse national security impacts of imported oil (Bartis, Camm, and Ortiz, 2008; Crane et al., 2009).

What would benefit the nation would also benefit DoD directly, in the form of lower fuel prices, and indirectly, in the form of a more stable geopolitical outlook.

## Study Scope

In this monograph, we examine key policy issues associated with DoD efforts to capture the potential benefits of using alternative or synthetic fuels in tactical systems. Our interest is solely fuels for tactical systems—namely, systems and equipment that are intended to be used in or support combat operations.[1] Henceforth, the phrases *alternative fuels* and *synthetic fuels* are used synonymously and refer to any liquid fuel produced from coal, natural gas, vegetable oil, animal fat, or various types of biomass, such as agricultural and forest residues, prairie grass, and algae.[2] In accordance with the Duncan Hunter National Defense Authorization Act for Fiscal Year 2009, this study covers the following four topics:

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[1] Per legislation and executive orders, alternative fuels, such as gasoline/alcohol blends and biodiesel, are widely used in nondeployable vehicles located at military installations within the United States. This nontactical use is not within the scope of our study.

[2] Our definition excludes fuels produced from crude oil, natural gas liquid condensates, and heavy oil because these are the conventional sources of the liquid fuels currently used for transportation. Fuels produced from oil shale or oil sands are also excluded, primarily because the prospects for commercial development of these resources in the United States remain highly uncertain (Bartis et al., 2005; Bartis, Camm, and Ortiz, 2008).

1. An examination of alternative approaches to reduce lifecycle emissions of greenhouse gases from the production and use of alternative and synthetic fuels. This includes examining alternatives for reducing carbon dioxide emissions during the conversion process, such as the viability of using nuclear, solar, and wind systems for powering the conversion process. This topic is addressed in Chapter Three.
2. An examination of the military utility of domestically produced alternative and synthetic fuels for military operations and for use by expeditionary forces, compared with the military utility and lifecycle emissions of mobile, in-theater synthetic fuel processes. Chapter Four addresses this topic.
3. A review of the goals and progress of the military departments related to the research, testing, and certification for use of alternative or synthetic fuels in military vehicles and aircraft. This topic is covered in Chapter Five.
4. An analysis of trends, levels of investment, and the development of refining capacity in the alternative or synthetic fuel industry and its preparedness for meeting fuel requirements for the Department of Defense. This topic is addressed in Chapter Six.

To frame our examination of these four issues, Chapter Two summarizes current DoD fuel requirements, the important properties required of military fuels, and the alternative fuels that are the most likely candidates for military applications over the next decade.

## Study Approach

Our study builds on recent RAND research on alternative fuels and energy security. From this prior work, we drew most heavily on *Producing Liquid Fuels from Coal: Prospects and Policy Issues* (Bartis, Camm, and Ortiz, 2008), *Imported Oil and U.S. National Security* (Crane et al., 2009), and *Near-Term Feasibility of Alternative Jet Fuels* (Hileman et al., 2009). The last of these studies was jointly conducted with the Partnership for AiR Transportation Noise and Emission Reduction (PARTNER) at the Massachusetts Institute of Technology. Another important source is a recent study by the National Academy of Sciences, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (NAS, 2009).

Updated with a literature review, these earlier studies form the basis for much of our analysis of alternative approaches to reducing lifecycle greenhouse gas emissions of alternative fuels, presented in Chapter Three. To examine the viability of using nuclear, solar, and wind power, we conducted an independent analysis based on fundamental engineering and chemical considerations. This part of the research was necessary, since most of the literature on this topic dealt only with advanced nuclear energy cycles. This analysis is documented in Appendix B.

Our examination of forward-based production concepts is based on a logic tree approach. Technical information about these concepts was developed through interviews with DoD personnel knowledgeable of them; from information obtained from organizations actively conducting research on these concepts; and, where available, technical reports. The results, presented in Chapter Four, benefited from insights provided by RAND staff expert in military operations and logistics and a joint review by Army officers participating in the RAND Arroyo Center Army Fellows Program and Air Force officers participating in the RAND Project AIR FORCE Fellows Program.

Our examination of the goals and progress of DoD organizations in alternative fuel research, testing, and certification is based primarily on interviews with service, Defense Advanced Research Projects Agency (DARPA), and DLA Energy personnel directly responsible for these activities. A list of DoD organizations where we conducted interviews or from which we received information is provided in Appendix C. In some cases, we held interviews with non-DoD participants associated with these activities. To encourage frank and open discussion, this latter set of interviews was generally conducted on a not-for-attribution basis.

Our analysis of the readiness of industry to invest in alternative fuels is based on a review of news reports, company websites, press releases, and discussions with senior executives.

Throughout, our work benefited from the useful perspectives on the role of alternative fuels in addressing DoD energy requirements provided in two reports sponsored by the Office of the Secretary of Defense: a JASON Defense Advisory Group study titled *Reducing DoD Fossil-Fuel Dependence* (Dimotakis, Grober, and Lewis, 2006) and a Defense Science Board study titled *More Fight—Less Fuel* (Carns and Schlesinger, 2008).

CHAPTER TWO

# Fuels for U.S. Military Operations

Since the early 20th century, petroleum has played an essential role in military operations. World War II provides a vivid example. Neither Germany nor Japan held within their boundaries appreciable reserves of petroleum. Their military strategies centered on securing petroleum supplies adequate to fuel their combat ground vehicles, aircraft, and ships. A top priority for Japan was the Indonesian oil fields, and, for Germany, the fortification and defense of the Ploesti oil fields in Romania. Further, Germany made the oil fields of the Caucasus a key goal when it invaded the Soviet Union in 1941. Relevant to our topic, the Germans also built and operated, before and during the war, a number of synthetic fuel plants that converted coal to liquid fuels.[1] The Allies were well aware of the vulnerability of the petroleum supply chains for both Germany and Japan, and the Allied strategy included targeting that supply chain.

Since that period, military emphasis on mobility and maneuver has further increased the importance of liquid fuels. As of 2009, the U.S. military services use about 340,000 bpd of petroleum-based fuels (Energy Information Administration, 2009b, Table 1.13). Nearly all of this fuel is used to power aircraft, ships, combat vehicles, and combat support vehicles. In fiscal year (FY) 2008, DoD spent about $16 billion to procure this amount of fuel—about triple what it would have spent at petroleum prices that prevailed in 2003. These amounts are sizable, making DoD the largest consumer of petroleum products in the United States. Considering all petroleum use by the federal government, DoD accounts for 93 percent.

Nearly all liquid transportation fuels fall into one of two groups:

- the gasoline group
- the distillate fuel group.[2]

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[1] One of the synthetic fuel processes used by the Germans is the Fischer-Tropsch method, which is described in detail later in the chapter.

[2] A small amount of residual oil is also used in transportation. Residual fuels are very viscous, difficult to ignite, and tend to be more polluting. In the United States, these fuels are primarily used in the large, slow diesel engines that are often found in large ships. DoD purchases of residual fuel oil are generally directed at powering large supply ships, which are designed and operated much like commercial ships.

Most Americans are familiar with the **gasoline group**. These fuels are highly volatile and easily ignited, making them ideal for the spark-ignition engines that power nearly all automobiles sold in the United States. Nationwide gasoline use, including gasoline-ethanol blends, averages about 9 million bpd (Energy Information Administration, 2009b).

The **distillate fuel group** includes diesel and jet fuel, as well as fuel oil used for industrial process heating and for heating residences and commercial buildings. In 2008, nationwide use of distillate fuel averaged 5.6 million bpd, of which about 1.5 million bpd was jet fuel. Because fuels in this group are less volatile and less prone to inadvertent ignition, they are preferred for military applications. Specifically, within the distillate group are the three fuels that dominate DoD fuel use:

- the two kerosene-based jet propulsion fuels, JP-8 and JP-5
- naval distillate fuel, NATO F-76.

Box 2.1 provides further information on these three fuels. JP-8 alone meets about 65 percent of U.S. military fuel needs. As a group, distillate fuels account for over 95 percent of military fuel purchases, as shown in Table 2.1.

If the military is to use alternative fuels in its tactical systems, it needs to be able to substitute them for one or more of these three petroleum-based distillate fuels that currently support the bulk of military operations.

**Table 2.1**
**Fiscal Year 2008 Petroleum Use by the U.S. Department of Defense**

| Fuel | Barrels per Day (thousands) | Principal User |
|---|---|---|
| Jet fuel: JP-8 and JP-5 | 252 | Air Force (JP-8): 163,000 bpd<br>Navy (JP-5): 47,000 bpd<br>Army (JP-8): 41,000 bpd |
| Naval distillate | 46 | Naval vessels |
| Other diesel/fuel oil | 19 | Army vehicles |
| Gasoline/gasohol | 4 | Noncombat vehicles |
| Other fuels, mostly residual fuel | 4 | Naval supply ships, permanent installations |
| Estimated non–DLA Energy purchases | 12 | All services when DLA Energy–procured stocks are unavailable |
| Total | 337 | |

### Box 2.1: DoD Military Specification Fuels JP-8, JP-5, and F-76

JP stands for jet propellant. JP-8 is used by all Air Force and Army aircraft, and Navy aircraft that are not deployed aboard Navy ships. Since the early 1990s, it has also been used by Army tactical battlefield equipment in support of the "single fuel on the battlefield" policy. This policy was initiated to simplify battlefield fuel supply logistics. JP-8 is identical in specification to commercial Jet A-1 fuel, with the addition of three additives: a corrosion inhibitor, an icing inhibitor, and a static charge dissipater (Chevron Global Aviation, 2006). Jet A-1 is the fuel used by commercial airlines in most of the world except in the United States.

JP-5 is used by Navy aircraft and Marine Corps aircraft and ground vehicles that are deployed aboard ships. The only significant difference between JP-5 and JP-8 is the minimum flash point: 140°F for JP-5 versus 100°F for JP-8. The higher flash point is required for shipboard fire safety reasons. All Air Force and Army tactical systems are qualified to use JP-5 as an alternative to JP-8. JP-5 has no commercial counterpart.

F-76 is a NATO-wide designation for a marine distillate fuel used by all Navy nonnuclear combatant ship systems. F-76, often referred to as naval distillate, is also the approved ship fuel for all NATO navies as well as other allied navies, such as those of Australia and New Zealand. F-76 also has a minimum flash point of 140°F. Basically, F-76 is a more tightly specified version of a commercial fuel that is used in civilian ships. The most important difference between F-76 and its commercial counterpart is a storage stability requirement to facilitate long-term storage of DoD reserve stocks without degradation.

## Critical Properties of Military Fuels

As turbine and diesel engine technology and fuel science and refining have evolved over the decades, so have the specifications of military fuels. Today, all fuels to be used by U.S. forces must meet specifications that promote handling and use that is safe and reliable in the high-stress environments associated not only with combat but also with combat training. In mentioning inadvertent ignition, we have already alluded to one of these specifications: the minimum acceptable flash point.[3] Examples of other important specifications are those that address

- **thermal stability:** important because high-performance engines often use the fuel for cooling certain components

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[3] The flash point is the lowest temperature at which the vapors above a flammable liquid will ignite on the application of an ignition source (Chevron Global Aviation, 2006).

- **lubricity and viscosity:** essential for reliable engine performance
- **freezing point and vapor pressure:** both must be within maximum values appropriate for high-altitude flight and cold-weather operation of ships and ground vehicles
- **storage stability:** essential for reserve stocks that may be stored for several years
- **energy density:** the more energy per gallon and per pound of fuel, the higher the range between refueling.

One other important consideration in setting fuel specifications is fuel availability. Here, the goal has been to keep military fuel specifications as close as possible to civilian counterparts in widespread use around the world. For example, the properties of JP-8 are very close to those of the most widely used civilian jet fuel in countries other than the United States, namely, Jet A-1. Making JP-8 from Jet A-1 is done by simply mixing in three additives (see Box 2.1).

This similarity between JP-8 and Jet A-1 has profound logistic and economic benefits. The JP-8 needs of deployed military forces can be met by refiners located in the vicinity of those forces, thereby allowing a more secure and less expensive fuel supply chain. Moreover, because the global demand for middle distillates and jet fuel in particular is so large, the jet fuel market is highly competitive and there is a strong motivation for refining innovations that can reduce production costs. These benefits from competition and innovation extend to JP-8, since JP-8 depends on the same technology base required for the manufacture of the much more widely used civilian jet aircraft fuels.

A third consideration in setting fuel specifications is the logistical efficiency of minimizing the number of different fuels that need to be delivered to deployed forces. While JP-8's specifications are driven by its use as a jet propellant, its properties are fairly close to standard diesel fuel.[4] This allows JP-8 to be used as a fuel in the diesel engines commonly found in combat and combat support vehicles, weapon systems, and electric generators that support deployed forces. And JP-8 is naturally suited for the gas turbine engines that power modern tanks and other large tracked vehicles. Even though JP-8 is not a "perfect" diesel fuel, the logistical efficiencies associated with delivering one less fuel to forward-based units have promoted the current DoD policy of having JP-8 serve the needs of the Air Force, Army, and land-based Marine Corps, Navy, and special forces.

Presently, DLA Energy and the military services are evaluating a change in the specification for JP-8 that would allow JP-8 to be formulated from either Jet A-1 or

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[4] The energy density (energy per gallon) of JP-8 is about 5 to 6 percent lower than typical automotive diesel fuels (Chevron Products Company, 2007). Also, the specification for JP-8 does not include a minimum cetane number. Use of a fuel with too low a cetane number in a compression ignition engine can cause rough operation, start-up problems, and excessive engine wear.

Jet A. The latter is the commercial jet fuel used in the United States.[5] Motivating this evaluation are the cost savings that would be realized if domestic JP-8 purchases were based on a fuel that is in widespread commercial use within the United States.

## Candidate Alternative Fuels for Military Use

*Two types of alternative fuels have emerged as the nearer-term candidates for military applications:*

- *Fuels produced via a method known as Fischer-Tropsch synthesis.*
- *Fuels produced by processing vegetable oils and animal fats with hydrogen. Various types of algae are also possible sources of oils that can be suitably processed with hydrogen.*

Numerous chemical and biochemical approaches are available to produce alternative middle distillate fuels that can substitute for military fuels (Regalbuto, 2009; NAS, 2009). Fuel research and testing being performed by the services have identified fuels produced via a method known as Fischer-Tropsch (FT) synthesis and fuels produced by hydrotreating renewable oils as the most promising nearer-term candidates for military use.

### Fischer-Tropsch Liquids

The FT method can be applied to a variety of carbonaceous feedstocks, including natural gas, coal, and biomass. As shown in Figure 2.1, the FT method begins with the conversion of the feedstock material to a gas containing carbon monoxide and hydrogen.[6] This gaseous mixture, which is often referred to as synthesis gas, is next sent to a chemical reactor, where it is converted to a mixture of liquid hydrocarbons via a process known as FT synthesis. These liquid hydrocarbons can be processed into fuels that can substitute for petroleum-derived transportation fuels.

An FT fuel production facility can be designed so that about two-thirds of its output would be middle distillates, including synthetic jet fuel, naval distillate, and

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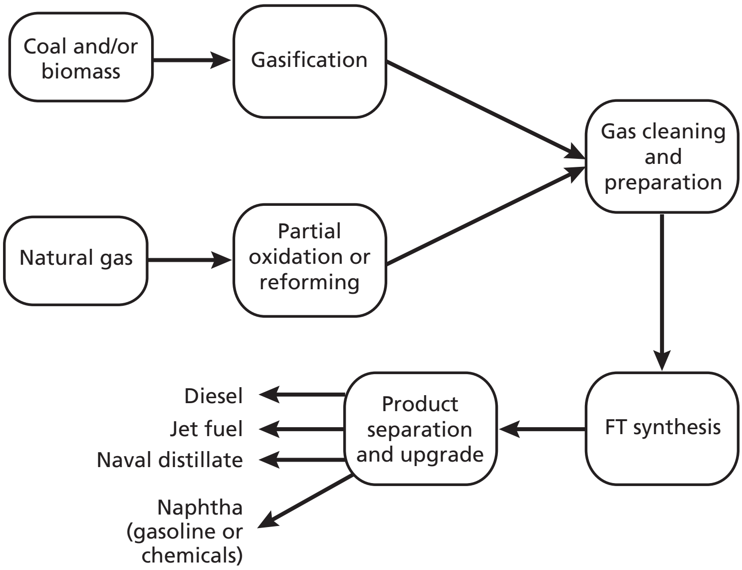
[5] The major difference between Jet A and Jet A-1 is that the maximum freezing point is –40°C for Jet A and –47°C for Jet A-1. This makes Jet A-1 more suitable for transpolar international flights, especially during the winter. Because of its less stringent specification, Jet A is slightly less expensive to produce (Chevron Global Aviation, 2006).

[6] When a solid material, coal or biomass, is the feedstock, this conversion step is known as gasification. When natural gas is the feedstock, the conversion is usually referred to as partial oxidation or reforming.

**Figure 2.1**
**Simplified Process Schematic for Fischer-Tropsch Liquids Production Showing Alternative Feedstocks and Fuel Products**



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synthetic diesel fuel for automotive uses. Synthetic jet fuels will generally constitute less than one-quarter of the product slate of an FT production facility.[7]

All available evidence suggests that a blend of an FT-derived jet fuel and petroleum-derived JP-8 or JP-5 can be formulated to meet the requirements of all applications now served by pure JP-8 or JP-5. In particular, the Air Force has established fuel formulation standards for a 50/50 FT/JP-8 blend and has certified that it can be safely used in a number of Air Force aircraft. While fuel formulation standards have not yet been established for blends of FT-derived fuels and either JP-5 or naval distillate, our discussions with fuel and fuel system experts in the Navy indicate that blends of up to 50 percent should not present problems.

Presently, commercial FT fuel production facilities are operating in South Africa, with coal as the feedstock, and in South Africa, Malaysia, and Qatar, with natural gas as the feedstock. By the end of 2010, construction is expected to be completed on a second FT fuel production plant in Qatar that would also use natural gas to produce 140,000 barrels per day of fuels. An FT production facility is also under construction in Nigeria, again using natural gas as the feedstock. By 2012, global production of FT fuels could exceed 350,000 bpd. In the United States, coal and biomass resources are

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[7] According to Freerks (2009), technical approaches to increase the jet fuel fraction beyond 25 percent are available for certain FT reactor designs. We do not have information on the cost implications associated with pushing the product yield to a high-jet-fuel fraction.

sufficiently large to support an industry producing a few million bpd of FT liquid fuels. U.S. natural gas is too costly to serve as a feedstock for an FT production facility; an exception might be certain Alaskan natural gas reserves that cannot be pipelined economically to demand centers in the lower 48 states.

**Special Benefits.** FT liquid fuels consist primarily of branched- and straight-chain saturated hydrocarbons, otherwise known as paraffins. The aromatic content is very low, and sulfur levels are nearly zero. As such, combustion of FT fuels instead of conventional jet or naval distillate fuels should result in reduced emissions of particulate matter, sulfur oxides, and possibly other air pollutants known to pose health threats. Reports abound of air pollution from jet fuel use (in electric generators and weapon systems) at forward operating bases. Our literature search, however, was unable to locate any DoD studies that quantify the extent that FT fuel use would reduce the adverse impacts of combustion-derived air pollution on the health of service personnel during training or while deployed.

An important environmental objective is reducing greenhouse gas emissions. For the FT fuels that are currently being commercially produced (from coal and natural gas), lifecycle greenhouse gas emissions are well above those of petroleum-derived fuels. But the prospects are promising that emerging technology will allow FT fuel production at lifecycle greenhouse gas emission levels that are well below those of petroleum-derived fuels. This topic is addressed more fully in Chapter Three.

Because of their low aromatic content, FT fuels have a very high cetane number. For ship and aircraft turbines, cetane number is irrelevant, but for the compression ignition (i.e., diesel) engines found in many military weapon systems, a minimum cetane number is required.[8]

Research conducted at the Air Force Research Laboratory shows that the thermal stability of FT jet fuels exceeds that of typical conventional military jet fuels. Higher thermal stability results in fewer carbonaceous deposits and should lower engine maintenance requirements (Edwards et al., 2004). As of fall 2009, it remained uncertain whether this benefit would result in cost savings sufficient to justify a price premium for FT liquids in military applications.[9]

**Costs.** When produced from coal, our best cost estimate is that FT liquid fuels are competitive at world market oil prices between $60 and $70 per barrel (2009 dollars).[10] This estimate holds for first-of-a-kind FT coal-to-liquids production facilities

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[8] As mentioned in footnote 4 earlier in this chapter, use of a fuel with too low a cetane number in a compression ignition engine can cause rough operation, start-up problems, and excessive engine wear.

[9] In contrast, near-zero sulfur content and high cetane number strongly suggest a price premium for FT liquids as a blendstock with petroleum-derived diesel for nonmilitary automotive applications.

[10] This cost estimate (rounded to the nearest five dollars) is derived from the $55 to $65 estimate of Bartis, Camm, and Ortiz (2008) by (1) escalating from first quarter 2007 to fourth quarter 2009 dollars using the implicit price deflator for the gross domestic product (Bureau of Economic Analysis, 2010) and (2) allowing for slightly higher (in real dollars) operational costs. The estimate includes costs associated with capturing (including

### Box 2.2: Why Not Gasohol and Biodiesel?

In the United States, as well as globally, a blend of ethanol and conventional gasoline, often referred to as gasohol, is currently the alternative fuel in greatest use. Spurred by federal subsidies, 2008 consumption of ethanol for fuel use in the United States was about 425,000 bpd (gasoline energy equivalent).[11] Although ethanol production in the United States is likely to increase over the next few years, ethanol is not a candidate for use as a military fuel, either neat or as a blend. Preventing its use in air, sea, and land military applications is its incompatibility with existing military power systems, nearly all of which are designed for jet or diesel fuels. But even if engines could be redesigned, ethanol use would pose a serious hazard due to its low flash point and high volatility. Additionally, ethanol has a low energy density and a propensity to attract water, which leads to corrosion problems.

Biodiesel has gained ground in civilian markets, especially in Europe. This fuel is most often made by processing vegetable oils, but animal fats are sometimes used. The current processing method is straightforward and results in an oxygen-containing fuel that is technically described as a fatty acid methyl ester (FAME).

FAME and blends of FAME with petroleum-derived fuels are currently banned from use in all deployable, tactical DoD military assets as well as in Coast Guard cutters and boats (U.S. Coast Guard, 2007). Problems preventing any military use center on fuel storage and handling, including water entrainment, formation of fuel-water emulsions, facilitation of microbial contamination, and chemical degradation. For aviation use, additional problems are low thermal stability and a high freeze point (Hileman et al., 2009).

**The bottom line**: Ethanol and biodiesel are unsuitable for use in weapon systems. They pose a severe safety risk, reduce performance, unduly complicate fuel delivery and storage, and generate maintenance problems.

producing at least 25,000 bpd of liquid fuels and is consistent with costs estimates in a recent report by the National Academy of Sciences (2009). As production experience is attained, we anticipate that production costs will decrease and FT liquids from coal might be competitive at world oil prices below $50 per barrel.

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drying and compressing) 90 percent of the plant's emissions of greenhouse gases but excludes costs (or payments) for transporting and sequestering those gases, under the assumption that the captured carbon dioxide will be used for enhanced oil recovery. We emphasize that this cost estimate is based on low-detail design analyses that are not site-specific.

[11] For 2008, consumption of fuel ethanol was reported to be 626,000 bpd. Since ethanol already contains oxygen, its volumetric energy density is only 68 percent of that of gasoline, yielding the gasoline energy equivalent of 425,000 bpd (Energy Information Administration, 2009b, Tables 10.3, A1, and A3).

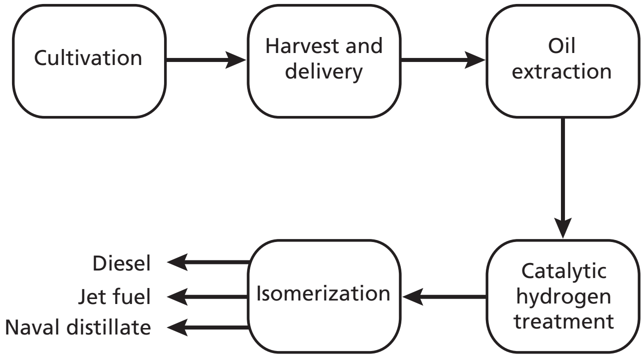
FT plants using stranded natural gas can be competitive at world oil prices below $50 per barrel (Hileman et al., 2009). But competitiveness depends very much on the costs of obtaining the natural gas feedstock.[12] Production concepts involving biomass or a combination of coal and biomass as the feedstocks are examined in Chapter Three.

### Hydrotreated Renewable Oils

Renewable oils include those from plants, such as soybeans, and algae. Animal fats, especially those collected during meat processing, also fall into this category. In their raw state, these oils and fats contain oxygen and have a chemical structure that makes them unsuitable for direct use as a fuel. But technical approaches are available that can convert renewable oils from their raw state to fuels appropriate for military applications. These approaches generally involve two main steps, both of which derive from technologies commonly used in petroleum refining:

- Vegetable oils (see Figure 2.2) or animal fats are first catalytically treated with hydrogen for the purpose of removing oxygen. This step yields straight-chain hydrocarbon molecules.
- These molecules are then cracked and rearranged to yield a mix of straight- and branched-chain hydrocarbon molecules similar to those found in petroleum-derived jet and diesel fuels. This mixture can be distilled to yield a synthetic diesel fuel for automotive use, a synthetic jet fuel, and, if desired, a synthetic naval distillate.

**Figure 2.2**
**Simplified Process Schematic for Producing Hydrotreated Renewable Oils from Oil-Yielding Crops**



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[12] For gas-to-liquids production facilities, economic viability at $50 per barrel world oil prices requires that delivered natural gas feedstock costs be less than $2.50 per million Btu (Hileman, 2009).

As with FT jet and naval distillate, all available evidence suggests that blends of hydrotreated renewable jet fuel and petroleum-derived JP-8 (or JP-5) can be formulated that meet the requirements of all military applications now served by pure petroleum-derived JP-8 (or JP-5). The same is true for blends of hydrotreated renewable naval distillate and petroleum-derived naval distillate. Supporting this finding are the successful results reported from flight-testing involving three commercial Boeing jet aircraft (Kinder and Rahmes, 2009). Also relevant are fuel analyses conducted by the Air Force Research Laboratory and others that show strong similarities in the chemical composition of FT and hydrotreated renewable oils (Rahmes et al., 2009). The question is not whether blends are possible, but rather what specifications such blends must meet.

So long as food crops and waste animal fats are the primary source of hydrotreated renewable oils, domestic production in the United States will likely be limited to less than 100,000 bpd (Bartis, Camm, and Ortiz, 2008; Hileman et al., 2009; U.S. Environmental Protection Agency, 2009). Of this amount, animal fats and recycled vegetable oils will likely account for at most 30,000 bpd. If the remaining 70,000 bpd is supplied via soybean cultivation, an amount of land equal to roughly 23 percent of the existing farmland devoted to soybean cultivation will need to be dedicated to fuel production.[13] A consequence of such a large diversion (in this case, about 17 million acres) of cropland from food to fuel production will be an increase in the price of the feedstock vegetable oils, as well as in the prices for food and animal feed. In addition, converting noncroplands to cultivation may be environmentally detrimental, especially with regard to climate change, as further discussed in Chapter Three.

**Special Benefits.** Since the chemical composition of hydrotreated renewable oils formulated for military applications is very close to that of the corresponding FT liquids, combustion of these fuels should result in reduced emissions of particulate matter. Likewise, cetane number and thermal stability should be superior to typical conventional military fuels.

With regard to greenhouse gas emissions, emerging technology should allow hydrotreated renewable oil use at lifecycle emission levels well below those of petroleum-derived fuels. But this requires that measures be taken to avoid large greenhouse gas releases during cultivation, as further discussed in Chapter Three.

**Costs.** Design-based cost analyses for the production of hydrotreated renewable jet fuel, naval distillate, or automotive diesel are not publicly available. Limited information is available from vendors of hydrotreating technology. For the production of a hydrotreated renewable diesel from vegetable oils at an existing petroleum refinery, UOP LLC reports a hydrogen requirement of 2.5 to 3.8 percent by weight and capital costs (inside battery limits) of between $6.00 and $11.00 per annual barrel of diesel

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[13] This estimate is based on the following: harvested soybean acreage in the United States, 75 million acres; average yield per acre, 43 bushels; average oil yield per bushel, 11.4 pounds; soybean oil density, 7.68 pounds per gallon (Interagency Agricultural Projections Committee, 2010).

production (UOP LLC, 2008a).[14] This information suggests that a hydrotreated renewable diesel can be produced from vegetable oil at a cost of roughly $0.30 to $0.45 per gallon.[15] For soybean oil priced at $3.07 per gallon (Interagency Agricultural Projections Committee, 2010), we estimate that hydrotreated renewable diesel would cost between $3.40 and $3.55 per gallon at the refinery gate, excluding consideration of federal subsidies. At these production costs, hydrotreated renewable diesel production starting with soybean oil is not economical unless world oil prices (using West Texas Intermediate as the benchmark) are in the range of or above $110 per barrel.

For processes that are designed to optimize hydrotreated renewable jet fuel production, production costs will be higher since the maximum yield of jet fuel is about 70 percent (UOP LLC, 2008b). At this yield, the lower value of the co-products—naphtha and fuel gas—will appreciably affect the net jet fuel production costs.

Development of advanced approaches for producing hydrotreated renewable oils is motivated by the need to reduce land requirements and overall cultivation costs. These advanced processes include oils from algae or from the action of bacteria or yeasts on cellulosic biomass feedstocks.

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[14] An inside-battery-limit (ISBL) estimate covers reactors and other equipment directly associated with the production of the hydrotreated renewable fuel. In general, an ISBL estimate does not include costs associated with utilities that may be needed to provide heat or power, hydrogen production systems, and other site-specific requirements associated with integrating the ISBL processes with the overall refinery and meeting environmental permitting requirements.

[15] The key assumptions underlying this cost estimate are that (1) total capital costs are twice ISBL capital costs, (2) hydrogen is valued at $10.00 per million Btu, (3) the process yield is at least 95 percent renewable diesel, and (4) the lower value of co-products (naphtha and fuel gas) can be ignored.

CHAPTER THREE

# Reducing Greenhouse Gas Emissions

Over the past few years, researchers have examined whether increasing the production of alternative fuels in the United States or elsewhere is compatible with the need to reduce global emissions of greenhouse gases. In the absence of government policies that require or promote minimizing these emissions, production and use of alternative fuels from coal, and possibly biomass, will likely have the opposite effect, resulting in greatly increased greenhouse gas emissions relative to conventional petroleum-derived fuels. In this chapter, we examine technical approaches that allow production of alternative fuels in ways that preserve national objectives for both energy security and the reduction of greenhouse gas emissions.

Our emphasis is on *lifecycle* greenhouse gas emissions—that is, all greenhouse gas emissions associated with the production and use of a fuel. For conventional petroleum fuels, these include greenhouse gas emissions associated with oil extraction, refining, delivery, and combustion in either a vehicle or aircraft. For coal-derived liquids, the life cycle begins with coal mining and includes emissions associated with the alternative fuel production facility, delivery, and final combustion. And for biofuels, the life cycle covers all aspects of cultivation and harvesting, delivery to a central processing facility, processing, and final combustion. Most importantly, it is now evident that land-use changes—both direct and indirect—can play a dominant role in the lifecycle greenhouse gas emissions of biofuels (NAS, 2009; Tilman et al., 2009). Our examination includes these emissions from land-use changes.

Fischer-Tropsch liquids and hydrotreated renewable oils that can substitute for military fuels have a chemical composition that is similar to their petroleum-derived counterparts. For that reason, both alternative and conventional fuels release on combustion nearly the same amount of greenhouse gases. Therefore, any significant differences in lifecycle emissions are associated with differences in how the alternative fuels are produced.

## Greenhouse Gas Management for Fischer-Tropsch Liquids

The lifecycle greenhouse gas emissions associated with alternative fuels produced by the FT method depend on (1) feedstock (coal, natural gas, or biomass) and (2) whether and how measures are taken to reduce greenhouse gas emissions that would otherwise occur during fuel production.

### Fischer-Tropsch Fuels from Coal

*Two approaches exist for producing alternative fuels from coal so that lifecycle greenhouse gas emissions are no worse than those of petroleum-derived fuels. Both approaches require that carbon dioxide gas emissions at the coal-to-liquids production facility be captured. In one of these approaches, the captured carbon dioxide would be used to enhance oil recovery. Enhanced oil recovery using carbon dioxide is proven and commercial. It is likely that the other approach, geological sequestration of carbon dioxide, will prove to be commercially viable in the United States. For a few locations in the United States, it may be possible to establish the commercial viability of geological sequestration by 2015.*

For the FT coal-to-liquids method in the absence of management of greenhouse gas emissions, each gallon of alternative fuel yields lifecycle greenhouse gas emissions about double those associated with conventional petroleum-derived fuels (Bartis, Camm, and Ortiz, 2008; NAS, 2009). Nearly all of the lifecycle greenhouse gas emissions are carbon dioxide, one half associated with combusting the fuel in a vehicle or aircraft engine and the other half emitted from the coal-to-liquids production facility. The main reason for these high emissions is the need to use part of the carbon in the input coal feed to make hydrogen and to produce heat needed in the overall fuel production process.[1]

Available commercial technology can capture nearly all (over 95 percent) of the carbon dioxide that would be otherwise released at a coal-to-liquids production facility. The additional costs for this level of capture are estimated to be about $5 per barrel of final liquid fuel product, which is equivalent to about $7 per ton of captured carbon dioxide.[2] These per-ton costs are much lower than those that would be incurred in capturing carbon dioxide emissions from fossil-fuel-fired electric power plants.

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[1] In general, for each atom of carbon in coal there is less than one atom of hydrogen. But for typical transportation fuels, there are about 2.2 hydrogen atoms per atom of carbon. To increase the hydrogen ratio, a portion of the carbon in the feedstock coal is reacted with steam, yielding both hydrogen and carbon dioxide.

[2] This equivalence is based on each barrel of fuel production causing the in-plant release of 0.7 tons of carbon dioxide (Bartis, Camm, and Ortiz, 2008). The capture costs include drying and compressing carbon dioxide to about 2,100 pounds per square inch.

At present, there is only one proven approach for disposing of the large amounts of carbon dioxide that can be captured at a coal-to-liquids production facility: using the carbon dioxide in an enhanced oil-recovery method known as *carbon dioxide flooding*. Between 30 and 40 million tons per year of carbon dioxide are currently used for recovering oil in the United States in this manner. Most of that carbon dioxide is obtained from natural reservoirs. Use of this approach should yield about two barrels of crude oil for each barrel of alternative fuel produced, thereby tripling the energy security benefits associated with coal-to-liquids fuel production while not increasing greenhouse gas emissions over what would be the case if the same amount of fuel were derived from imported petroleum. Moreover, payments for carbon dioxide could reduce overall plant operating costs, at least for early coal-to-liquids production facilities. Over the longer term, a conservative estimate is that potential demand for carbon dioxide use in enhanced oil recovery is sufficient to cover the carbon dioxide captured by an FT coal-to-liquids industry producing between 0.5 million and 1.2 million bpd.

For FT coal-to-liquids facilities that are not located near active oil basins that are appropriate for carbon dioxide flooding, the only other near-term approach for disposing of captured carbon dioxide is geological sequestration. This approach involves transporting by pipeline the captured and compressed carbon dioxide to a site where it can be injected into a suitable geological formation, such as a deep saline formation. Several projects outside the United States have been injecting large amounts of carbon dioxide underground. Ongoing experience from these projects suggests that geological sequestration is a technically viable approach for managing greenhouse gases.

The U.S. Department of Energy's Regional Carbon Sequestration Partnerships are moving forward with moderate-scale tests in the United States, in some cases over 1 million tons per year. But establishing the commercial viability of geological sequestration, which includes attaining public acceptance, will require several long-duration demonstrations at full commercial scale (i.e., a few million tons per year) (Bartis, Camm, and Ortiz, 2008). With an accelerated schedule for such demonstrations, it may be possible to establish commercial viability for at least a few geologies and technical approaches by 2015.

A conservative estimate of the costs of transporting and sequestering captured carbon dioxide is an additional $5 in production costs per barrel, which is equivalent to $7 per ton of carbon dioxide. Considering both capture and sequestration, total estimated costs are $10 per barrel of liquid fuel production, or, equivalently, about $15 per ton of carbon dioxide. With such low costs, FT coal-to-liquids production facilities offer a highly cost-effective source of carbon dioxide for large-scale, long-duration demonstrations. Moreover, policy measures that place a cost on emitting carbon dioxide should be highly effective in promoting greenhouse gas management in FT coal-to-liquids facilities.

The greenhouse gas emissions emanating from a coal-to-liquids facility can also be eliminated using hydrogen supplied by nuclear or renewable energy sources. But these approaches are unlikely to be competitive with geological sequestration over the next few decades, as discussed later in this chapter.

### Fischer-Tropsch Fuels from Biomass

*When biomass is used as the feedstock for the Fischer-Tropsch method, lifecycle greenhouse gas emissions can range from nearly zero to negative, depending on whether carbon dioxide releases during production are captured and sequestered. But such favorable performance can only be achieved when the biomass feedstock is produced in such a way as to avoid direct or indirect land-use changes that would release large amounts of carbon dioxide into the atmosphere.*

Biomass affords the *possibility* of fuel production at lifecycle greenhouse gas emission levels that are significantly below those of conventional fuels. This is because releases of carbon dioxide into the atmosphere during both liquid fuel production and combustion in a vehicle or aircraft can be compensated for by removal from the atmosphere of about the same amount of carbon dioxide during growth of the biomass used to make that fuel. However, achieving these beneficially low lifecycle greenhouse gas emissions requires that the biomass feedstock be produced in a manner that does not cause a large direct release of greenhouse gases and that does not displace food production. Basically, this requires that the production of biomass feedstock does not result in land-use changes that cause the release of large amounts of carbon dioxide, as further explained in Box 3.1.

Production of FT fuels from biomass is similar to FT fuel production from coal, except the size of the plant is smaller because of limitations on the amount of biomass that can be harvested within a reasonable distance of a production plant. Considerations of delivery logistics suggest that, with few exceptions, average daily biomass deliveries will be limited to a few thousand tons, which implies that liquid fuel production levels will generally be less than 5,000 bpd (Bartis, Camm, and Ortiz, 2008; NAS, 2009; Tarka et al., 2009).

Other than size, the only significant difference in the design of biomass-to-liquids versus coal-to-liquids facilities is in the operations required for preparing and gasifying the feedstock. Commercial systems are available for preparing and gasifying biomass, but not at the high throughput and high pressure required for FT biomass-to-liquids applications. Establishing the design basis needed to support commercial applications will require materials testing and the design, construction, and operation of a few large test rigs. Early coal-to-liquids fuel production facilities might provide cost-effective sites for both testing and demonstrating commercial performance. It is likely that an aggressive commercial development program could establish commercial viability within five years (NAS, 2009).

### Box 3.1. Reducing Greenhouse Gases via Biomass-Based Fuels

When a new fuel crop is grown, it must displace a previous crop or ecosystem. Depending on cultivation choices, changes in the above- and below-ground biomass can result (Searchinger et al., 2009). A net loss of biomass—or "carbon debt"—leads to *direct* greenhouse gas emissions, which can dominate total feedstock emissions. The carbon debt from growing corn for ethanol on abandoned croplands in the United States, for example, could take decades to repay (Fargione et al., 2008; Piñeiro et al., 2009).

Additionally, *indirect* land-use change can occur. Displacing food with fuel crops in the United States might result in cultivation of "replacement" food crops in other areas. As an extreme example, clearing tropical rainforests to grow such "replacement" food crops would create a carbon debt requiring hundreds of years to repay (Searchinger et al., 2008).

The exact magnitude and mechanisms of these changes are still being debated in the scientific community (Ross and Associates Environmental Consulting, Ltd., 2009), but under many plausible scenarios, land-use changes can cause increases in greenhouse gas concentrations in the atmosphere that would persist well beyond 2050. This would directly conflict with recent pledges by the leaders of industrialized nations to make an 80 percent reduction in greenhouse gas emissions by 2050 (Fletcher and Fahrenthold, 2009).

However, appropriate biomass feedstocks can greatly reduce the lifecycle greenhouse gas emissions of biofuels. Candidate feedstocks that do not compete with food and minimize nonbeneficial direct and indirect land-use changes include (Tilman et al., 2009; NAS, 2009) the following:

- perennial plants, when grown on degraded abandoned lands
- crop residues, such as corn stover, when harvested conservatively to maintain soil quality
- forest residues, when harvested appropriately
- double and mixed cropping
- municipal and industrial wastes.

**The bottom line:** Fuels from biomass will reduce greenhouse gas emissions relative to fossil-based alternatives only if feedstocks are chosen that do not lead to large positive direct or indirect land-use change emissions.

A recent analysis of U.S. biofuel resources estimates that about 400 million tons per year of biomass feedstock are presently available via sustainable production methods (see Box 3.1) and suitable for biofuel production using the FT method (NAS, 2009). That analysis also finds that advances in technology and agricultural practices could increase this amount to about 550 million tons per year in 2020. If this entire amount were to be converted to liquid fuels via the FT method, the net liquid fuel yield would be about 2.2 million bpd.[3] Because some portion of the U.S. biofuel resource base is likely to be directed at electricity production, this estimate should be viewed as an upper bound.

In general, the only greenhouse gas emissions associated with using a sustainably grown biomass feedstock in an FT fuel production facility are those associated with the fuel use and chemicals involved in cultivating, harvesting, and delivering the biomass to a central facility where it would be converted to liquid fuels. Various studies agree that lifecycle greenhouse gas emissions can be close to zero and, in most cases, less than 15 percent of those of petroleum-based fuels (Bartis, Camm, and Ortiz, 2008; Tarka et al., 2009; NAS, 2009).

Just as in the case of FT coal-to-liquids production, carbon dioxide that would otherwise be released in an FT biomass-to-liquids facility can be captured and sequestered. In Table 3.1, the columns labeled "Biomass-to-Liquids" summarize our calculations of the lifecycle greenhouse gas emissions for FT liquids produced in a hypothetical facility processing switchgrass. The crucial assumption in these calculations is that the switchgrass is cultivated in a way (specifically, without adverse land-use changes)

**Table 3.1**
**Estimated Greenhouse Gas Emissions for Biomass-to-Liquids and Coal/Biomass-to-Liquids (50/50 by Energy) Plants with and without Carbon Capture and Sequestration**

| | Greenhouse Gas Flows (pounds CDE per gallon FT diesel) | | |
|---|---|---|---|
| **Major Process Step** | **Biomass-to-Liquids without Carbon Capture and Sequestration** | **Biomass-to-Liquids with Carbon Capture and Sequestration[a]** | **Coal/Biomass-to-Liquids (50/50) with Carbon Capture and Sequestration[a]** |
| Feedstock production and transportation | 3 | 3 | 4 |
| Biomass growth | –64 | –64 | –32 |
| Plant-site emissions | 44 | 4 | 4 |
| End-use emissions | 20 | 20 | 20 |
| Net emissions | 3 | –37 | –4 |

SOURCE: Bartis, Camm, and Ortiz, 2008, Appendix B.

[a] Assumes that 90 percent of plant-site emissions are captured and sequestered.

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[3] This estimate for net liquid fuel yield is based on 1.1 million dry tons per year of biomass yielding 4,410 bpd of liquid products (NAS, 2009, Table 4.2).

that avoids large releases of greenhouse gases.[4] For the case in which carbon dioxide is not sequestered, overall, relatively low amounts of greenhouse gases are emitted into the atmosphere, primarily as a result of the use of fossil fuels and fertilizers in the cultivation, harvest, and transport of the biomass to the alternative fuel facility. For the case in which plant-site emissions are captured and sequestered, about 37 pounds of greenhouse gases (measured as carbon dioxide equivalents [CDEs]) are removed from the atmosphere for each gallon of FT biomass fuel produced and consumed. For reference, producing and using petroleum-derived diesel with the energy equivalent of a gallon of FT diesel would put about 26 pounds (CDE) of greenhouse gases into the atmosphere.[5]

Unfortunately, the cost of producing liquid fuels using the FT biomass-to-liquids method is very high. For facilities that do not sequester carbon dioxide emissions, recent cost estimates suggest that competitive production requires crude oil prices that are above $130 per barrel (NAS, 2009; Tarka et al., 2009); with carbon dioxide sequestration, the breakeven crude oil price is above $140 per barrel. Two factors combine to cause high production costs. First, the fuel production levels of about 5,000 bpd are well below the output required to achieve economies of scale, especially considering the performance of currently available FT technology and the product upgrading required for the various fuels produced by the FT method. The second factor driving high production costs is the higher delivered cost of biomass, especially as compared with coal. For example, the National Academy of Sciences report on coal- and biomass-derived transportation fuel estimates delivered prices of biomass at more than double the price of coal, on an energy-equivalent basis (NAS, 2009). Recent RAND and Department of Energy research suggests even higher delivered costs (Tarka et al., 2009).

### Fischer-Tropsch Fuels from Coal and Biomass

*The use of coal and biomass in a single facility provides a means of capturing both the economic benefits of coal use (low feedstock costs and larger-scale operations) and the environmental benefits of biomass (very low greenhouse gas emissions), but only when used in combination with capture and sequestration of plant-site emissions of carbon dioxide. Additionally, the biomass feedstock must be produced in such a way as to avoid land-use changes that would release large amounts of carbon dioxide into the atmosphere.*

For this dual-fuel case, overall costs and environmental performance depend on the fraction of the feedstock that is biomass. Based on engineering analyses conducted by

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[4] While our calculations apply specifically to switchgrass, the overall results should be valid for other sources of biomass that do not require extensive energy expenditures during cultivation. In particular, our results should also apply to corn stover, other agricultural residues, and forest residues.

[5] A gallon of FT diesel contains about 92 percent of the energy of a gallon of petroleum-derived ultra-low-sulfur automotive diesel fuel.

RAND, the National Academy panel on liquid transportation fuels, the Princeton Environmental Institute, and the National Energy Technology Laboratory, it is clear that FT coal/biomass-to-liquids systems employing carbon capture and sequestration can produce alternative liquid fuels with no lifecycle greenhouse gas emissions (Bartis, Camm, and Ortiz, 2008; NAS, 2009; Kreutz et al., 2008; Larson et al., 2009; Tarka et al., 2009). For example, the column labeled "Coal/Biomass-to-Liquids (50/50)" in Table 3.1 shows the greenhouse gas flows for the case in which the energy fraction of the biomass feed (switchgrass) is 50 percent and 90 percent of the plant's carbon dioxide emissions are captured and sequestered. In this case, lifecycle greenhouse gas emissions are negative—four pounds of carbon dioxide are removed from the atmosphere for each gallon of fuel produced. Figure 3.1 illustrates this same case.

In the case of a coal/biomass-to-liquids plant employing 90 percent capture and sequestration of plant-site carbon dioxide emissions, a rough estimate of the reduction in total fuel cycle greenhouse gas emissions relative to conventional petroleum is provided in Figure 3.2.[6] From the graph, breakeven (100 percent reduction) occurs when the energy fraction of the biomass feed is about 40 percent. Whereas a biomass-only plant is limited to a liquid fuel output of less than 5,000 bpd, the 60/40 coal/biomass combined feed allows the plant size and production level to more than double, reaching roughly 10,000 bpd.[7] Smaller biomass fractions still yield significant greenhouse gas reductions and allow even larger plant sizes and greater production levels, as well as higher efficiencies. For example, a 75/25 coal/biomass feed would allow production of about 16,000 to 18,000 bpd at lifecycle greenhouse gas emission levels that are about 65 percent (as shown in Figure 3.2) below those of conventional petroleum fuels.

By having the majority of energy supplied by lower-cost coal instead of just biomass and by operating at a larger scale, the FT combined coal/biomass method should yield alternative fuels at production costs that are intermediate between those associated with a large FT coal-to-liquids plant and those associated with a small FT biomass-to-liquids plant. For instance, the same analysis that suggests that biomass-to-liquids fuel production (without carbon dioxide sequestration) will be competitive when crude oil prices are about $130 per barrel also suggests that the 60/40 coal/biomass-to-liquids configuration (with carbon dioxide sequestration) may be cost-competitive when crude oil prices are roughly $105 per barrel (NAS, 2009). In addition, the FT combined coal/biomass method with carbon sequestration significantly increases fuel production from the limited biomass resource base. At a 60/40 coal/biomass ratio, the 550 million tons

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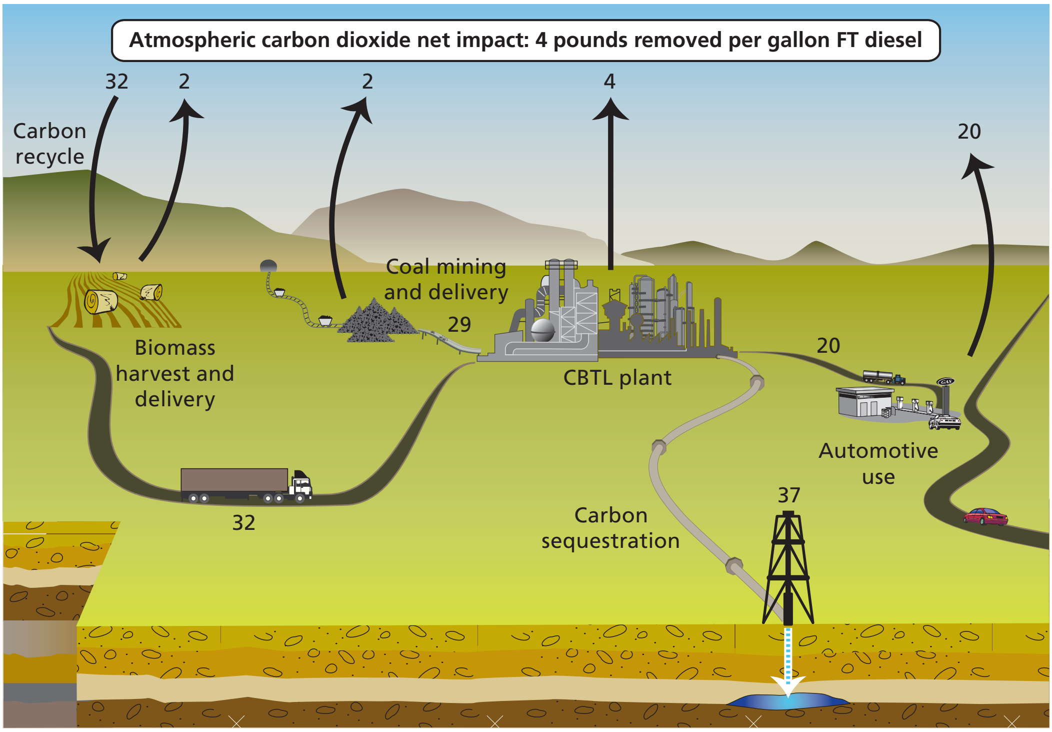
[6] The relationship shown in Figure 3.2 is from Bartis, Camm, and Ortiz (2008, p. 40) and assumes that a greenhouse gas emission credit is allowed for the electric power that would be produced as a by-product of FT fuel production.

[7] For example, an engineering analysis of a biomass-only FT plant calculates total liquids production of 4,410 bpd from a plant receiving 3,950 tons per day of biomass (NAS, 2009, Table 4.2). For an FT plant designed to accept 3,030 tons per day of coal in addition to 3,950 tons per day of biomass, total liquids production would be 10,000 bpd (NAS, 2009, Table 4.3). The latter case represents a 58/42 coal/biomass energy ratio.

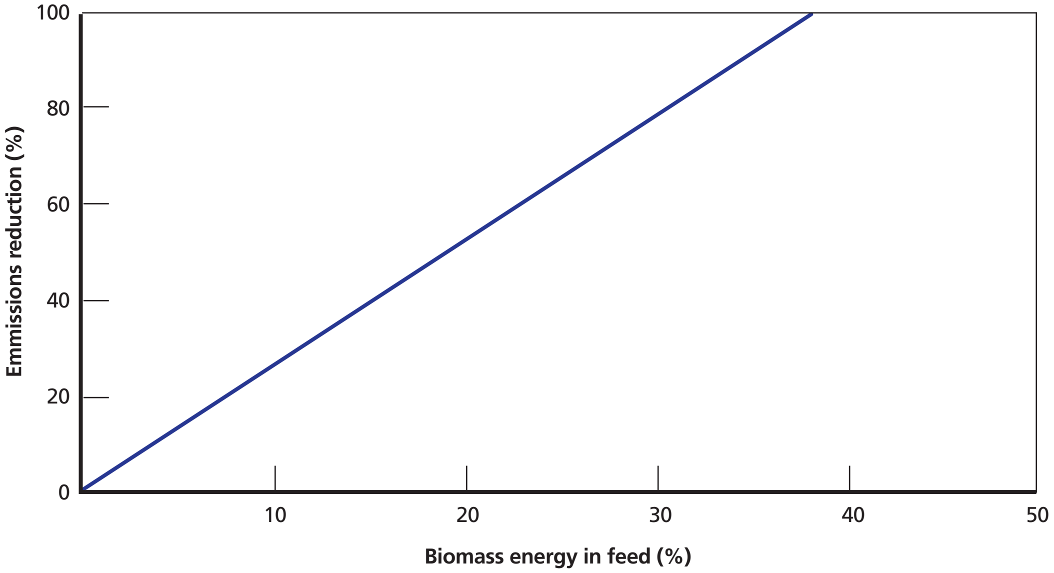
**Figure 3.1**
**Estimated Carbon Balances for a Dual-Feed Coal- and Biomass-to-Liquids Facility with Carbon Capture and Sequestration**



SOURCE: Bartis, Camm, and Ortiz, 2008.
NOTES: Plant energy input is 50/50 coal and biomass. Carbon flows are expressed as equivalent pounds of carbon dioxide per gallon of FT diesel produced, or carbon dioxide equivalents (CDEs). The 2 pounds of CDEs shown entering the atmosphere from biomass harvesting and delivery are associated with fuel and chemicals used in those operations. For coal mining and delivery, the 2 pounds of CDE emissions include methane released during mining operations. For each gallon of FT diesel produced and used, 28 pounds of CDE emissions enter the atmosphere and 32 pounds are removed from the atmosphere by biomass growth, yielding a net reduction of 4 pounds.
**RAND** *MG969-3.1*

estimate of annual biomass availability will support between 5.0 and 5.5 million bpd of alternative fuel production. A recent analysis suggests that as much as 4 million bpd of production capacity could be in place by 2035 (NAS, 2009).

**Figure 3.2**
**Increasing Biomass Feed Yields Greater Reductions of Greenhouse Gas Emissions Relative to Petroleum-Derived Fuels**



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## Fischer-Tropsch Fuels from Natural Gas

*Without incentives to manage greenhouse gas emissions, producing liquid fuels from natural gas will result in lifecycle emission levels that are comparable to or slightly higher than those of petroleum-derived fuels. Applying carbon dioxide capture and sequestration should result in lifecycle emission levels equal to or slightly lower than those of petroleum-derived fuels.*

In contrast to coal, natural gas has a higher hydrogen-to-carbon ratio than liquid transportation fuels, and, as would be expected, lifecycle greenhouse gas emissions of FT fuels produced from natural gas are much lower. The potential sources of greenhouse gas emissions include carbon dioxide and methane releases associated with natural gas production and treatment, and carbon dioxide emissions associated with providing heat and electric power within the FT gas-to-liquids production facility. In the absence of incentives to manage greenhouse gas emissions, lifecycle greenhouse gas emissions for alternative fuels produced from natural gas via the FT method are likely to be comparable to or slightly higher than those associated with conventional petroleum fuels.

Modest incentives to manage greenhouse gas emissions should result in natural gas–derived FT fuels with lifecycle greenhouse gas emissions that are equal to or slightly lower than those of conventional petroleum-derived fuels. Technical options for reducing greenhouse gas emissions include incorporating steam-methane reforming (rather than the partial methane oxidation approach currently used by Shell and SASOL) and sequestering carbon dioxide removed from the raw feed gas. For production facilities located so that captured carbon dioxide can be either used in enhanced oil recovery or geologically sequestered, eliminating nearly all production-related greenhouse gas emissions should increase fuel production costs by less than $3.00 per barrel of finished product.

## Greenhouse Gas Management for Renewable Oils

Most of the hydrotreated renewable oils that are near-term candidates for military applications are associated with lifecycle greenhouse gas emissions that are comparable to or greater than those of conventional petroleum-derived military fuels. The single most important factor driving high greenhouse gas emission levels are the greenhouse gas releases associated with direct and indirect land-use changes that occur when new lands are cleared and used to grow oil-bearing crops or to replace lost food production when lands that were devoted to food production are used for fuel production (as discussed in Box 3.1). Considering the rising global demand for food and animal feeds, especially from developing nations, any production of fuel from soybeans or *any other food crop* will be associated with such land-use changes. For example, a recent estimate of lifecycle greenhouse gas emissions for hydrotreated renewable jet fuel, averaged over 30 years, ranges from 20 percent greater to more than four times greater than the lifecycle greenhouse gas emissions from petroleum-derived jet fuel, with the lower estimate assuming grassland conversion and the upper estimate assuming rainforest conversion (Hileman et al., 2009).[8]

Near-term options for producing hydrotreated renewable fuels with much lower greenhouse gas emissions may be available, but production potentials and lifecycle greenhouse gas emission reductions are limited or uncertain. For example, animal fats and waste oils may provide a low-greenhouse-gas emission route to hydrotreated renewable fuels, but, at least until 2020, it is highly unlikely that these feedstocks can support domestic production of more than 25,000 bpd of hydrotreated renewable diesel fuel or more than 20,000 bpd of hydrotreated renewable jet fuel. Moreover, waste vegetable oils and much of the wastes generated during animal processing already have commercial applications; in fact, the oleochemical and animal feed producers that use

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[8] The lower end of this range (20 percent greater than petroleum-derived jet fuel) is higher than the Environmental Protection Agency estimate for 30-year greenhouse gas emissions (4 percent greater) for soy-derived biodiesel (U.S. Environmental Protection Agency, 2009). This is due to the additional greenhouse gas emissions involved in hydrotreating the raw oil, as compared with the process used to create FAME-type biodiesel.

these materials consider them commodities, not wastes.[9] Current uses include animal feed additives; soaps, detergents, and household cleaners; cosmetics; candles; and resins and plastics. If these waste oils and animal processing by-products are diverted from their current applications, other sources will be used instead. For example, the primary raw material for the U.S. oleochemical industry is tallow, an animal fat that is a by-product of meat processing. If tallow is diverted to the production of fuels, the likely replacement will be foreign-grown palm oil (Griesing, 2007). Increasing palm oil production will likely result in the destruction of rain forests, the net result being a very large increase in greenhouse gas emissions (Fargione et al., 2008).

### Jatropha Oil

*Jatropha is an oil-yielding plant that can grow on lands unsuitable for food production, but it remains highly uncertain whether jatropha can ever be an economically viable biofuel feedstock without causing the adverse greenhouse gas emissions associated with land-use changes.*

Another alternative is to use oil-yielding plant species that can grow on lands that are unsuitable for food production. *Jatropha curcas* (jatropha) has often been cited as the ideal plant for renewable oil production. Jatropha is a wild shrub that produces seeds that can have an oil content as high as 45 percent. Claims supporting jatropha include the fact that it can grow on marginal lands and tolerate drought conditions and that it has low nutrient requirements, low labor requirements, and high per-acre oil yields (Hileman et al., 2009). But initial field tests of jatropha cultivation suggest that high oil yields require that the plant receive water, nutrients, and soil conditions that are comparable to many food crops. The claims of low-labor requirements have yet to be verified (U.S. Environmental Protection Agency, 2009).[10] On the contrary, commercial producers indicate high labor requirements, especially for harvesting.

Because of its intolerance to frost and need for a minimum of 500 mm per year of rainfall, jatropha cultivation in the United States would be limited to a fairly small region, namely, southern Louisiana and Texas and most of Florida. However, even in these locales, it remains highly uncertain whether jatropha can ever be an economically viable biofuel feedstock without causing the adverse greenhouse gas emissions associated with land-use changes.

Although commercial jatropha oil farms are not operating in the United States, commercial production is underway or being established abroad. For example, the Abundant Biofuels Corporation, which is headquartered in California, has jatropha

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[9] For example, the cash prices of certain tallows are routinely listed in the *Wall Street Journal*.

[10] Through selective breeding, one company claims that it has produced a jatropha shrub that allows seeds to be harvested mechanically, rather than by hand (Dalton, 2009).

cultivation projects underway in the Philippines, Columbia, Peru, and the Dominican Republic (Fischel, 2009). D1 Oils plc of London, United Kingdom, has announced large projects in India, Malawi, and Zambia. A number of companies are reported to have recently acquired rights to cultivate jatropha in Ghana (Dogbevi, 2009). The central and some state governments of India are promoting jatropha production on tens of millions of acres, although these efforts have been criticized for potential adverse impacts on forested areas, biodiversity, and food production. Early yields in India have been below expectations (Orange, 2009). We do not have sufficient information to determine the extent, if any, to which these current and planned projects involve direct or indirect land-use changes that will result in large greenhouse gas emissions.

### Camelina Oil

*Camelina has gained some attention as a potential source of renewable oil production, but it is unclear whether it can be grown sustainably, and the plant's per-acre oil yields are too low for it to become an appreciable source for alternative fuel production.*

*Camelina sativa* (camelina) is also receiving attention as an "ideal" plant for renewable oil production. Camelina is an annual plant native to northern Europe that grows to a height of 1 to 3 feet. Its seeds have an oil content of about 40 percent. It has been cultivated in Europe and the former Soviet Union, its oil having been used for cooking, lighting, and the manufacture of soap, varnishes, and cosmetics (Zubr, 1997).

Camelina is recognized as a low-input crop that can be grown at water, fertilization, and pesticide levels well below common sources of biodiesel, such as soybeans. It is fast-growing and can serve as a rotation crop. It also can be grown on marginal lands. For these reasons, advocates claim that camelina production does not compete with production of food crops (Great Plains Oil and Exploration, 2008).

Because of its potential to serve as a sustainable source of renewable oils, camelina has attracted the attention of commercial aviation and military fuel scientists. In January 2009, Japan Airlines conducted a successful flight test of a jet fuel blended with hydrotreated renewable oils produced primarily from camelina oil.[11] In September 2009, DLA Energy awarded two contracts for the delivery to the Navy and Air Force of a total of 140,000 gallons of hydrotreated renewable jet fuel produced from camelina (see Chapter Five).

Camelina production in the United States is relatively new. Current cultivation appears to be competing with food crops, as evidenced by the dramatic decrease in camelina cultivation during 2008 in response to high wheat prices. Nonetheless, it

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[11] The flight test consisted of a one-hour burn in a single engine of a Boeing 747-300 (Kinder and Rahmes, 2009). The test blend was a 50/50 mix of conventional jet fuel and hydrotreated renewable oil. The sources of the hydrotreated renewable oil were camelina (84 percent), jatropha (16 percent), and algae (less than 1 percent).

is likely that some level of camelina cultivation can be conducted in a sustainable manner that does not cause unacceptable greenhouse gas emissions via direct or indirect changes in land use. But at present, there exist no independent analyses of how much it costs to cultivate camelina in a sustainable manner and what levels of oil production are possible with sustainable cultivation practices. While camelina advocates assert the environmental benefits of camelina cultivation over such alternative biofuel sources as corn and soybeans, they have joined the biodiesel community in opposing consideration of indirect land-use changes in calculating greenhouse gas emissions relevant for implementing Renewable Fuel Standards (Schill, 2009).

Even if the problem of sustainable production can be solved, seed crops are unlikely to provide appreciable amounts of alternative fuels. For example, obtaining 200,000 bpd (about 1 percent of U.S. oil consumption) of alternative fuels from camelina would require the cultivation of at least 34 million acres, which is about 10 percent of the total cropland under cultivation in the United States.[12]

### Algal Oils

*In the longer term, it may be possible to produce appreciable amounts of diesel and jet fuel from algae in a climate-friendly way. Because all methods for liquid fuel production from algae are at early stages of development, lifecycle greenhouse gas emissions for commercially produced algae-derived fuels remain uncertain.*

The limited near-term opportunities for producing renewable oils in a sustainable manner in the United States have motivated interest in advanced, but longer-term, approaches using microalgae that offer very high per-acre oil yields.

High-yield algae cultivation using sunlight requires a source of carbon dioxide. To enhance productivity, most algae cultivation schemes for fuel production involve using carbon dioxide concentrations that are well above the atmospheric level of only 0.035 percent by weight. Often, these schemes involve using the stack gases from a coal-fired electric power plant, which are generally over 10 percent carbon dioxide by weight. Due to the early stage of development of algal oil processes, greenhouse gas emissions during algal oil production remain uncertain. If only a small fraction (e.g., under one-tenth) of the carbon dioxide sent to an algal oil production facility is released into the atmosphere during algae growth and processing, photosynthetic algal oil production provides an alternative to capturing and geologically sequestering the carbon dioxide emissions from the fossil fuel–fired power plant. Specifically, lifecycle greenhouse gas emissions would be close to those that would be achieved if carbon

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[12] This estimate is based on an average oil yield of 100 gallons per acre, which is likely to be well above that obtainable on marginal lands, and assumes that losses during hydrotreatment are 10 percent, which is also optimistic.

capture and sequestration were employed at the power plant and crude oil, as opposed to algae, were the source of the liquid fuel. Overall, algae-derived oil production using stack-gas carbon dioxide has about the same effect on greenhouse gas emissions as capturing and sequestering the greenhouse gas emissions associated with fossil fuel–fired power generation, or displacing fossil fuel–derived electricity with electricity generated by nuclear or renewable systems.

Technical approaches are available that can go beyond this limitation and lead to algae-based alternative fuels that are truly renewable. One approach is to use carbon dioxide gas derived from renewable sources, such as electric power plants operating on biomass or biomass-conversion processes (e.g., the FT biomass-to-liquids process or fermentation-based methods being developed to produce alcohols or hydrocarbons from cellulosic feedstocks). Another approach is to forgo direct photosynthesis in algae cultivation and instead grow algae via fermentation of biomass, as is the case for the Solarzyme process (Solarzyme, Inc., 2009). But as always when considering biomass use, favorable performance can only be achieved when production of the biomass feedstock does not result in land-use changes that cause the release of large amounts of carbon dioxide. In particular, algal-oil processes that require sugar, corn, or similar feedstocks will result in environmentally unfavorable land-use changes.

## Alternative Fuel Production with Greenhouse-Gas-Free Power

In this section, we summarize analyses conducted by RAND for this monograph on the potential benefits of using greenhouse-gas-free power sources in producing alternative military fuels from coal or biomass. Our examination covers greenhouse-gas-free power from nuclear and renewable sources, such as wind, photovoltaic, and solar thermal systems.[13] Our work draws on recent analyses conducted at the Massachusetts Institute of Technology (Forsberg, 2009a, 2009b) and the Idaho National Laboratory (Cherry, 2008; McKellar, Hawkes, and O'Brien, 2008; Hill, 2009)

A nuclear power plant or a solar thermal power plant can provide a liquefaction facility with electric power and heat. The electric power produced by nuclear or solar thermal power plants can also provide hydrogen via electrolysis of water. Wind and photovoltaic power plants can provide electric power, and with that power these two low-temperature renewable sources can also provide hydrogen via electrolysis of water.

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[13] We follow popular practice in describing power generated from nuclear, wind, and solar technologies as "greenhouse-gas-free." A detailed lifecycle analysis would reveal greenhouse gas emissions, albeit fairly small, associated with producing the materials and components used in such power-generating systems and possibly from land-use changes associated with deploying such systems (see, for example, Weisser, 2007).

## Processes Based on Gasification (Such as the Fischer-Tropsch Method)

*For alternative fuel production based on gasification, such as facilities that would use the Fischer-Tropsch method, nuclear and wind power can be used to produce hydrogen (via electrolysis of water). Doing so could significantly reduce feedstock (biomass or coal) use and greenhouse gas emissions, eliminating the need for carbon capture and sequestration. However, there are large investment costs associated with providing hydrogen to alternative fuel production plants in this manner, such that it is questionable whether this approach will be economically viable over the next two decades.*

Let us step back and consider the overall process of making a liquid fuel from coal or biomass or a combination of the two. The fundamental objective is to take a substance—coal or biomass, which has a low hydrogen-to-carbon ratio—and convert it to transportation fuels, which have a hydrogen-to-carbon ratio that is generally higher by a factor of three to four. For liquefaction processes that begin with gasification, such as those involving the FT method, the higher hydrogen content of the liquid products is achieved by using a large portion of the carbon that was in the feedstock to make hydrogen.[14] The overall chemistry for this process is

$$\mathrm{C\ (feedstock)} + 2H_2O \rightarrow 2H_2 + CO_2,$$

namely, a reaction of the carbon in the feedstock with steam to yield hydrogen and carbon dioxide. If an external source of hydrogen were available, there would be less or no need to use carbon in the feedstock to make hydrogen, and the resultant carbon dioxide emissions would be reduced. In this event, more carbon could be used to make liquid fuels, resulting in an increase in liquids yield per ton of input feedstock.

A small amount of feedstock (or fuel gas derived from the feedstock) is generally used to make electric power in FT and similar types of liquid fuel production facilities. If an external low-cost source of power were available, this energy could be used to slightly increase the amount of liquid fuel produced by the facility. This might slightly decrease the lifecycle greenhouse gas emissions of alternative fuels, but the overall magnitude of lifecycle greenhouse gas emissions for alternative fuels relative to petroleum-derived fuels would remain roughly the same: Without carbon dioxide capture and sequestration, lifecycle emissions would be about double those of conventional fuels, and with carbon dioxide capture and sequestration, lifecycle emissions would be comparable to those of petroleum-derived fuels.

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[14] This approach applies to all indirect liquefaction processes (including the FT method) as well as direct liquefaction processes. An alternative approach, which is used in pyrolysis-based liquefaction, increases the hydrogen-to-carbon ratio by removing carbon. Pyrolysis-based methods for coal liquefaction have not yet been shown to be useful for widespread application.

While there is an evident role for external hydrogen and a minor role for external power at a coal-to-liquids or biomass-to-liquids plant, there appears to be no or very little benefit from an external source of thermal energy. This is because gasification-based processes create fairly high-quality thermal energy. That thermal energy can be used to meet heating requirements within the plant and to cogenerate electric power, some of which would be used within the plant and the rest sold.

To examine the implications of an external source of hydrogen, we conducted a series of engineering analyses at a level of detail sufficient to provide rough quantitative estimates. These analyses are documented in Appendix B. For reducing greenhouse gas emissions, the case of greatest interest is one in which sufficient externally produced hydrogen is available (from a nuclear or renewable source) so that there is no need to make any hydrogen from carbon in the fuel production facility. In this case, nearly all of the carbon originally in the feedstock would be present in the liquid fuel products. In addition, certain portions of the alternative fuel plant can be eliminated or significantly downsized. Adding more hydrogen produces no additional benefit. We term this the "maximum-hydrogen" case. Adding less hydrogen does not allow the investment and operational savings associated with completely eliminating certain portions of the alternative fuel plant. For the maximum-hydrogen case, our engineering analysis indicates that

- Liquid fuel production per ton of coal would increase by a factor of about 2.5, and per ton of biomass by a factor of about 3.
- Plant-site greenhouse gas emissions would be very small, leading to lifecycle greenhouse gas emissions that would be
  - near-zero when biomass is the feedstock[15]
  - slightly (5 to 10 percent) less than those of petroleum-derived fuels when coal is the feedstock
  - at levels intermediate between the above when a combination of coal and biomass is the feedstock.
- The capital and operating costs of making liquid fuels would significantly decrease, but these savings would be exceeded by the costs of producing hydrogen. For the maximum-hydrogen case, between 50 and 65 pounds of hydrogen are required per barrel of final liquid product.
- Using nuclear or renewable power sources to supply hydrogen for liquid fuel production could require large amounts of generating capacity. For example, providing hydrogen to support 100,000 bpd of alternative fuel production would require the electrical output of 5 to 6 gigawatts of conventional nuclear power-generating capacity.

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[15] Assuming that the cultivation of biomass does not result in direct or indirect land-use changes that cause appreciable releases of greenhouse gases.

The two principal advantages of the maximum-hydrogen case are that (1) all plant-site greenhouse gas emissions are eliminated without the investment and operating costs associated with carbon capture and sequestration and (2) the large increase in liquids output per unit of feed input. In the case of a coal-only plant, hydrogen addition allows the same liquids production and greenhouse gas emissions as a conventional FT coal-to-liquids plant employing carbon capture and sequestration, but at about 60 percent less coal use, allowing a significant reduction in all of the adverse environmental impacts of mining coal (Bartis, Camm, and Ortiz, 2008).

Both of these benefits have a greater significance for biomass-to-liquids and combined coal/biomass-to-liquids plants than for FT plants in which coal is the only input. For the former, constraints on the amount of biomass that can be delivered force plant designs that are significantly smaller than needed to achieve economies of scale, especially with regard to equipment required for upgrading the raw products produced in the FT reactors. Biomass-to-liquids plants employing hydrogen addition could yield between 14,000 and 15,000 bpd, as opposed to the 5,000 bpd production level that is often regarded as an upper bound for most potential locations in the United States (NAS, 2009). At these higher productivity levels, the National Academy's estimated national sustainable biomass production level of 550 million tons per year would yield roughly 6 million bpd of liquid fuel production. For combined coal/biomass-to-liquids plants (50/50 coal and biomass by energy content) with hydrogen addition, our engineering analysis indicates that alternative fuel yields of over 25,000 bpd can be anticipated, with lifecycle greenhouse gas emissions at less than 50 percent of those of petroleum-derived fuels.

Electrolysis of water produces both hydrogen and oxygen. Having an external source of both gases allows significant savings in the construction and operation of a gasification-type alternative fuel plant. For example, investment and operating costs associated with cryogenic air separation and carbon dioxide removal and compression would not be incurred. Also, the liquid fuel output of the plant would be increased without any additional investment in the gasification-related portion of the plant. For the case of FT plants designed to accept biomass or a combination of biomass and coal, larger product flows allow economies of scale on the back end of a production plant.

**Nuclear Power.** But these savings come at a potentially very high price. For the maximum-hydrogen case, each 100,000 bpd of alternative fuel production would require the construction of 5,000 to 6,000 megawatts of nuclear power capacity (see Appendix B), which is the output of about five or six full-scale power plants.[16] On a per-barrel basis, if nuclear power were used for hydrogen production, investment costs for

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[16] This power requirement assumes state-of-the-art commercial electrolysis technology. Advanced concepts, such as high-temperature steam electrolysis using both thermal and electrical energy from a very high-temperature nuclear reactor, might lower the power requirement to about 5,000 megawatts per 100,000 bpd of production (Boardman, 2009).

the required generating capacity would be between $100,000 and $240,000.[17] Additional investment costs would be incurred for the electrolysis system. Somewhat offsetting these investment costs for hydrogen production would be reduced investment costs for the alternative fuel production facility, since throughput would be higher and certain sections of the facility could be eliminated or downsized. There would also be major reductions in operating costs, especially in feedstock costs.

Our best estimates of the investment costs of FT coal-to-liquids and FT biomass-to-liquids plants (without external hydrogen) are roughly $120,000 and $160,000, respectively, per daily barrel of production capacity (Bartis, Camm, and Ortiz, 2008; NAS, 2009). Even if we assume that an external source of hydrogen would allow significant reductions in these investment costs, it appears that total investment costs would increase significantly.

While a detailed economic analysis is beyond the scope of our study, capital cost estimates for nuclear power plants suggest that hydrogen addition will not be economically competitive for coal-to-liquids plants unless carbon dioxide sequestration is not an option and the cost of emitting greenhouse gases is very high. But if those two conditions simultaneously prevail, it is highly likely that FT production plants based on a biomass or a combined coal/biomass feedstock, as opposed to coal-only plants, will be the economic choice for liquid fuel production (NAS, 2009). Hydrogen addition might be cost-effective for biomass-to-liquids and combined coal/biomass-to-liquids plants if constraints on biomass availability for energy applications increase delivered costs beyond expectations and also if the costs of building new nuclear plants are on the low side of current expectations.

A special case that is more economically attractive is to use nuclear power to generate hydrogen during periods of low power demand. For example, a single combined coal/biomass-to-liquids (50/50 coal/biomass by energy) plant producing about 28,000 bpd could be designed with sufficient hydrogen storage so that electrolysis would primarily be conducted during low-demand hours, namely at night (see Appendix B, Table B.1). If half of the nuclear-generated power were for hydrogen and half for the grid, this single alternative fuel production plant would cover the lower-value output of about 3,000 megawatts of installed nuclear generating capacity.[18]

**Wind and Solar Thermal.** Wind and solar thermal power systems operate at much lower utilization rates than nuclear power plants. If these systems were to be built as dedicated hydrogen suppliers to a gasification-based alternative fuel plant, the required

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[17] Because of technology changes and the decades that have passed since the last nuclear plant was built in the United States, nuclear power plant construction costs in the United States are highly uncertain. Here, we assume construction costs ranging from $2,000 to $4,000 per installed kilowatt, with the lower end reflecting potential long-term advances in nuclear technology and the upper end based on current technology and recent construction experience (Deutch, 2009).

[18] This estimate is based on nuclear systems operating at a capacity factor of 90 percent and an external power requirement for electrolysis of 1,227 kilowatt-hours per barrel of alternative fuels (see Table B.1).

generating capacity would be much greater than that in the nuclear case above. Each 100,000 bpd of alternative fuel production would require roughly between 13,000 and 16,000 megawatts of installed wind capacity and between 21,000 and 25,000 megawatts of installed solar thermal (see Appendix B). For comparison, total installed wind capacity in the United States at the end of 2008 was estimated at about 24,000 megawatts. Total installed solar generating capacity, including photovoltaic and thermal, is about 500 megawatts (Energy Information Administration, 2009c).

As of 2009, the installed costs (per kilowatt) for wind turbines were much lower than nuclear plants. Because intermittency of supply is less of a concern for hydrogen production than for delivery to the grid, wind appears to compete favorably with nuclear for hydrogen production.[19] Moreover, as was the case for nuclear power, producing hydrogen for FT biomass-to-liquids fuel and combined coal/biomass-to-liquids fuel facilities provides a means of productively using wind-derived electricity when grid-based demand is low. As wind turbine generating capacity in the United States grows, coupling wind capacity to a few combined coal/biomass-to-liquids fuel production facilities may be a competitive alternative for the lower-value power output. For example, a single alternative fuel production plant could consume the low-value output of about 8,000 megawatts of installed wind turbine generating capacity.[20]

Considering current and emerging technologies, it is highly unlikely that solar thermal power systems can compete with either wind or nuclear as a source of hydrogen for gasification-based alternative fuel production.

### Hydrotreated Renewable Oils

*For the production of hydrotreated renewable oils, the most beneficial way to use greenhouse-gas-free power sources is to produce the hydrogen (via electrolysis of water) required for hydrotreating the raw oil. There may also be some demand for the electric power.*

For hydrotreated renewable oils, most of the lifecycle greenhouse gas emissions can be attributed to three sources: (1) direct and indirect land-use changes, as discussed earlier in this chapter, (2) seed crop or algae cultivation and extraction of the raw renewable oil, and (3) production of the hydrogen required for hydrotreating the raw oil. Under the assumption that production will not involve land-use changes that result in appreciable greenhouse gas emissions, hydrotreated renewable oils should have lifecycle greenhouse gas emission levels that are less than half of those of their corresponding

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[19] Whether wind or nuclear will be more favorable for hydrogen generation depends very much on location and the course of future technology developments in lowering production costs.

[20] This estimate is based on wind systems operating at a capacity factor of 35 percent, with low-value power representing half of total electric energy generated, and an external power requirement for electrolysis of 1,227 kilowatt-hours per barrel of alternative fuels.

conventional petroleum products (UOP LLC, 2008a). More than half of these greenhouse gas emissions are associated with the production of hydrogen from fossil fuels.

If a greenhouse-gas-free source of electric power is available, the greenhouse gas emissions associated with hydrogen production could be greatly reduced or eliminated. Instead, hydrogen could be produced from electric power via electrolysis of water. In this case, we estimate that between 190 and 240 kilowatt-hours of electric power would be required for each barrel of renewable hydrotreated oil produced.[21] Roughly, each 100,000 bpd of alternative fuel production capacity would require the dedicated output of a full-scale (i.e., about 1,000 megawatt) nuclear power plant. If the source of the electric power were wind turbines, the required dedicated generating capacity would increase to about 2,500 megawatts, reflecting the lower utilization rate of wind turbines as compared to nuclear power systems.

Additionally, there may be some demand for electric power to operate equipment used for fuel production. For alternative fuels derived from seed oils, electricity requirements are fairly small, being limited primarily to equipment required for crushing and oil extraction. For algae cultivation, power demand should be greater, since electricity is required for mixing, circulation, and water and nutrient management. But the current stage of technology development for algae-derived fuels precludes a reliable estimate of power demand.

### Prospects for Fuel Production with Greenhouse-Gas-Free Power

*The high demand for electric power and other economic considerations make it unlikely that greenhouse-gas-free power will be used for alternative fuel production (via hydrogen addition) in the next two decades. However, over the longer term, alternative fuel production with greenhouse-gas-free power may eventually be a viable economic choice for the production of military fuels as well as certain civilian fuels.*

If a national effort to reduce greenhouse gas emissions is implemented, major emphasis is likely to be placed on emissions associated with electric power generation, particularly coal-fired power generation. This effort will require very large investments to ensure that electric power demand for traditional uses continues to be met. For this reason, we are skeptical that additional hundreds of billions of dollars can be available for investments in power generation that would be dedicated to alternative fuel production.

Another important consideration is cost. As discussed in Appendix B (Table B.1), the external power requirement for hydrogen addition in FT and other gasification-

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[21] This estimate is based on the following assumptions: hydrogen requirement between 2.5 and 3.0 percent by weight, oil density of 7.7 pounds per gallon, and 75 percent energy efficiency for electrolysis (electricity to hydrogen).

based fuel production is roughly 1,300 kilowatt-hours per barrel of product. New nuclear generation systems are unlikely to yield power at wholesale costs significantly less than $0.08 per kilowatt-hour (Deutch, 2009). At those rates, power costs alone would be about $100 per barrel of alternative fuel. This suggests that hydrogen addition is not economically viable unless the prices (including fees, if any, for releasing greenhouse gases into the atmosphere) of conventional fuels are above $150 per barrel.

For light-duty civilian vehicles, electric drive technology has already achieved public acceptance, as evidenced by growing demand for hybrid vehicles. Further technical advances may open the civilian marketplace to plug-in hybrids as well as all-electric vehicles. Our analyses indicate that if such electric vehicles were available, it would be about twice as efficient, in terms of lifecycle energy use, and thereby less costly, to use nuclear or renewable electric power in those vehicles as opposed to using that power to produce hydrogen for the purpose of manufacturing alternative liquid fuels for use in gasoline- or diesel-powered vehicles. This efficiency argument, however, is not valid for certain civilian applications, such as commercial aviation, marine transport, and long-haul trucking, for which electricity is not an option. Likewise, electricity is not appropriate—from technical, logistical, and operational viewpoints—for powering military aircraft, tactical vehicles, and most naval vessels.

Over the longer term, it is possible that advances in electric power generation will result in lower costs for nuclear and renewable electricity. Further, the combined development of advanced nuclear generating systems that operate at high temperatures and high-temperature hydrogen production systems could allow more efficient and economic production of hydrogen. Over the next two decades, however, these advanced technologies will likely see very limited commercial applications (Patterson and Park, 2008).

Using greenhouse-gas-free power for alternative fuel production does offer benefits that may be important over the longer term. For example, this approach provides an alternative path for greatly reducing plant-site greenhouse gas emissions in the event that carbon dioxide sequestration proves to be not as broadly applicable as currently anticipated. Also, this approach greatly increases product yield per unit of feedstock. This attribute could prove important if increasing demands on agriculture for both food and fuel drive up the costs of biomass feedstocks. Finally, this approach provides a productive use of nuclear and renewable power during periods of low demand, thereby allowing a greater fraction of overall power demand to be supplied by a combination of nuclear and renewable technologies.

These considerations suggest that alternative fuel production with greenhouse-gas-free power may eventually be a viable economic choice for the production of military fuels as well as certain civilian fuels (e.g., for long-haul trucks and commercial jets). However, this is not a promising option over at least the next two decades, especially considering the very large investments required over the coming decades for meeting traditional electricity demand while reducing greenhouse gas emissions from power generation.

CHAPTER FOUR

# Forward-Based Military Fuel Production

Per the requirements established by Congress (see Appendix A) for this study, we report on our examination of the military utility of mobile, in-theater synthetic fuel processes.

These forward-based fuel production concepts fall into one of the following two categories:

1. Local-feedstock-based concepts: small- to large-scale facilities that would use locally available carbon-containing feedstocks (e.g., natural gas, biomass, coal, or a concentrated stream of carbon dioxide) to produce liquid fuels.
2. Waste-disposal concepts: Small-scale facilities that would use carbon-containing wastes generated on forward bases or on ships to produce liquid fuels.

The only other possibilities would be either a process that uses carbon-containing feedstocks that would be delivered from outside the theater of operations, or a process that does not require any carbon-containing feedstocks. We could find no credible forward-based production concepts that use feedstocks delivered from outside the theater of operations. The costs and logistical complexity of securing delivery of feedstocks far outweigh any advantage of in-theater fuel production. Simply put, it is less expensive and easier to produce out-of-theater and deliver products over a long distance than to deliver feedstocks over a long distance and produce products locally. This is because the volume and weight of the feedstocks that would need to be delivered far exceed the volume and weight of the liquid fuel products that those feedstocks would produce. Also, it is much easier to load and unload liquid fuels than solids (coal or biomass) or liquefied natural gas.

In principle, it is possible to synthesize alternative military fuels using just water and carbon dioxide. While water is available in many locations, carbon dioxide is not, unless at the extremely low concentrations found in the atmosphere and in seawater. While scientifically possible, obtaining carbon dioxide from such low-concentration sources would be technically daunting and prohibitively expensive.

## Local-Feedstock-Based Production

Examples of forward-based concepts that require a feedstock include the following:

- An alternative fuel plant could be built on a barge that could be towed to a location within or near the theater of operations and where natural gas is available. Each floating plant could produce 10,000 to 20,000 bpd of fuel. If the floating plant is sufficiently close to forward operating units, the produced fuel could be transferred by helicopter; otherwise, it could be offloaded onto a Navy oiler.
- A small biomass-to-liquids plant could be built within or near a forward operating base. The fuel plant could produce between a few hundred and as much as 1,000 bpd using biomass delivered by local farmers.

While there are many variations of the above two cases and many in between, all of the local-feedstock-based production concepts examined in this study present serious operational, institutional, or logistical problems that significantly limit their military utility, as compared to producing fuel outside of the theater of operations and shipping that fuel to the theater of operations.

### Floating Production

*Large floating production facilities are vulnerable to attack and have limited application, since appropriate feedstocks may not be available. There is no evidence that a floating production facility would be less expensive than delivering finished military fuels produced outside the zone of conflict.*

For production levels of over 10,000 bpd, floating production plant concepts require a barge that is roughly the size of an aircraft carrier. Putting a barge of this size in the vicinity of or within a conflict zone would likely require protection by dedicated naval assets. Most importantly, the concept has limited application. The concept for floating production that has been most extensively examined involves jet and diesel fuel production from natural gas via Fischer-Tropsch synthesis.[1] Short-duration conflicts would not support the time and expense necessary to bring the barge to theater, secure a natural gas supply, and conduct equipment shakedown. There is also the question of whether permission to access the needed natural gas feedstock at reasonable prices and within a reasonable time would be granted by the nation (or nations) claiming ownership of the natural resource. Such permission might be delayed due to political reasons,

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[1] The primary advocate for this concept was the Syntroleum Corporation, headquartered in Tulsa, Oklahoma. Based on design and evaluation work conducted from 2003 through 2005, the concept involves obtaining natural gas from offshore production fields and converting it to 12,000 bpd of a synthetic fuel that can be blended with JP-8 and JP-5 (Syntroleum, 2003a, 2003b).

but there are also valid economic and technical reasons. If the natural gas is already being extracted, diversion to alternative liquids production would leave other applications and customers without supplies. If the natural gas is in an undeveloped reservoir, the owner nation may be concerned that a rush to production may preclude the reservoir characterization and engineering necessary for sustainable production.

Finally, there is no evidence that a floating production plant would be less expensive than using Navy oilers or commercial oil tankers to bring JP-8, JP-5, and diesel fuel directly to forward-based oil depots. Production economics further suffer from the need to produce a fairly narrow product slate, namely, middle distillates, which will require extensive upgrading or flaring of light hydrocarbon liquids and gases. Also, a production facility capable of producing roughly 10,000 bpd of fuel cannot sit idle in storage and then be expected to operate when needed. When not deployed, such a plant will need to be operated, and such operations could incur net annual losses.

Variations of this floating-barge production concept include using nuclear power to provide hydrogen from water, using coal rather than natural gas, and using co-produced water to meet the water needs of forward-based forces. So long as natural gas is the feedstock, there would be no shortage of hydrogen, and therefore no benefit from a nuclear source of hydrogen.

There would be no logistical advantages of using coal as the feedstock, even if the coal were to come from a local source. We are aware of no credible analysis that suggests that the costs of loading, unloading, storing, and processing coal in a mobile facility would be less than the costs of transporting finished fuels produced outside the zone of conflict.

While it is true that water can be a co-product of an FT gas-to-liquids plant, a search of the literature reveals that there is no experience, globally speaking, in using industrial wastewater for human consumption and very little experience in using industrial wastewater for irrigation of food crops. Even if research revealed that such use would be appropriate, significant water treatment and monitoring resources would be required to ensure that appropriate water quality standards were continuously met.

## Small-Scale Production

*It is difficult to identify a credible operational scenario in which having forward-based units carry and operate a small-footprint, modular alternative fuel plant would be an asset. The logistics and operational burden of having forward-based units secure a carbon-containing feedstock is greater than that of delivering finished fuels to those units.*

Motivating interest in small-scale alternative fuel production concepts is the potential to co-locate military fuel production with tactical units. Ongoing advances in chemical microprocessing offer the possibility of designing small-footprint, modular alternative fuel plants that can be delivered to or carried by a forward operating unit. Presumably, a tactical unit supported by such a plant would require less logistics support. In situations in which logistics lines are at risk of attack, fewer fuel-delivery trucks means fewer drivers at risk and fewer military assets dedicated to convoy security.

In our analysis of small-scale, forward-based military fuel production concepts, we considered both technical viability and military utility. From a strictly technical perspective, a number of the concepts being supported by DoD funds might be viable.[2] From a military utility perspective, all of these concepts appear to place a logistical and operational burden on forward-based tactical units that is well beyond that associated with the delivery of finished military fuels, either synthetic or conventional, produced outside the theater of operations. Specifically, all of these concepts require delivery of a carbon-containing feedstock. For all known fuel conversion processes, the weight and volume of the required feedstock deliveries would far exceed the weight and volume of the fuel deliveries that would be displaced. Considering fuel-delivery issues, the diversion of combat strength involved in protecting local extraction and delivery of feedstocks, and the additional personnel required to deliver, set up, operate, and maintain a forward-based military fuel production facility, we have difficulty identifying credible operational scenarios in which such a facility would be a military asset.

## Liquid Fuels from Military Wastes

*Small-scale systems that would convert carbon-containing wastes to fuel do not offer a measurable military advantage. Their development should only be pursued if they offer a cost-effective alternative to other means of managing the wastes generated by forward operating units.*

Forward operating bases and ships generate wastes that can be used to produce military fuels. Waste-to-fuel production systems potentially offer two benefits. First, they would reduce the amount of waste that needs to be otherwise disposed. Second, they would create a useful product—JP-8 is often the goal—and thereby reduce the amount of material that must be delivered to a tactical unit. In general, if all carbon-containing wastes generated by a military unit were converted to military fuels, the amount of fuel produced would be a small fraction (e.g., less than 5 percent) of the fuel needs of that unit. These concepts do not free a unit of the need for fuel deliveries; rather, they reduce the volume of these deliveries by a small amount.

Based on an examination of forward-based fuel production concepts and their operational implications, we find that these concepts may offer economic benefits, but

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[2] Some of the concepts being supported by DoD may also have nonmilitary applications. At the time of our examination, sufficient information was not available to judge whether economic and environmental performance is adequate to allow these advanced small-scale concepts to be commercially viable for nonmilitary applications.

only if further technology-development efforts show that they are more cost-effective and operationally superior to other alternatives for managing the waste. Otherwise, we find no significant military benefits to the approach of using wastes to create military fuels. The tactical unit with this waste-to-fuel capability will still require resupply, including fuel. Moreover, there are other options for managing wastes. For example, a tactical unit's wastes can be packaged so that the empty trucks, aircraft, or ships conducting resupply can remove those wastes.

Since successful development of waste-to-liquids systems would not yield a measurable military advantage, investments in developing tactical waste-to-fuel systems need to be evaluated based on their cost-effectiveness. With the need for cost-effectiveness in mind, we question the utility of focusing research and development (R&D) on systems capable of producing a specification-grade military fuel, such as JP-8 or JP-5. Attempting to do so requires incorporating in the system a number of fuel-upgrading steps and quality assurance procedures that add to costs, especially for small-scale systems. A more achievable, although still challenging, objective would be waste-to-electricity. In this alternative, the wastes would be converted to either a gaseous fuel or nonspecification liquid that would be used in an engine-generator set specially designed to accept a broad range of fuels.

## Summary

Review of mobile, forward-based fuel-production systems that have been or are under consideration within DoD indicates that none offer a compelling military advantage and some pose significant military burdens, as compared to delivery of conventional or alternative fuels produced outside the theater of operations. Because the military utility of mobile, forward-based fuel production systems is marginal at best, a comparative study of environmental performance, including greenhouse gas emissions, is not appropriate.

CHAPTER FIVE

# Alternative Fuel Activities in the U.S. Department of Defense

## Framing Our Examination

With regard to fueling deployable weapon systems, alternative fuel activities within DoD fall into the following three categories:

1. testing and establishing fuel specifications and certifying that they are compatible with current military equipment
2. developing advanced technology for producing alternative fuels
3. promoting commercial production.

Over the past decade, DoD has spent hundreds of millions of dollars on these activities. For the first item, there is a clear rationale for a DoD role. Putting the wrong fuel into weapon systems can jeopardize not only the major national investment in these systems but also the health and safety of service personnel. In this chapter, our examination of fuel testing, specification, and certification activities covers primarily the scope, timing, and adequacy of the efforts of the services in light of which new alternative fuels are or may soon be available for military applications.

The rationale for devoting DoD and service resources to the other two activity areas is less apparent. For activities in these areas, there are no department-wide goals. Moreover, our interviews with senior officials and officers found a lack of consensus on what the roles and goals should be. We saw a wide divergence in views, which was surprising since the people we interviewed were selected because of their direct involvement in or oversight of activities associated with alternative fuels.

One policy position is that DoD and the services should not be involved in directly supporting the development of alternative fuels for “mainline” weapon systems. This position recognizes that DoD demand, as large as it is, remains a very small percentage (about 1.7 percent) of total U.S. petroleum consumption. As such, the large investments required to develop and commercialize alternative fuel technologies should be driven by the prospects for civilian applications, not demand by DoD.[1]

A contrary policy position calls for strong DoD support for alternative fuel development and an active role in catalyzing the development of a U.S. alternative fuel industry that can produce fuels appropriate for military applications. This position recognizes that the U.S. government and particularly the U.S. Department of Energy have done very little to promote the development of a domestic alternative fuel industry that would produce the middle distillate fuels needed by the armed forces, such as JP-8, JP-5, and naval distillate. Advocates of this position also claim that the development of an industrial base capable of producing alternative jet and naval fuels would provide direct benefits to DoD in the form of lower fuel costs and more-reliable supplies.

Establishing where federal policy should fall between these two positions depends on two issues: the future availability of middle distillates—specifically, jet fuel—and the prospects for a domestic alternative fuel industry that can meet that demand. There is also an important implementation issue regarding the roles and responsibilities of DoD and the U.S. Department of Energy.

## The Outlook for Jet Fuel

**The Long-Term Outlook.** Over at least the next 20 years, most jet fuel is likely to continue to be derived from crude oil. Global crude oil resources are finite, and, as the global resource base diminishes, we anticipate that, over the long term (i.e., many decades), prices will rise and substitutes will enter the market. The magnitude of this long-term price rise in crude oil is highly uncertain. The long-term crude oil price trajectory depends on the rate and size of new oil field discoveries, on future technological advances that could allow increasing amounts of crude oil to be extracted from existing fields, on the extent to which alternative fuels enter the marketplace, and on the degree to which the governments of oil-rich nations, including the United States, impede or promote crude oil extraction. The long-term price trajectory of crude oil also depends on factors outside of the oil and fuel production business: Equally important are the rates of growth in demand for motor vehicle fuels in the developing world, the degree to which oil consumers will reduce demand in response to higher prices, and the extent to which national governments will implement policy measures that reduce crude oil demand for purposes of promoting energy security or reducing greenhouse gas emissions. With these factors in mind, it is clearly not possible to generate a confident prediction of where world oil prices are heading over the next decade or two.

These observations on the inherent uncertainties of the global crude oil market strongly suggest that private investment in commercial alternative fuel production will be postponed until investors have confidence that the alternative fuel produced by their

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[1] This position was also put forth in a 2006 JASON Defense Advisory Group study commissioned by the Director of Defense Research and Engineering (Dimotakis, Grober, and Lewis, 2006).

project will be competitive with petroleum-derived products. Considering the volatility of world oil prices over the past 15 years, establishing investor confidence will likely require that world oil prices remain well above the "breakeven" costs of a commercial alternative fuel project for an extended period of time.

Likewise, any consideration of federal investment or subsidies directed at alternative fuels should include the inherent uncertainty of where oil prices are heading over the next few decades. Basically, it is not possible to predict whether future world oil prices will be in or below the $60 per barrel range, in which case alternative fuel production would provide minimal or negative economic benefits, or in or above the $100 per barrel range, in which case alternative fuel production could provide a compelling economic benefit.

The same fundamental uncertainties associated with crude oil supply and prices pertain to jet fuel. But for jet fuel, additional forces are at play because jet fuel is one of a number of refined products derived from crude oil. Available analyses of demand for refined petroleum products suggest a shift from gasoline toward middle distillate fuels (Shore and Hackworth, 2009; ExxonMobil, 2009; Energy Information Administration, 2009a). This demand shift is occurring now and is likely to continue over the next few decades, as more energy-efficient light-duty vehicles are produced and as alternatives, such as ethanol-gasoline blends and electricity, are used to power light-duty vehicles. This demand shift has already caused the historical price differentials between gasoline and middle distillates to shift so that there is a greater incentive to produce jet and diesel fuels at the expense of gasoline.

Over the past few years, a number of U.S. refineries have responded to these price signals through operational modifications, as opposed to investments in new refinery hardware, that have allowed them to shift production away from gasoline and increase middle distillate yields by a few percentage points (Shore and Hackworth, 2009, slide 21). But as the shift to middle distillates from gasoline continues over the coming decades, higher relative prices for diesel and jet fuel will likely persist, as they provide the motivation for the major investments by refiners that are required to increase middle distillate yields.

These observations on distillate versus gasoline demand suggest that the private sector has good reasons to consider alternative fuels that offer to displace demand for petroleum-derived diesel and jet fuels. The market for these fuels is growing while that for gasoline is flat globally and decreasing in important markets such as the United States and Europe.

**Fuel Supply Disruptions.** We also cannot predict whether or when the world oil market will suffer from a large and extended disruption in oil supplies as a result of conflict or natural disaster.[2] But if such an abrupt disruption in global oil supplies were to occur, the United States as a whole would not suffer a physical shortage. If

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[2] For an attempt at focusing expert judgment on this problem, see Beccue and Huntington (2005).

the disruption is short-lived, a release of the strategic petroleum reserves held by many oil-importing nations would serve to prevent a significant disruption in deliveries or increase in prices. If the disruption is so large that it cannot be fully mitigated by the release of strategic reserves, world oil prices would rise sharply, and this would cause the United States and other consumers to reduce their use of petroleum products. Prices for alternative fuels would also rise, as they should, to promote market-induced conservation.

No matter what the cause, a large unanticipated decrease in international oil supplies would immediately cause spot-market fuel prices, including spot prices of alternative fuels, to increase sharply so that demand would match supply. Prices for fuels, including alternative fuels, purchased under contract would also rise, albeit more gradually, depending on cost-escalation provisions and the time span of the contract. The underlying causes of the supply disruption would be resolved eventually, but it might require a few more years for petroleum prices to return to the underlying long-term trend. Meanwhile, greatly increased petroleum prices would have adverse economic consequences for the United States and other oil-importing countries. The less dependent the economy is on oil and oil substitutes, the less the adverse economic impact on industry and final customers.

If a competitive alternative fuel industry is in place in the United States, a generally favorable consequence will be a reduction in long-term world oil prices as compared to what those prices would be in the absence of such an industry.[3] Lower petroleum prices would promote greater demand, with the net result being an economy that would be more dependent on liquid fuels and thereby potentially more vulnerable to a sudden disruption in world oil supplies. These considerations lead to the conclusion that a generally unfavorable consequence of a competitive alternative fuel industry is slightly greater vulnerability to the price shocks that would accompany a sudden disruption in world oil supplies.[4]

Increased domestic liquid fuel production does provide the government with potentially powerful policy options for reducing the adverse effects of an oil-supply disruption. The price shock that would accompany a large supply disruption would result in large and unanticipated excess profits to domestic petroleum and alternative fuel producers. Greater domestic liquid fuel production means that more of the excess

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[3] To have an appreciable impact on long-term world oil prices, a domestic alternative fuel industry would need to produce millions of barrels per day. This production level is well beyond DoD requirements.

[4] This greater vulnerability to a supply disruption is partially mitigated by the positive effects associated increased diversity of liquid fuel supplies. Specifically, alternative fuel production should cause a decrease in conventional petroleum production from most nations and regions, as compared to what conventional petroleum production would otherwise be. Consequently, a disruption of any particular source of crude oil would involve a smaller volume of oil and have less effect on petroleum prices. How large this secondary effect would be depends on how production in various oil-producing states responds to the lower world market oil prices induced by commercial alternative fuel production.

profits could be, for example, heavily taxed by the federal government and redistributed to oil consumers. We question, however, whether effective legislation to address the wealth transfer problem can be enacted, especially in a crisis atmosphere, without impairing market-induced deployment of additional productive capacity (Bartis, Camm, and Ortiz, 2008).

About 45 percent of the operating refinery capacity of the United States is located in the hurricane-prone states of Texas, Louisiana, and Mississippi. Because alternative fuel production would likely occur in diverse locations throughout the United States, a domestic alternative fuel industry would improve the resiliency of the petroleum supply chain, especially against natural disasters. Increasing the geographical diversity of fuel production implies that a smaller fraction of supplies would be affected by any natural disaster. As such, we anticipate less economic disruption as the remaining supplies are allocated to users.

If an appreciable fraction of military fuel needs were met by alternative fuels produced from domestic feedstocks, would DoD be less vulnerable to fuel supply disruptions? If an appreciable fraction of DoD fuel purchases were covered by mid-to-long-term contracts with provisions that would mitigate price escalation, DoD's total fuel expenditures could rise more slowly and to lower peaks than would otherwise be the case. Alternative fuel producers are good candidates for such cost-escalation mitigating contracts, but so are conventional fuel refiners. Available information does not support the contention that DoD can strike more favorable terms from suppliers of alternative fuels as opposed to suppliers of petroleum-derived fuels.

During a period of high prices, it is in the best interest of the nation for the military to take such emergency measures as possible to minimize its fuel use, consistent with national security requirements. This would be the case whether or not the military has access to low-cost fuel supplies. National security needs, however, may require an increase in DoD's use of JP-8, JP-5, and naval distillate at the same time that many refineries are producing less fuel. A consequence of an overall decrease in refinery output will be a proportional decrease in each of the refined products. For example, if gasoline production decreases by 20 percent, diesel and jet fuel production will decrease by roughly 20 percent. At the same time, high fuel prices will likely cause a disproportionately high decrease in jet fuel use by commercial aviation, since fuel costs are a large portion of the operating costs of commercial airlines. Although *overall* fuel supply would reduced, the decrease in commercial use could result in a net increase of *available* jet fuel for DoD purchases.

DLA Energy procures military fuels from a small fraction of the total number of refineries that operate in the United States. During the market turmoil that would accompany a sudden disruption in petroleum supplies, it is possible that some of these refineries may not be able to obtain sufficient crude oil to refine and deliver the amount of military jet and marine fuels needed by DoD. If an appreciable portion of DoD fuels were procured from alternative fuel producers, this problem would be lessened. Alternative fuels, however, represent but one approach available to the federal government. Most notably, the Defense Production Act of 1950 (50 U.S.C. Appx § 2061 et seq.), as amended, contains provisions for performance on a priority basis of contracts for the production, refining, and delivery of petroleum products to DoD and its contractors. If DoD determines that the provisions of the Defense Production Act are inadequate, other options include establishing a DoD-operated military fuel reserve or establishing agreements with traditional fuel suppliers that would grant priority to DoD during disruptions (Bartis, Camm, and Ortiz, 2008).

The above approaches (alternative fuels, use of the Defense Production Act, military fuel reserves, and emergency agreements) for responding to international energy supply disruptions can also address disruptions to the domestic fuel supply chain. Additionally, DLA Energy could include geographic diversity as a criterion in selecting suppliers of military fuels.

The foregoing considerations suggest that a competitive alternative fuel industry in the United States can reduce DoD's vulnerability to fuel supply disruptions. Other approaches, however, are available, and it is not evident that DoD investments directed at accelerating the establishment of a domestic alternative fuel industry are cost-effective, from the perspective of DoD, as compared to these other approaches. Overall, the major benefits of promoting early commercial experience in alternative fuels are at the national level, stemming from the economic and broad national security benefits of profitable domestic production, lower world oil prices, and reduced wealth transfers.

### The Prospects for Alternative Fuels

Fischer-Tropsch liquids stand out as the most promising nearer-term alternative fuels for military applications. In addition, a small amount of the military demand for tactical fuels might be met by hydrotreated renewable oils derived from animal processing wastes, recycled vegetable oils, and seed-bearing crops. These technologies are ready for initial commercial application in the United States, and a few commercial projects are in development (see Chapter Six). While there are some important technology-development needs for these approaches, technical viability is not the issue driving the commercial prospects of these approaches. Rather, private investment in initial commercial plants is being impeded by uncertainty of the future course of world oil prices, unfavorable economics or uncertainty about the costs and performance of first-of-a-kind alternative fuel plants, and uncertainty regarding the methods and legal requirements for managing greenhouse gas emissions. For FT approaches, these issues are discussed in recently published examinations (Bartis, Camm, and Ortiz, 2008; NAS, 2009). For hydrotreated renewable oils, they are equally valid. Available information regarding oils derived from food crops suggests that production costs, absent federal subsidies, are well beyond those required to be competitive with petroleum-derived fuels (Hileman et al., 2009). For fuels produced from seed-bearing plants, animal processing fats, and waste oils, procedures have not yet been established for ensuring that greenhouse gas emissions and other adverse environmental impacts are controlled via sustainable cultivation and prevention of adverse land-use changes (see Chapter Three).

In particular, Section 526 of the Energy Independence and Security Act of 2007 (P.L. 110-140) requires that alternative and synthetic fuels procured by federal agencies for mobility-related use have greenhouse gas emissions that are less than or equal to those of the corresponding conventional fuel. Because there currently does not exist an agreed-upon, analytic methodology for determining the lifecycle greenhouse gas emissions of biomass-derived fuels, it remains highly uncertain whether seed oils, by-product fats, or waste oils can be procured for use in military applications in a manner consistent with the provisions of Section 526.

Moving beyond the near-term candidates for alternative fuels, technology performance and cost uncertainties naturally increase. With regard to supporting basic research, research managers, whether in government or the private sector, generally base their decisions to fund particular investigations on their consideration of fundamental scientific or engineering principles. But when it comes to supporting technology development directed at complex systems, costs increase, and back-of-the envelope calculations or gut reactions are not enough. There are a plethora of advanced approaches for converting coal or biomass into alternative fuels that are suitable for military use. Most of these approaches are technically feasible, so long as economic and environmental considerations are irrelevant. But when it comes to alternative fuels, economic viability and environmental performance are very important.

As the Department of Energy has learned, many energy systems, especially those involving alternative fuels, are highly complex. Picking winners is very difficult, as shown by the fact that very few of the energy technologies developed under Department of Energy sponsorship have seen commercial application. For this reason, the trend in technology-development programs at the Department of Energy has been increasing reliance on independent engineering systems analyses.[5] For example, the National Energy Technology Laboratory has an entire group devoted to evaluating, through engineering analyses, energy systems under development or consideration by the fossil energy technology-development program.

Our review of the alternative fuel development work being carried out within DoD or sponsored by DoD funding revealed that funding decisions are not being adequately supported by independently conducted engineering design analyses. In particular, we were unable to locate any documentation of independent engineering systems analyses conducted by any DoD organization sponsoring or conducting alternative fuel development work. In many cases, the only source of funding for these technology-development efforts is the federal government; cost-sharing is not required.

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[5] We consider an engineering analysis to be "independent" when it is conducted by an organization that is financially independent of the firm or institution that is receiving external funds to support that research.

Given this situation, we are concerned that DoD research managers may lack the information needed to make informed decisions regarding the commercial prospects of these technologies, even under the assumption that all of the technical goals of the project are achieved.

### U.S. Department of Energy Programs in Alternative Fuels

Our review of DoD R&D directed at developing advanced processes for alternative fuel production indicated that nearly all had applications for producing civilian fuels. The civilian demand for middle distillates is much larger than military fuel needs; having an alternative fuel that is able to compete in the civilian fuel market provides a much greater national benefit and a much greater financial reward to developers of new technologies than capturing the small military market. This being the case, why are defense dollars being directed at developing alternative fuel production technologies? Would it not make more sense to wait for commercial deployment directed at the large civilian markets for diesel and jet fuel, and then conduct research, if indeed needed, to formulate product streams appropriate for military applications? If the government's objective is to accelerate development of new technologies and commercial production of alternative fuels, should not the responsibility for meeting that objective be with the U.S. Department of Energy?

DoD officials interested in alternative fuels for military applications did initially turn to the Department of Energy and its national laboratories. They found in-depth technical expertise and a willingness to cooperate. But from a program viewpoint, they found an empty cupboard. Over most of the past decade, Department of Energy research on alternative fuels for transportation has been narrowly directed at only two fuels: ethanol and hydrogen, neither of which addresses the growing civilian demand for diesel and jet fuel in the United States, not to mention military applications. For example, in the Department of Energy's report, *Biomass: Multi-Year Program Plan*, "jet fuel" is mentioned just once (U.S. Department of Energy, 2009). The low world market oil prices of the 1990s, combined with a myopic view of the time frame for energy R&D, caused the 1996 termination of the Department of Energy's research and technology-development program for algae-derived fuels. The 1990s also saw the termination of nearly all Department of Energy work on coal-derived liquid fuel production.

The takeaway message from DoD interactions with the Department of Energy was clear: If DoD and the services want to accelerate development of alternative fuels capable of meeting military applications, they would need to take an active role in technology development and promoting commercial production. The danger is that this position might conflict with DoD's historical fuel policy of relying on competition in the civilian marketplace to drive innovation in fuel production and refining. Developing technology directed only at DoD applications has the risk of creating fuel production technologies that would have limited or no commercial value for the production of nonmilitary fuels and that would, thereby, not be "dual-use."

The Department of Energy has recently shifted from its historical position and has begun supporting the development of advanced technologies for producing middle distillate fuels from biomass. Specifically, the Aquatic Species Program at the National Renewable Energy Laboratory has been revived, with FY 2010 funding of $35 million. Thermochemical and biochemical approaches to middle distillate production are also being supported.

In May 2009, the Secretary of Energy announced that funds available from the American Recovery and Reinvestment Act (P.L. 111-5) would be used to accelerate biofuel R&D and specifically included alternative jet fuel production. In December 2009, the Department of Energy announced the investment of $170 million from the American Recovery and Reinvestment Act in seven pilot-scale and one demonstration-scale biorefinery projects that would produce middle distillate fuels.[6] Three of these projects specifically address jet fuel production.

In January, 2010, the Secretary of Energy announced that an additional $77.8 million in funds from the American Recovery and Reinvestment Act would be used to support advanced research on producing fuels derived from biomass (Chu, 2010). These funds are being directed at two consortia. The National Alliance for Advanced Biofuels and Bioproducts, led by the Donald Danforth Plant Science Center in St. Louis, Missouri, is to receive $44 million (plus $11 million in nonfederal funds) for the purpose of advancing the production of algae-derived fuels. The National Advanced Biofuels Consortium, led by the National Renewable Energy Laboratory and the Pacific Northwest National Laboratory, will receive $33.8 million in federal funds (plus $8.5 million in nonfederal funds) for the purpose of producing infrastructure-compatible biofuels, including middle distillates. Both consortia include multiple universities, national laboratories, and private companies.

These recent, large investments by the Department of Energy in advanced technologies for the production of alternative middle distillate fuels raise the issue of whether DoD efforts in developing advanced alternative fuel production technologies should continue and, if so, what should be the roles and responsibilities of DoD and the Department of Energy in this technology-development endeavor.

## Fuel Testing and Certification

Each of the services maintains laboratories that include expertise and research on fuels. Military systems often employ engines that are designed to operate in difficult environments at operating levels well beyond the limits of their commercial counterparts. Also, certain weapon applications, such as torpedoes and missiles, require specially formulated fuels, albeit not in large quantities. As new alternative fuels have been intro-

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[6] An additional $125 million of nonfederal funds would also be invested in these eight projects (Chu, 2009).

duced to civilian applications, these laboratories have examined their potential application in weapon systems. In some cases, such as alcohol fuels and biodiesel, testing and evaluation have determined that the alternative fuel is unable to pass muster as safe and appropriate for military use. But in other cases, such as FT fuels and hydrotreated renewable oils, the fuel science experts in the service laboratories have been at the forefront of efforts to establish standards and specifications, not only for military applications but also for civilian use.

Starting around 2000, researchers at the Air Force Research Laboratory (specifically in the Propulsion Directorate located at Wright-Patterson Air Force Base, Ohio) began examining the potential operational and environmental benefits of using alternative fuels created via FT synthesis in military aircraft and ground vehicles. Approval had recently been granted to fuel commercial aircraft with a blend that included FT fuel produced at single facility located in South Africa.[7] Also motivating this research were engineering assessments sponsored by the U.S. Department of Energy that indicated low production costs for FT middle distillate fuels produced from coal or natural gas (Bechtel Corporation, 1998). In 2002, the Army Tank Automotive Research, Development and Engineering Center (specifically, the National Automotive Center, located in Warren, Michigan) also began a small program directed at investigating FT fuels. As jet fuel prices began to rise in the mid-2000s, the scope of Air Force research efforts was expanded to establishing standards for the use of FT fuel blends in military aircraft. The objective was to cover blends produced from any FT process, as opposed to those from a single facility. As crude oil prices continued to rise, the Army and Navy increased their own efforts in testing and evaluating alternative fuels.

For the purpose of better incorporating energy considerations in its planning and business processes, the Secretary of Defense established in May 2006 an Energy Security Task Force that would be chaired by the Director of Defense Research and Engineering. In February 2007, Deputy Defense Secretary Gordon England directed that “the Department should consider energy efficiency and the ability to use alternative sources in its weapons platforms and tactical vehicles . . . where practical” (England, 2007). Most recently and in compliance with the provisions of the 2009 National Defense Authorization Act, DoD created within the Office of the Secretary of Defense the Office of the Director for Operational Energy Plans and Programs. The nominee for this position is awaiting Senate confirmation (as of March 15, 2010). Among other

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[7] Since 1999, the jet aircraft refueling facility at O. R. Tambo International Airport, serving Johannesburg, South Africa, has routinely received a blend of conventional jet fuel and coal-derived synthetic kerosene. Until 2008, the blend was limited to up to 50 percent synthetics produced by Sasol Ltd. using FT synthesis. Approval and requirements for this blend were established in a 1999 revision of Defence Standard 91-91 and were based on research that was specific to an alternative fuel produced at one particular plant in Secunda, South Africa. (Defence Standard 91-91 is issued by the United Kingdom Ministry of Defense and generally covers commercial jet fuel use outside of North America and Russia.) In 2008, Defence Standard 91-91 was modified to allow use of unblended synthetic jet fuel, but again only from the Secunda facility (Defence Fuels Group, 2008).

responsibilities, this new office will have planning and oversight responsibilities that cover all alternative fuel activities, including fuel testing and certification within DoD.

As of late 2009, each of the services is actively engaged in fuel testing and evaluation. In this work, they have been supported by DLA Energy. DARPA has also fostered work in this area. Overall, activities in this area are well coordinated; all of the major players appear to be aware of one another's efforts and concurrent work taking place in setting fuel standards for commercial aviation. To ensure interoperability, DoD fuel certification efforts include coordination with U.S. allies, including NATO members as well as Sweden, Japan, Australia, and New Zealand.

Through participation in the Commercial Aviation Alternative Fuels Initiative (CAAFI), DoD organizations have promoted and assisted commercial aviation in evaluating, testing, and certifying alternative aviation fuels. CAAFI was organized in 2006 by the Federal Aviation Administration (FAA) and aviation trade associations.[8] The goal of CAAFI is "to promote the development of alternative fuel options that offer equivalent levels of safety and compare favorably with petroleum-based jet fuel on cost and environmental bases, with the specific goal of enhancing security of energy supply" (CAAFI, 2009). DoD participation in CAAFI is important, since it is in the interest of DoD that the standards and specifications for alternative fuels for military applications are consistent with those adopted by commercial aviation, which dominates the domestic and global markets for jet fuel.

CAAFI is organized around four teams: (1) Fuel Certification and Qualification, (2) Research and Development, (3) Environment, and (4) Business and Economics. About 350 people from stakeholder firms (in the United States and abroad) and government organizations actively participate on one or more of these teams (Altman, 2009). DoD representatives participate in all four teams. As discussed in the following section, U.S. Air Force participants have played a leading role on the Fuel Certification and Qualification team, in fuel evaluation work on the R&D team, and in studying lifecycle emissions on the Environment team. DARPA has contributed to the R&D team in its evaluation of fuels and in developing CAAFI's R&D roadmap, especially in the area of hydrotreated renewable jet fuel. The Navy is represented on the R&D team. DLA Energy is an active participant in CAAFI, especially on the Business and Economics team, which is directed at facilitating and promoting the deployment of alternative jet fuels in the marketplace.

### Major Achievements

Notable progress has been achieved over the past two years. Much of this achievement is clearly due to efforts by the Air Force—specifically, the continuing work of the Pro-

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[8] Besides the FAA, the sponsors of CAAFI are the Airports Council International–North America, the Aerospace Industries Association, and the Air Transport Association of America.

pulsion Directorate of the Air Force Research Laboratory and the Alternative Fuels Certification Office of the Aeronautical Systems Center. These achievements include

1. Modification of the military specification (MIL-DTL-83133F) for JP-8 to cover blends of conventional JP-8 and synthetic kerosene from FT fuel production plants with a synthetics content of up to 50 percent (Air Force Petroleum Agency, 2008).
2. For blends meeting MIL-DTL-83133, certification of unrestricted use on B-52, C-17, B-1B, F-15, F-22, F-4, T-38, and C130J aircraft, as of March 10, 2010.
3. Publication in September 2009 by ASTM International of D7566-09, the first Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ASTM International, 2009). This standard allows use of alternative fuels and blends to meet FAA requirements for existing commercial jet aircraft (Rumizen, 2009). Presently, the standard covers synthetic kerosene produced using the FT method and allows blends containing up to 50 percent synthetics.
4. Completion of laboratory tests that show that a kerosene prepared from hydrotreated renewable oils contains much the same chemicals as a synthetic kerosene produced from the products of FT synthesis.
5. Establishment of preliminary specifications for hydrotreated renewable kerosene for blending with JP-8, JP-5, and Navy distillate, in support of alternative fuel purchases for testing and certification by the Air Force and Navy.

Publication of D7566-09 (the third item in the preceding list) directly affects 19 Air Force aircraft types that retain FAA certification, which should make it unnecessary for the Air Force to conduct platform-by-platform certification. The new ASTM standard is also designed to incorporate additional synthetic jet fuels, such as hydrotreated renewable oils, as further information from testing and evaluation becomes available. Air Force assistance to the ASTM standards-setting process for alternative aviation fuels is widely acknowledged (Maurice, 2009; Rumizen, 2009). Beyond active participation in formulating and implementing the standard-setting process, Air Force help included sharing Air Force engine test data and funding and executing fit-for-purpose fuel tests required to ensure that fuel properties will not impair aircraft operations or cause maintenance problems.

The fourth item in the achievement list is also noteworthy. At the request of DARPA, the Air Force Propulsion Directorate (of the Air Force Research Laboratory) examined the chemical characteristics and fuel-related properties of small amounts (100 liters) of hydrotreated renewable oils that were produced as part of DARPA's program to develop hydrotreatment technology applicable to oil obtained from crops. Taking place in 2007 and 2008, this work established that fuels produced from the FT method and from the hydrogenation of renewable oils were very similar, both consisting primarily of branched- and straight-chain saturated hydrocarbons, otherwise known as paraffins. This similarity implies that the knowledge base established for developing standards for certifying blends containing FT fuels is directly applicable to developing standards for and certifying blends of hydrogenated renewable oils. This fact, combined with the framework developed for expanding the ASTM standard, should greatly speed the standard-setting process and significantly reduce the need for extensive engine tests, including flight-testing.

### Current Programs and Goals

**Air Force.** The Air Force program on fuel testing is the largest within DoD. Program goals were established in a policy memorandum approved by the Secretary of the Air Force in December 2008 (Donley, 2008). These goals are formally implemented in Air Force Policy Directive 90-17 and Air Force Instruction 90-1701, both dated July 16, 2009 (U.S. Air Force, 2009a, 2009b). For fuel testing and certification, the main program goal is to complete certification of FT blends (up to 50 percent synthetic) for all Air Force aircraft and systems by FY 2011. The Air Force approach to certification of the FT blends involves flight-testing each aircraft type. This is an expensive undertaking and is driven by institutional requirements that derive from the Air Force approach to aircraft management. Fuel and propulsion experts in the Air Force agree that there is no technical reason for conducting such an extensive number of flight tests; the Air Force Alternative Fuel Certification Office is making efforts to minimize unneeded testing. Beyond personnel and aircraft costs, the entire flight-test program has required the purchase of approximately 800,000 gallons of FT fuel at a total cost of about $5 million. The Air Force anticipates completing certification of Air Force aircraft, fuel infrastructure, support equipment, and vehicles on the FT fuel blend by early calendar year (CY) 2011.[9]

With regard to FT fuels, the Air Force Research Laboratory has purchased a modular facility that allows small amounts of FT fuel to be produced adjacent to its laboratories at Wright-Patterson Air Force Base. A portion of this facility can be used to modify (via distillation) alternative fuel samples from outside sources. This would apply broadly to any alternative fuels that may be appropriate for aviation. This ability to reformulate fuel samples, including obtaining samples that are purposely designed to not meet specifications, is an important capability that could result in improving the knowledge base for establishing fuel standards, with the ultimate benefit of improving confidence and allowing greater flexibility in setting fuel specifications.

The portion of this facility that involves an FT reactor provides little benefit to the Air Force fuel testing program. The knowledge base for producing FT fuels is closely held within the private sector. We see little chance that the Air Force Research Laboratory will be able to improve on this technology base or optimize this process.

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[9] Email to authors from Jeffrey J. Braun, Director, U.S. Air Force Alternative Fuels Certification Office.

Consideration has been given to adding a small coal gasifier and gas cleanup system to the modular facility that is already in place. Since the quality of FT fuels does not depend on the source feedstock, there is no need to incorporate an expensive, complex process to produce small batches of FT fuels. Operating and managing this addition would divert both funds and talent from more productive research. Our discussions with Air Force Research Laboratory technical staff knowledgeable of this coal gasification proposal support this finding.

Currently, the Air Force plans to extend its testing and certification work to hydrotreated renewable oils. To support this effort, DLA Energy has procured 400,000 gallons of hydrotreated renewable kerosene that meet the preliminary specifications developed by the Air Force. The average cost of this fuel is about $65 per gallon. It is anticipated that this amount of fuel will be sufficient to obtain full certification of all Air Force assets. Initial fuel deliveries are anticipated during late CY 2009. Detailed goals and schedules are not yet final. Based on conversations with Air Force Alternative Fuel Certification Office management, certification of all Air Force assets will likely require about three years, under the assumption that a modified certification process can be implemented. This modified process would involve flight-testing only a few fleet-representative aircraft, as well as those deemed to represent the greatest challenge.

For the longer term, the Air Force Research Laboratory Propulsion Directorate is directing its attention at examining the fundamental characteristics and production prospects of advanced biomass-derived fuels, such as synthetic jet fuels produced by microbial fermentation processes.

**Navy and Marine Corps.** Certification efforts are the responsibility of the Naval Fuels and Lubricants Cross-Functional Team (hereafter referred to as the Navy Fuels Team) (Kamin, 2009). Rather than beginning with a particular alternative fuel, the Department of the Navy focused its initial efforts on establishing its *process* for certifying fuels. The first-generation version of this process is now being applied to the certification of both FT and hydrotreated renewable oils.

Unlike the Air Force certification process for FT fuel, the Navy process does not require individual certification of every Navy and Marine Corps system. Instead, the Navy process focuses on testing components that are common to several systems, with emphasis on systems that are known to be most sensitive to changes in fuel properties. As the Navy gains experience with this process, the Navy Fuels Team anticipates that it will be able to progressively simplify the process. The goal is to evolve to a certification process that minimizes large-scale testing and reduces the time and cost of certifying future alternative fuel candidates (Kamin, 2009). In support of this goal, the Office of Naval Research is considering a redirection of a portion of its alternative fuel science and technology resources to develop improved fuel characterization and hardware testing procedures.

For certifying FT fuels, the Navy approach is to build on the extensive work that the Air Force has already done. Navy certification efforts will focus on systems and operating environments (e.g., shipboard) unique to the Navy and Marine Corps. The goal is certification of all Navy and Marine Corps systems on 50/50 blends of FT products and conventional fuels by the end of 2011, which is very close to the Air Force goal.

Over the past two years, the Navy has also chosen to move forward with certifying hydrotreated renewable oils that can replace or be blended with naval distillate F-76 and JP-5. The Navy plan is to first certify blends of these alternative fuels with petroleum-derived fuels. This would be followed by certifying "neat" (i.e., not blended with petroleum-derived fuels) alternative fuels. To support initial efforts, DLA Energy procured 60,055 gallons of hydrotreated renewable fuels in September 2009. This amount includes 20,055 gallons, at a cost of $424 per gallon, of algae-derived fuel for blending with naval distillate; and 40,000 gallons, at a cost of $67.50 per gallon, of camelina-derived fuel for blending with JP-5 (DESC, 2009).

As of late 2009, the Navy is reformulating its fuel testing and certification efforts in response to the Secretary of the Navy's October 2009 announcement that the Navy would demonstrate operation of a "green" strike group in 2012, in which ships and aircraft would be fueled with biofuels or nuclear power (Mabus, 2009). At present, the goals of this accelerated program have not yet been established. In particular, it is uncertain whether the Secretary's announcement requires that pure formulations be certified by 2012. Budget and resource estimates, including additional quantities of test fuels, for this new program are not yet available.

**Army.** To reduce the logistics burden of providing multiple fuels to forward-based units, the Army began in the late 1980s to use aviation fuel, specifically JP-8, in its mobility assets that contain compression ignition engines (commonly referred to as "diesel" engines). This conversion resulted in some compromises in engine performance, although within levels considered acceptable by the Army (see Chapter Two, footnote 4). For the Army, the focus on establishing alternative fuel specifications and certifying use is on whether a compromise fuel, namely JP-8, remains acceptable when its specification is broadened to allow blending with alternative fuels. Also, Army progress on alternative fuel testing and certification[10] should be considered in the context of the recent shift to ultra-low-sulfur diesel fuel for all civilian vehicular applications in the United States and Europe (see Box 5.1).

The Army's National Automotive Center was an early partner of the Air Force Research Laboratory in investigating the properties of FT fuels. Motivating initial Army interest in FT fuels were positive reports regarding the performance of FT diesel fuel in commercial trucks with compression ignition engines similar to those used in many Army vehicles (Clark, 1999). Commercial FT production plants in South Africa

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[10] Within the Army, what the Air Force describes as "certification" is generally referred to as "qualification." To avoid confusion, we use the term *certification* to describe the Army's efforts to establish safe and appropriate fuel use in its combat assets.

### Box 5.1: Ultra-Low-Sulfur Fuels and Army Mobility

All new heavy-duty engines (including on- and off-road applications) being manufactured for the civilian market in the United States and Europe incorporate emission control systems that require the use of ultra-low-sulfur fuel. To meet this requirement, diesel fuel sold in the United States is required to have a sulfur content below 15 parts per million. But the maximum sulfur specification for aviation fuels, including JP-8, is 3,000 parts per million. In recent years, the average sulfur content of jet fuel (commercial plus military) sold in the United States has been about 700 parts per million, but individual fuel purchases vary greatly around this average (Taylor, 2009).

According to Army fuel and propulsion experts, putting higher-sulfur fuel in a compression ignition engine designed for ultra-low-sulfur diesel fuel will result in engine failure. If the Army continues to allow JP-8 in its combat mobility systems, it will be forced to purchase vehicles with engines that are fundamentally different from those in the civilian sector. This policy might lead to increased vehicle acquisition costs and isolate the Army from future technical advances in the performance of heavy-duty compression ignition engines. But if the Army procures combat vehicles with engines designed for ultra-low-sulfur diesel, provisions need to be made to ensure the availability of such fuel during combat operations.

As of December 31, 2009, this problem remained unresolved. In the interim, some allied nations are modifying engines designed to operate on ultra-low-sulfur fuel to operate on high-sulfur fuels, such as conventional petroleum JP-8.

(using coal) and Malaysia (using natural gas) had clearly established that an FT diesel fuel could be formulated and used in compression ignition engines.

For the Army, the challenge is not whether FT *diesel* fuel can be used, but rather whether and under what specifications FT *jet* fuel can be used in Army military vehicles with diesel engines.[11] Initial Army activities focused on laboratory and component evaluations, including documentation of relevant fuel properties and evaluations of the compatibility and potential performance of FT fuels when used in Army land vehicles and tactical generators.

During FY 2009, the Army completed a field test of a 50/50 FT/JP-8 blend in 45 vehicles (eight different types, four different engines). This test program consumed approximately 16,000 gallons of blended fuel. During testing, no adverse problems

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[11] For example, the energy density (energy per gallon) of FT jet fuel is about 3 percent lower than that of typical petroleum-derived jet fuels (Moses, 2008). And jet fuels have an energy density that is about 6 percent lower than typical automotive diesel fuels. Thus, certain batches of synthetic FT blends could have energy densities that are appreciably below (e.g., greater than 10 percent difference) that of automotive diesel. This would reduce vehicle operating ranges between refuelings and could adversely affect vehicle performance, especially acceleration.

were reported by the test manager. The data from this field test are still under analysis, but expectations are that no serious barriers to the use of FT blends will be encountered. Rather, if problems are encountered, they can likely be solved by changing the specification of the blend.

The Army has not formally established quantitative goals and schedules for completing the testing and certification of alternative fuels. Army efforts continue on evaluating vehicle and tactical generator performance, with primary emphasis on the same FT/JP-8 blend that the Air Force is currently certifying. Specifically, the National Automotive Center's technical approach is to minimize changes, if any, to the standard already established by the Air Force, MIL-DTL-83133, for its aviation and ground support assets. With regard to Army ground vehicles and aviation, current plans call for leveraging the work that the Air Force has and will be doing. This approach should result in meeting the Army's certification goals at significantly reduced costs.[12]

For the longer term, the Army is staying current with Air Force and Navy work on testing and evaluating hydrotreated renewable oils. The National Automotive Center also has plans to conduct engine tests of hydrotreated renewable oils. If this work, including that by the other services, indicates that hydrotreated renewable oil blends perform much the same as FT blends, full Army qualification may be possible based on the results obtained from synthetic FT blends.

**Defense Advanced Research Projects Agency.** While DARPA has not had a direct role in fuel testing and certification, it has made two important contributions through its support of the development of technology to produce hydrotreated renewable oils. As discussed previously under "Major Achievements," DARPA was able to provide a bio-derived kerosene sample to the Air Force Research Laboratory for testing and evaluation. The early provision of this sample provided important technical information that has shaped the entire DoD approach to testing and certifying hydrotreated renewable oils.

DARPA's support for R&D directed at hydrotreating renewable oils may have accelerated the availability of the larger amounts of these fuels that have already been used in flight tests of commercial aircraft and that have been procured by DLA Energy to support DoD certification efforts (Kinder and Rahmes, 2009).

**Defense Logistics Agency Energy.** In fuel testing and certification, DLA Energy's principal contribution has been supporting the services by procuring large test samples. An important aspect of this support is ensuring that purchased fuel samples are not contaminated during transfer and delivery to the final service users. DLA Energy plays a key role in promoting coordination of all DoD efforts to establish fuel standards. DLA Energy has also encouraged the development of a more streamlined process for

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[12] Because the adverse consequences of engine failure during testing of ground vehicles and tactical generators are much less than for aircraft, Army pre-test preparations for most of its combat assets can be less extensive, leading to additional cost savings.

certifying alternative fuels, in particular, one that requires less full-scale engine and platform testing.

## Developing Advanced Technology

DARPA, DLA Energy, and each of the services are sponsoring the development of advanced technology for producing alternative fuels. We also found a single R&D project being managed from the Office of the Deputy Under Secretary of Defense for Science and Technology. With the exception of DARPA, none of the sponsoring organizations have established a research program—i.e., a portfolio of projects working toward broadly defined goals, with technical interactions among project leaders, and guided by considerations of risks, costs, and benefits. Rather, the non-DARPA work is best described as a collection of separate projects. In contrast to DoD efforts on fuel testing and certification, there is very little coordination among the various sponsoring groups.

### DARPA Alternative Fuel Development Program

Most of the DARPA effort is focused on developing advanced processes to produce a synthetic JP-8 or JP-8 blend stock from renewable feedstocks. The emphasis of this biofuel program is on processes that can produce JP-8 at reasonable costs, with low lifecycle greenhouse gas emissions, and without competing with food crops for land. In response to a congressional add-on to its budget, DARPA also has a coal-to-jet-fuel program directed at demonstrating the feasibility of innovative coal-to-liquids concepts that offer greatly superior economic and environmental performance, as compared to available FT approaches.

**DARPA Biofuels.** Initially, the DARPA biofuel program focused on accelerating the application of refining technology to the problem of converting oils from seed crops into a synthetic JP-8. In this endeavor, DARPA support may have been responsible for the accelerated demonstration of hydrotreating/isomerization systems capable of converting vegetable and animal oils to hydrotreated renewable oils that can be formulated for military and civilian use.[13] If so, this work by DARPA can be credited as enabling the successful test flights of bio-derived jet fuel blends by commercial airlines in 2008 and 2009. Moreover, all of the bio-derived jet fuels purchased by DLA Energy in 2009 are being processed by firms that participated in the DARPA hydrotreating/isomerization program. Analysis by the Air Force Research Laboratory of fuel samples from this program led to the important finding that the chemical constituents and proper-

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[13] A number of firms, including BP, Syntroleum, Conoco-Philips, Neste Oil (Finland), and Petrobras (Brazil), appear to have developed hydrotreating/isomerization technology without DARPA support (Washington State Department of Agriculture, 2007).

ties of hydrotreated renewable oils and FT liquids are very similar. This portion of the DARPA biofuel program was completed in late CY 2008.

Currently, the DARPA biofuel program is directed at deriving JP-8 from renewable sources that do not compete with food crops. One component of this approach is directed at cellulosic feedstocks; the other is directed at using algae and sunlight to produce oils. With regard to cellulosic feedstocks, the main effort is directed at a single project that uses a combination of biological/biochemical processes (fermentation and sachrification) and thermochemical processes (pyrolysis and high-temperature/high-pressure hydroliquefaction) to produce JP-8. This work is managed by Logos Technologies, Inc., of Arlington, Virginia, and involves 12 subcontractors. The near-term (fourth quarter, FY 2010) goal of this project is to develop a process that can achieve 30 percent energy efficiency in the conversion of cellulosic biomass to JP-8 and produce JP-8 at a cost of under \$3.00 per gallon. If DARPA support for this project continues beyond FY 2010, the long-term goal would be to demonstrate 50 percent energy efficiency. DARPA is also funding a small Swedish technology firm, Swedish Biofuels, AB, to demonstrate that firm's proprietary process for converting certain agricultural wastes to JP-8.

DARPA's program on algal oil is focused on developing a process that can affordably produce JP-8. The program covers the entire fuel creation cycle, including algae selection and growth, nutrient and waste stream management, oil extraction, and refining to JP-8. The near-term program goal is to establish processes that, when implemented at commercial scale, are able to produce algal oil at less than \$2.00 per gallon and JP-8 at less than \$3.00 per gallon. To implement the algal oil program, DARPA is supporting two teams: one led by General Atomics with 18 subcontractors and one led by Science Applications International Corporation with 10 subcontractors. Each team has been awarded an 18-month, \$20 million contract (not including options).

**DARPA Coal-to-Liquids.** As a result of a congressional add-on to DARPA's FY 2008 and FY 2009 budgets, DARPA solicited proposals to investigate advanced coal-to-liquids production concepts that offer greatly reduced capital costs as compared to what DARPA considers conventional approaches, namely, indirect liquefaction (such as the FT method) and direct liquefaction (which is being attempted in China, but with U.S.-developed technology).[14] Additionally, DARPA requires that fuel production using these advanced coal-to-liquids production concepts have zero greenhouse gas emissions and consume less than two barrels of water per barrel of fuel produced.

DARPA has not responded to RAND requests for information regarding its current contracts or plans for its coal-to-liquids program. Our review of its coal-to-liquids

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[14] DARPA also requires that the processes produce JP-8 at less than \$3.00 per gallon, but this production cost goal is above that which can be achieved using existing FT approaches for converting coal or a combination of coal and biomass to liquid fuels (Bartis, Camm, and Ortiz, 2008; NAS, 2009).

solicitation suggests that the program is strongly oriented toward concepts based on coal pyrolysis, either above or below ground.[15]

**Program Review and Findings.** In its programs directed at cellulosic, algae, and coal feedstocks, DARPA is funding high-risk research that offers a potentially high payoff. Moreover, it is working in research areas and on liquid fuel products that, until recently, were not covered by Department of Energy technology-development programs. Many of the private sector and university participants in the DARPA alternative fuel program have impressive credentials in fuels, petrochemical, and biochemical technology development.

Our major concerns with the DARPA alternative fuel program center on the appropriateness of its strategic and management approach to fuel technology development.[16] With regard to its strategic approach, our greatest concern is that the DARPA program is vastly underestimating the difficulty of developing alternative fuel technologies that offer acceptable economic and environmental performance. This is evidenced by DARPA's support of short-term projects, each centered on the definition of a process that can meet DARPA-established performance goals, such as less than $3.00 per gallon for JP-8 derived from renewable fuels. In this regard, DARPA appears to be falling into the same trap that has plagued the Department of Energy's technology-development programs: A rush toward early demonstration and underfunding of the scientific and engineering fundamentals required for long-term progress. Based on our experience in energy technology development, we are concerned that the result for these DARPA efforts will be a clear demonstration of technical viability, but at fuel production costs that are prohibitive, due to the high likelihood that DARPA's contractors will be unable to develop an environmentally sustainable and economically competitive system without substantially greater investments in component and process development.

We are also concerned that DARPA formulated this program under two unfounded premises: that DoD fuel sources are at risk and that DoD fuel needs should be met with processes that offer very high yields of JP-8. The first premise is clearly wrong. For a nation that currently produces about 7 million bpd of crude oil and natural gas liquids, and that has additional highly secure imports from Canada, we can find no credible scenario in which the U.S. military would be unable to access the 340,000 bpd that it needs to defend the nation. With regard to the second premise, DARPA requires that its alternative fuel contractors develop technologies that can be configured to achieve at least 50 percent JP-8. All of the processes that we examined during

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[15] In a pyrolysis process, coal is heated in the absence of oxygen. This heating releases gases and liquids and leaves behind a solid char that is mostly carbon. Compared with the original coal, the pyrolysis gases and liquids have a higher hydrogen-to-carbon ratio so that, in principle, they can be upgraded to transportation fuels without requiring a lot of additional hydrogen. Burying the char, or leaving it underground, serves the same purpose as sequestering carbon dioxide.

[16] DARPA has informed RAND that it disagrees with certain findings presented in this section of the report.

this study produce a slate of products. These processes can be modified to emphasize one particular product, such as JP-8, but forcing the product slate to emphasize one particular product at such a high level can significantly increase production costs. Our discussions with DARPA staff indicated that DARPA does recognize that lower JP-8 yields are commercially appropriate and that their alternative fuel contractors are now encouraged to examine technology configurations that yield much lower JP-8 yields and allow co-products, such as automotive diesel, commercial jet fuel, marine distillates, and home heating oil.

With regard to program management, DARPA is using its standard model, in which a small number (sometimes just one) of federal employees manage the program and the individual projects. Technical assistance in program and project management and evaluations of project performance are provided by engineers and scientists obtained through one or more Scientific, Engineering, Technical and Analytical (SETA) contracts. We recognize that this model of program and project management has been highly successful in establishing the viability and accelerating the availability of numerous technologies relevant to national defense. Nonetheless, we are concerned that this standard model is not appropriate to managing alternative fuel development programs over the longer term or for purposes of demonstrating scalable production capability. Alternative fuel production facilities are highly complex and can cost hundreds of millions, or even billions, of dollars. Technical progress often requires simultaneously advancing performance in multiple subsystems and understanding the intricate interfaces among these systems. A strong and disciplined engineering assessment program is essential, especially when the contractors are not required to cost share, as is usually the case in DARPA-sponsored research. If DARPA plans to continue its efforts in developing alternative fuels, the agency should consider strengthening its independent engineering assessment capability, including an independent capability to perform conceptual designs, conduct risk analyses, and establish costs for the commercial-scale facilities that might result from the successful development of the technologies in its portfolio. This could be done in-house or via an independent contractor that has experience in scaling up first-of-a-kind technologies.

Our examination suggests that the true value of DARPA's efforts in alternative fuels will remain uncertain for some years. For the DARPA biofuel program, the answer hinges on whether the coming decade will see the development of a commercial industry producing appreciable amounts of middle distillates from renewable feedstocks in the United States. If that industry does develop, DARPA's biofuel efforts will likely be shown to have played a contributing role. But at present, there remains considerable uncertainty regarding the prospects for technologies in DARPA's portfolio. Whether or not appreciable amounts of plant-derived oils, such as jatropha or camelina, can be sustainably cultivated in the United States remains uncertain. The production costs and environmental implications of both cellulose-derived and algae-derived fuels are highly uncertain. Finally, there are the overriding uncertainties associated with the future course of world oil prices and how global measures to address greenhouse gas emissions will affect both alternative fuel technologies and world market oil prices.

### Other DoD Alternative Fuel Development Activities

Beyond DARPA, alternative fuel development activities center on specific projects that are not conducted as part of a goal-oriented program. In some cases, these projects are undertaken by service laboratories; in others, by contractors. Many of these projects are funded through congressional earmarks.

Most of these projects appear to be conducted by university-based researchers or small businesses. A project-by-project review was not in the scope of our study. From those projects that we did examine and from our discussions with DoD managers with oversight responsibilities, we offer the following findings:

- Some of the projects appear to be conducted by highly competent organizations and offer innovative approaches for producing alternative fuels.
- Nearly all of these projects are directed at forward-based alternative fuel production. As such, these projects focus on systems that offer no compelling military advantage and some that would pose significant burdens on the military (see Chapter Four).
- But many of these projects might offer significant benefits for civilian production of alternative fuels. Examples include microprocessing concepts that might enable affordable and small-scale production of fuels from biomass, microbial and algal processes for producing renewable oils, and advanced electrolysis concepts that offer an economic approach for hydrogen production.
- Across the board, we found shortfalls in the analytic basis for program planning and project selection. Beyond congressional direction, the most common reason for selection of a project was the interest of a single researcher in a service laboratory. In many cases, project advocates are making exaggerated claims, especially with regard to economic performance, that are not substantiated by engineering analyses.
- We found a few projects that were poorly conceived, in that they are directed at goals that offer neither military nor civilian benefits. Examples include projects to produce specification fuels from water and from carbon dioxide extracted from air or water. Developing deployable systems that can accomplish this is technically daunting. If successfully developed, the approaches currently being supported would require very large expenditures of energy and very high front-end capital costs, and they would appear to place heavy operational burdens on forward-based units.
- Overall, management and evaluation of these projects is hampered by the fact that they are so widely dispersed throughout DoD. Congressional earmarks are often viewed as not requiring technical management. In some cases, government

project managers do not have adequate knowledge, experience, or resources to provide meaningful technical direction.

Most of the adverse findings stem from the fact that beyond DARPA, alternative fuel development work is basically a collection of independent projects, with no single agency managing a sufficient number to warrant hiring the fuel production expertise and gathering the resources, e.g., engineering analyses tools, such as the AspenTech process simulation system, required for developing a program and providing effective technical oversight and direction.

## Promoting Commercial Production

### Current Policies and Goals

Each of the services has established programs and goals to reduce dependence on fossil fuels. Each of these programs includes provisions for improving the efficiency of fuel use at both installations and in tactical systems. These programs also cover legislative mandates and executive orders that require increased use of renewable energy at military installations. In response to these requirements, military installations are using alcohol fuels and biodiesel, but not in tactical systems that are intended for deployment.

Neither legislation nor executive orders require the use of alternative fuels in tactical systems. Also, the Secretary of Defense has not issued guidance or directives calling for alternative fuel use in tactical systems. However, each of the services has addressed tactical use of alternative fuels in its energy strategies or plans. These programs differ greatly among the services.

On October 14, 2009, Secretary of the Navy Ray Mabus announced plans to create "a *Green Strike Group* composed of nuclear vessels and ships powered by biofuels" and to deploy that fleet by 2016 (Mabus, 2009). Additionally, by 2020, the Navy is to ensure that at least 50 percent of total Navy and Marine Corps energy consumption comes from alternative sources. The Navy and Marine Corps goals, as articulated on October 30, 2009, do not include consideration of fuel costs. By committing itself to using increasing amounts of biofuels, such as JP-5 and naval distillate, during the coming decade, the Navy is providing a strong motivation for commercial production of renewable military fuels. At present, the Navy has not announced the mechanisms, if any, that it will use to promote early production, control fuel acquisition costs, and ensure that its use of renewable fuels does not lead to increased greenhouse gas emissions, per the requirements of Section 526 of the Energy Independence and Security Act of 2007 (P.L. 110-140).[17] It is also uncertain whether low-greenhouse-gas-emitting

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[17] Further information on Navy energy policy can be found in "Naval Energy: A Strategic Approach" (Naval Energy Office, 2009).

FT fuels produced from a combination of coal and biomass will qualify as alternative fuels under the new Navy energy strategy.

For the Air Force, the overarching goal is to increase fuel supplies and reduce greenhouse gas emissions (U.S. Air Force, 2009a). But with regard to fuels for its tactical assets, these goals are moderated by considerations of cost. Specifically, the Air Force goal is as follows:

> By 2016, be prepared to cost competitively acquire 50 percent of the Air Force's domestic aviation fuel requirement via an alternative fuel blend in which the alternative component is derived from domestic sources produced in a manner that is greener than fuels produced from conventional petroleum. (U.S. Air Force, 2009a)

The Air Force approach focuses on preparedness to use alternative fuels contingent on fuel prices and availability, in contrast to the Navy commitment to purchase and use biofuels.

The Army has not established goals and plans for alternative fuel use in its tactical systems (Army Senior Energy Council, 2009).

At present, DoD's contracting authority is severely limited by law (10 USC 2306b) to a duration of no more than five years[18] and a total amount of less than $500 million, unless specifically authorized otherwise by Congress. These constraints limit DoD's ability to provide incentives for private investments, especially those for FT fuels, which generally involve high capital investments.

### Prior Office of the Secretary of Defense and Air Force Initiatives

During the tenure of Under Secretary Michael Wynne, the office of the Under Secretary of Defense for Acquisition, Technology, and Logistics developed the Clean Fuel Initiative (Barna, Sheridan, and Harrison, 2005). At the recommendation of Wynne's successor, Under Secretary John Young, this initiative was renamed the Assured Fuels Initiative "to emphasize its defense importance" (Young, 2005). The primary goal of this initiative was to catalyze industry development and investment in alternative fuels for the military. The initiative involved extensive outreach to industry, Congress, and state governments, emphasizing that "DoD has a vested interest in catalyzing the development of energy resources to reduce dependence on foreign oil" (Young, 2005). Although the message emphasized that "DoD would like to see all energy resources developed in an integrated manner" (Young, 2005), the primary emphasis of the Clean Fuel/Assured Fuels Initiative was on alternative fuels from coal and oil shale.

Although this initiative did catalyze interest, it also spread confusion and ultimately disappointment. Its outreach program left industry and state governments with the impression that DoD was prepared to subsidize production, but did not give any

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[18] The law also involves five one-year options, for a total of ten years. But since the option years are not binding, they do not change our conclusion that DoD's ability to promote private investment is severely limited.

details on how that would be done. Attention to this initiative appears to have terminated in early FY 2007, apparently due to inadequate support within the Office of the Secretary of Defense.

With the appointment of Michael Wynne as Secretary of the Air Force in November 2005, advocacy for commercial alternative fuel production shifted to the Air Force. As before, senior officials emphasized the importance of alternative fuels. The Air Force established its fuel test and certification program and began the large fuel purchases necessary to implement that program. The Secretary announced that the Air Force planned to enter into long-term contracts to purchase alternative fuels, and was considering locating coal-to-liquids fuel plants at U.S. Air Force bases.

The Air Force did examine the feasibility of locating a coal-to-liquids fuel production facility at Malmstrom Air Force Base in Montana. In January 2009, the Air Force announced that the concept was inappropriate, citing "possible conflicts with the wing's mission, including degradation of security in the vicinity of weapons storage areas; interference with existing missile transportation operations; and issues with explosive safety arcs and operational flight safety" (Air Force News Service, 2009).

In response to congressional direction in the 2009 Defense Appropriations Bill, the Air Force is conducting a $10 million study on locating a coal-to-liquids fuel plant at Eielson Air Force Base, which is located near Fairbanks, Alaska.

### RAND Analysis of Federal Incentives for Early Industrial Experience

A recent RAND study included an analysis of various incentives that the federal government could use to induce early experience in producing alternative fuels.[19] By examining incentives from the perspectives of the federal government as well as private investors, that analysis revealed that a balanced and cost-effective approach would include a price floor on purchases of fuel from pioneer production facilities, an investment incentive (such as an investment tax credit, a loan guarantee, or both), and an income sharing agreement, in the event that world market oil prices significantly increase during the term of the incentive agreement.

If DoD were given authority to grant long-term contracts (i.e., at least ten years), it could offer price floors to investors to protect them against low world oil prices. DoD could include price discounts to allow income sharing during periods of high oil prices. To be more cost-effective, however, fuel contracts designed to promote early commercial production should be part of a broader package of incentives, such as investment tax credits, accelerated depreciation, and loan guarantees.

The RAND analysis also argues against long-term contracts that establish a guaranteed or fixed price without recourse to adjusting prices. Such agreements are rarely

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[19] This section is taken from Bartis, Camm, and Ortiz (2008). A detailed analysis of alternative federal incentives and a fuller explanation of why a price guarantee is undesirable are provided by Camm, Bartis, and Bushman (2008).

observed in contracts between private parties and are far less likely to serve the federal government's interests. When transaction prices under an agreement depart from market prices for long periods of time—say, several years—the parties to a fixed-price agreement no longer share a mutual interest in continuing the agreement. The longer such dissonance persists, the harder it becomes to prevent termination of the contract. As a result, long-term contracts with fixed prices rarely survive their term, particularly in markets with prices as volatile as those of petroleum.

CHAPTER SIX

# Industrial Preparedness

In this chapter, we examine the key factors that determine the preparedness of domestic firms to supply alternative fuels to DoD. We begin with a brief analysis of potential demand for fuel on the part of DoD, and a review of the overall investment climate for alternative fuels. This is followed by a review of trends and prospects for alternative fuels produced by FT synthesis or by hydrotreating renewable oils.

## Potential Alternative Fuel Demand by the U.S. Department of Defense

Total DoD use of middle distillates is about 337,000 bpd (see Table 2.1 in Chapter Two). Of this amount, roughly 50 percent is purchased within the United States. As further measures are implemented to promote energy conservation and efficiency, DoD's fuel consumption is likely to decrease, although the rate and magnitude of this decrease remains uncertain. Future decisions on force size, force composition, and operations will also affect DoD fuel demand.

Presently, DoD certification efforts for alternative fuels are centered on synthetic/conventional blends, with the alternative fuel component being as high as 50 percent. If and when suitable alternative fuels become commercially available at affordable prices, it is likely that fuel specifications could be established that would allow a much higher alternative fuel component in the blend.

For the purpose of examining industrial readiness to meet potential DoD demand in the coming decade, we use a lower bound of roughly 80,000 bpd and an upper bound of roughly 200,000 bpd. The lower bound is based on three assumptions: (1) the domestic fraction of DoD petroleum purchases will remain at about 50 percent, (2) the synthetics content of blends will average 50 percent, and (3) alternative blends will be used only for domestic purchases. This lower bound has been established solely for our examination of industrial readiness. Whether DoD actually purchases any alternative fuel for its tactical vehicles will depend on whether the costs of alternative fuels will be competitive with conventional fuels and, if not, whether DoD (or more broadly, the federal government) is willing to pay the additional costs required to purchase those fuels.

With regard to the upper bound, we purposely set it to be exceptionally optimistic. For example, to reach the upper bound requires blends containing over 80 percent synthetics on average and a purchasing policy that requires such blends in over 80 percent of worldwide fuel purchases.

## The Investment Climate for Military Alternative Fuel Production

The investment climate for military alternative fuel production is highly uncertain. Although the Navy has announced a program that will involve large fuel purchases, it has not yet provided sufficient detail to encourage investment of private funds. Other DoD components have not announced that they will pay a premium price for alternative fuels for use in their tactical systems.

This situation means that the private sector will look to the civilian fuel market for signals as to whether to invest in alternative fuels. For civilian applications, the prospects for alternative fuels also remain highly uncertain. At current world market oil prices, the only military alternative fuel that might be competitive without subsidy is an FT jet or FT Navy distillate derived from natural gas, coal, or a mix of coal and a small amount of biomass. But even for these leading technologies, there remains uncertainty regarding investment and production costs, especially for the first production facilities that would be built in the United States.

With the $1.00 federal subsidy that has supported biodiesel production, some amount of biodiesel from crops cultivated on farmlands appears to be competitive with petroleum-derived diesel so long as world oil prices are above $50 per barrel (2009 dollars, West Texas Intermediate).[1] But for renewable oils that are produced with lifecycle greenhouse gas emissions that are less than those from petroleum products, greater subsidies or higher crude oil prices may be required. As discussed in Chapter Three, there is little information available on the costs of producing hydrotreated renewable oils from jatropha, camelina, or other nontraditional crops, and even less on the economics of algae-derived fuels.

Another factor impeding investment in alternative fuels is uncertainty regarding the prospects and details of legislation and regulations aimed at reducing greenhouse gas emissions in the United States. Legislation that assigns costs to emitting greenhouse gases will modify the relative competitiveness of different alternative fuels vis-à-vis petroleum-derived fuels. For example, for each $10 per ton charged for emitting carbon dioxide into the atmosphere, the price of conventional JP-8 would increase by about $0.13 per gallon.

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[1] Production of biodiesel from soybean oil grew dramatically in both 2005 and 2006. In 2005, the average spot price (in 2009 dollars) for West Texas Intermediate was about $52 per barrel, and in 2006, about $63 per barrel. Considering the lead time between a decision to invest in a biodiesel production facility and actual production, a $50 per barrel spot price appears sufficient to motivate the large production increase during those years.

Finally, there remain the inherent uncertainties in the global crude oil market. Private investment in alternative fuel production will not occur until investors have confidence that the alternative fuel produced by their project will be competitive. This is an especially important consideration for capital-intensive approaches, such as those that would use FT technology to produce alternative fuels from a combination of coal and biomass.[2] Considering the volatility of world market oil prices over the past 15 years, establishing investor confidence will likely require that world market oil prices remain consistently well above the "breakeven" costs of a commercial alternative fuel project for an extended period of time.

## Fischer-Tropsch Fuels

*Five projects using FT methods to produce fuels are in advanced stages of planning in the United States. Two are based on a combination of coal and biomass (total output: 53,000 bpd of distillate fuels), and three are based on waste biomass (total output: 1,400 bpd). By 2015, domestic FT distillate fuel production of roughly 60,000 bpd might be achieved. If investment conditions are satisfactory, 300,000 bpd might be possible by 2020. Although it is likely that this production will be directed at civilian markets, in principle, this level of domestic FT production would be sufficient to meet all military needs, but only by or slightly before 2020.*

### FT Coal-and Biomass-to-Liquids

Within the United States, a number of FT projects have been announced over the past five years. However, as of October 2009, no FT project in the United States has started detailed engineering design or construction. Two FT projects that would use a combination of coal and biomass have proceeded into front-end engineering design. One would be located on the Mississippi River near the city of Natchez, Mississippi; the other would be located on the Ohio River near Wellsville, Ohio.

The Natchez project would produce about 30,000 bpd of fuels and chemicals, starting with coal (and possibly petroleum coke) and a small amount of biomass (roughly 10 percent by energy input). The project developer is Rentech, Inc., a small firm specializing in gasification and FT conversion technologies. The facility would capture carbon dioxide, and all such captured carbon dioxide would be used in nearby enhanced oil recovery operations, under an agreement between Rentech and Denbury Resources. Current plans call for producing 20,000 bpd of synthetic jet fuel at Natchez. By using biomass and sequestering carbon dioxide, Rentech plans to produce

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[2] For example, a facility designed to accept a combination of coal and biomass and to produce 10,000 bpd of alternative fuels is estimated to require a capital investment of roughly $1.3 billion (NAS, 2009, Table 4.3). This cost estimate is for a design that would yield near-zero lifecycle greenhouse gas emissions.

this jet fuel so that overall lifecycle greenhouse gas emissions are lower than those of petroleum-derived jet fuel. As of October 2009, the project is securing permits required to proceed with construction.

The project in Wellsville, Ohio, is Baard Energy's Ohio River Clean Fuels project. In this planned facility, a mixture of coal and biomass would be gasified to produce about 52,000 bpd of FT liquids. Roughly 33,000 bpd would fall in the distillate range and could be formulated as a blend stock for JP-8, JP-5, and Navy distillate. Current plans, however, call for fuels directed at commercial markets. The project includes capturing plant-site carbon dioxide emissions, with the goal, according to Baard, of reducing lifecycle greenhouse gas emissions below those of petroleum-derived fuels. The project has obtained environmental permits, but these permits have been challenged by a lawsuit filed by the Sierra Club and the Natural Resources Defense Council.[3]

Both the Natchez and Wellsville projects are multibillion dollar ventures. Considering where these projects are in planning and design, the earliest possible date for commercial fuel production would be late 2013.

### FT Biomass-to-Liquids

The largest FT biomass-to-liquids plant built to date is a 300 bpd plant located in Freiberg, Germany. Built and operated by CHOREN Industries, GmbH, this plant was scheduled to start operations in 2008. Because of technical and safety concerns, as of December 2009, CHOREN was still working on starting the plant, and fuel production was scheduled for the second quarter of 2010 (Bilas, 2009). Although the Freiberg facility is described by CHOREN as the world's first commercial plant, its construction and operation are intended to provide a design base for much larger plants (i.e., plants that would produce about 5,000 bpd of FT liquids [Kiener, 2008]).

In the United States, design efforts and planning are underway on three projects that would convert biomass, specifically waste biomass, to liquid fuels using FT technology. As such, these potential plants offer the possibility of producing middle distillate fuels that would have extremely low lifecycle greenhouse gas emissions. Rentech is considering construction of a small commercial facility that would gasify biomass wastes and produce both electricity (35 megawatts) and FT liquids (600 bpd). This project would be located in Rialto, San Bernardino County, California. According to Rentech, California's Renewable Portfolio Standard and Low Carbon Fuel Standard are key factors motivating investor interest in this project. The FT liquid production would be naphtha (roughly one-third) and diesel (roughly two-thirds). Rentech has announced that it has concluded a multiyear agreement to supply up to 1.5 million gallons per year (about 100 bpd) of synthetic diesel for use in ground support equipment at Los Angeles International Airport (Rentech, 2009).

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[3] According to the Natural Resources Defense Council, Baard has not officially committed to either using biomass or capturing and sequestering plant-site carbon dioxide emissions (Stevenson, 2008).

The second FT biomass-to-liquids project that has moved to advanced stages of planning is the Flambeau River Biofuels project. The project would be located at a pulp and paper mill in Park Falls, Wisconsin, that is operated by Flambeau River Papers, LLC. The biomass feedstock for the plant would be by-products and residuals from forestry and agricultural sources. The plant would produce about 600 bpd of FT diesel and 600 bpd of waxes. The waxes would be sold for diverse, nonfuel applications (Byrne, 2009).

The third project is being developed by the NewPage Corporation and would be located at a pulp and paper mill owned by NewPage and located in Wisconsin Rapids, Wisconsin. This project would produce 370 bpd of FT diesel fuel, starting with mill residues and unmerchantable forest biomass.

As of October 23, 2009, the NewPage project is in front-end engineering design. Plans call for operational startup in 2012. The other two projects (Rialto and Flambeau River) have not yet progressed to front-end engineering design. Considering the development status of these projects, production from either is unlikely prior to late 2013. All other FT projects for converting biomass to liquid fuels that we have identified in the United States are at earlier stages of definition and development.

### FT Gas-to-Liquids

Alaska holds a very large amount of stranded natural gas, that is, gas that cannot reach markets and therefore has low value. FT gas-to-liquids facilities have been mentioned as a possible means of monetizing this gas. BP p.l.c. built and operated a 300 bpd FT gas-to-liquids pilot plant in Nikiski, which is located on the Kenai Peninsula southwest of Anchorage. In September 2009, BP announced that it would close the Nikiski pilot plant by the end of the year (Juneau Empire, 2009). Although some organizations are promoting gas-to-liquids fuel production in Alaska, neither BP nor any organization with the resources required to build and operate a commercial plant has announced plans to do so in Alaska.

### FT Investment and Production Potential

Our review indicates that five commercial domestic FT projects are in advanced stages of development, but none is yet in construction. For some of these projects, planning and engineering have been supported by government funds. There are also a number of U.S. firms that have been developing technology that is planned for use in these projects. Many of these firms have also benefited from government support of their efforts. Considering where these FT commercial projects are in the development process, we estimate that cumulative private-sector expenditures directed at FT applications over the past five years are in the range of a few tens of millions of dollars.

This estimate does not include expenditures by large companies, including major oil companies, chemical firms, and large equipment vendors. From discussions with representatives of these firms, we are aware of significant work taking place. This work appears to be motivated by global opportunities, especially projects that would produce diesel fuel from natural gas. However, much of this work would likely be applicable to FT projects based on gasification of coal, biomass, or a combination of coal and biomass.

Considering the five FT projects now in the commercial pipeline and the absence of federal programs directed at promoting early FT production experience using a combination of coal and biomass, 2015 production of FT liquids (gasoline and distillate fuels) is likely to be less than 100,000 bpd. By 2020, this level might reach as high as 500,000 bpd, but only if early operating experience in the United States is attained and investors are more certain of the prospects for a competitive industry (Bartis, Camm, and Ortiz, 2008). This level of FT liquid production would yield about 300,000 bpd of middle distillates.

## Hydrotreated Renewable Oils

*In 2009, domestic production of renewable oils for fuel applications was about 32,000 bpd. Nearly all of this production was from soybeans and was formulated as a FAME-type biodiesel. Domestic production of renewable oils that might not compete with food production is very limited. Production from jatropha and camelina combined is estimated at less than 100 bpd for 2009. This is less than one-thousandth of what will likely be required to meet DoD military fuel needs. Commercial-scale hydrotreatment and upgrading facilities would also need to be built to produce military fuels from these oils.*

*The commercial viability of a large-scale production system for producing transportation fuels from algae has not yet been demonstrated, but there is private funding of longer-term approaches for the development of algae-derived fuel production.*

### Seed Crops

In 2008, domestic production of renewable oils for fuel applications averaged 50,600 bpd, of which 27,000 bpd were consumed in the United States. Partial-year data for 2009 (through October) indicate a 37 percent drop in domestic production and a 20 percent drop in domestic consumption (Energy Information Administration, 2010). Nearly all of this production is from soybean oil and is used to formulate FAME-type biodiesel. We were unable to determine whether any of this oil was hydrotreated.

Focusing on seed oils produced from plants that might be cultivated without competing with food production and without adverse land-use changes, we find very limited production in the United States. In the United States, oil production from jatropha appears to be negligible. In Florida, the state program for permitting biomass production covers about 100 acres of jatropha cultivation. State officials estimate that the total cultivated area is less than 1,000 acres. Much of the cultivation in Florida is in abandoned citrus groves (Byrd, 2009).

A few thousand acres might be under cultivation in California and Texas (Dalton, 2009). Overall, these figures suggest that annual domestic production of jatropha oil is currently well below 10,000 barrels per year. All commercial U.S. jatropha oil production is used for producing FAME-type biodiesel. Farmers interested in jatropha can purchase seeds or seedlings from a very limited number of U.S.-based firms.

Camelina is currently cultivated in at least 12 states (Great Plains Oil and Exploration Company, 2008). Most of the production is from grain-producing areas in the Northern Plains. U.S. Department of Agriculture statistics cover only Montana, which produced roughly 5,000 barrels of camelina oil in 2008. A portion of this production is not used for fuels. Firms specializing in camelina cultivation anticipate that domestic camelina oil production in 2009 could reach about 35,000 barrels (Johnson, 2009; Hutteneauer, 2009).[4]

The above figures indicate that current domestic production of oil from jatropha and camelina combined is less than 100 bpd. Considering these production levels, cultivation of both jatropha and camelina should be viewed as experimental. About an 800-fold increase would be required to meet our low estimate of DoD military fuel needs.

To produce military fuels from these oils requires commercial-scale hydrotreatment and upgrading facilities. Most likely, these facilities would be integrated with existing refineries, but stand-alone facilities are also possible so long as a source of hydrogen is available. Construction of commercial-scale hydrotreatment facilities is unlikely until investors perceive that hydrotreated renewable oils are competitive, considering tax treatment and other subsidies, in the domestic market for fuels. This requires favorable crude oil prices and crop production prices, including land rents and agricultural inputs (fertilizers, equipment, fuels, and labor). Competition in the marketplace also requires that customers will be willing to pay a premium for hydrotreated fuels above the going price for FAME-type biodiesel. Otherwise, renewable oil production for fuels will continue to be directed at FAME-type biodiesel, which is less costly to produce than a hydrotreated renewable jet fuel.

Once market conditions are appropriate, there appear to be no barriers to putting required hydrotreatment capacity in place. Meanwhile, renewable oil production from jatropha and camelina will continue to be directed at the FAME-type biodiesel and, in the case of camelina, some nonfuel applications.

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[4] By *domestic production*, we refer only to production from camelina seeds grown in the United States. Oil is also extracted from seeds imported from Canada. The firms we contacted anticipated that 2010 production of camelina-derived oil would appreciably exceed 2009 levels.

## Algae

A commercially viable, large-scale production system for producing transportation fuels from algae has not yet been demonstrated. A number of small firms claim to have technologies that are ready or will soon be ready for large-scale demonstration. At present, it is highly uncertain whether any of the near-term approaches for the production of algae-derived liquid fuels will offer a competitive product and also meet environmental requirements.

There is some private funding of longer-term approaches for the development of algae-derived fuel production. The most notable of these is the recent announcement by ExxonMobil of an alliance between ExxonMobil Research and Engineering and Synthetic Genomics that is focused on biofuel production from photosynthetic algae. If R&D milestones are successfully met, ExxonMobil has announced that it is prepared to allocate more than $600 million to this effort (ExxonMobil Corporation, 2009).[5]

Of the eight biorefinery projects receiving Department of Energy grants for the purpose of producing middle distillate fuels from biomass (as mentioned in Chapter Five), two would produce oil from algae. One of these is a pilot-scale project by Solarzyme, Inc., in which the Department of Energy grant amount is $21.8 million and the nonfederal amount is about $3.9 million. The second is a demonstration-scale project by Sapphire Energy, Inc., in which the Department of Energy grant amount is $50 million and the nonfederal amount is about $85 million (Chu, 2010; Chu and Vilsak, 2009).

Overall, our literature review and discussions with researchers involved in algal oil production strongly suggest that algae-derived oils are an important topic for research, but that the commercial prospects of this approach remain highly uncertain. Better information should be available within a few years, as information becomes available from a few pilot and demonstration-scale facilities. If nothing else, the operation of these early facilities will provide important information as to where further R&D should be directed. These findings are supported by a recent survey that concludes

> In closing, we reiterate our belief that 10 to 15 years is a reasonable projection for the development of a sustainable and economically viable process for the commercial production of biofuels from algal biomass (Wijffels and Barbosa, 2010)

and a recently published, multiclient study by Nexant, Inc. To wit,

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[5] It is also notable that the efforts by ExxonMobil and Synthetic Genomics focus initially on algae development, growth, harvesting, and bio-oil recovery. Work on the conversion of bio-oil to bio-fuel is phased so that it occurs much later in the development process—in fact, just prior to commercial production. This is in contrast to the DoD approach, which would test algae-derived fuels prior to establishing their commercial viability.

> The science is sound for using selected microalgae to convert $CO_2$ [carbon dioxide] to natural oils and other biomass. Commercialization to produce specialty chemical products is well advanced. However, commercialization to produce high volume biofuels faces extensive challenges with regard to biological, engineering, and economic factors. For biofuels via microalgae to succeed, Nexant expects that significant genetic breakthroughs will be needed, and high volume fuel production will need to be supported by other income streams such as from co-production of higher value specialty products, and/or wastewater treatment charges. (Nexant, 2009)

Considering the extensive technology development required to bring down the costs of an algae-derived fuel with favorable lifecycle greenhouse gas emissions, it is highly unlikely that algae-derived fuels will be able to meet an appreciable fraction of military liquid fuel demand over the next decade. A much longer period (at least two decades) would be required for algae-derived fuels to have a significant role in the larger commercial marketplace. This longer time scale is based on the current status of algae-derived fuel technology, the technical development requirements to move beyond niche applications, and the extremely large investment (in algae production facilities as well as in hydrogen production and hydrotreatement facilities) that would be associated with bringing this technology to the point where it can deliver 1 million or more bpd in the United States. This time scale is also consistent with experience across a broad range of technologies, including such energy technologies as coal gasification–based power generation, alcohol fuels, fuel cells, wind, and solar energy systems, and many defense technologies.

CHAPTER SEVEN

# Findings and Recommendations

Our examination of alternative and synthetic fuel issues related to military applications leads to the following findings and recommendations.

## General Findings on Alternative Fuels

**Developing a competitive alternative fuel industry in the United States offers important benefits to the nation.**

Our examination of alternative fuels for military applications confirms the findings of recently completed work at RAND (Bartis, Camm, and Ortiz, 2008). That work shows that a domestic alternative fuel industry could yield large economic profits within the United States. By reducing demand for conventional petroleum, alternative fuel production would also lower world oil prices, countering efforts of certain foreign oil suppliers to control prices by restraining their production. Because U.S. oil consumption is substantial, the United States would benefit considerably from lower oil prices. Our 2008 analysis found that spending from $6 to $24 more per barrel for alternative fuels than the market price for petroleum could yield offsetting economic benefits in terms of lower world market prices. Additionally, a domestic alternative fuel industry would improve the resiliency of the petroleum supply chain and thereby reduce somewhat the adverse consequences of fuel supply disruptions caused by natural disasters, such as hurricanes.

**Over the next decade, Fischer-Tropsch liquids produced using carbon dioxide capture and sequestration and derived from the gasification of coal or a combination of coal and biomass provide the most promising option for affordable and environmentally sound production of diesel and jet fuel for military as well as civilian use.**

This finding is based on consideration of commercial readiness, production costs, production potential, and lifecycle greenhouse gas emissions. Specifically, if plant-site carbon dioxide emissions are captured and sequestered, fuels derived from coal can have lifecycle greenhouse gas emissions that are comparable to those of petroleum-derived fuels, and fuels derived from a mixture of coal and biomass can have lifecycle greenhouse gas emissions that are much lower (i.e., less than half) than those of petroleum-derived fuels. For fuels derived from the gasification of biomass, lifecycle greenhouse gas emissions can be near zero without the need to capture plant-site greenhouse gas emissions. The findings concerning biomass are valid only if the biomass feedstocks are those that do not lead to large greenhouse gas emissions because of direct or indirect land-use changes.

Although climate-friendly FT technology is ready for initial commercial applications, its prospects for near-term production depend crucially on the availability of government incentives for first-of-a-kind facilities.

**It is highly uncertain whether seed oils can be affordably grown in appreciable quantities in the United States without causing land-use changes (direct or indirect) that result in large releases of greenhouse gases.**

There is very little experience in the commercial cultivation of oil-bearing plants on degraded lands or in a manner that does not displace food production. In particular, claims that jatropha or camelina oils can be sustainably produced in the United States have yet to be proven. Further research into sustainable cultivation practices is required to resolve this issue.

**Using clean power with gasification-based alternative fuel plants can greatly reduce plant-site greenhouse gas emissions and greatly increase liquid fuel yield, but this is an expensive option.**

Nuclear power or power from renewable sources, such as wind, can be used to produce hydrogen. With sufficient additional hydrogen, nearly all of the carbon in the coal or biomass feedstock would end up in the final liquid products, and there would be virtually no plant-site emissions. This would eliminate the need for carbon dioxide capture and sequestration in FT and other processes that involve gasification as the first major process step. Hydrogen addition would greatly increase liquid fuel yields. Without adding hydrogen, the U.S. biomass resource base is estimated to be sufficient to produce, at most, 2.2 million bpd of liquid fuels, and more likely appreciably less, as biomass can also be used for electric power production. By adding hydrogen, production levels could approach an upper bound of 6 million bpd. But hydrogen production from nuclear or renewable sources is expensive and would require large additions to current generating capacity.

## Findings on Military Use of Alternative Fuels

**There is no direct benefit to the Department of Defense or the services from using alternative fuels rather than petroleum-derived fuels.**

Our analysis of forward-based production concepts indicated that none provide a compelling military benefit. In contrast, most, if not all, would increase the logistics burden on deployed units.

If a domestic alternative fuel industry does develop, alternative fuels will be sold at the then-prevailing fuel prices, which over the foreseeable future will be determined by crude oil prices in the world oil market. There is no evidence that producers of alternative fuels will offer their products at lower or more stable prices than producers of petroleum-derived fuels.

Using climate-friendly alternative fuels in tactical weapon systems offers a means for DoD to greatly reduce greenhouse gas emissions. However, over at least the next decade, the availability of climate-friendly alternative fuels will be limited by the prevailing technical uncertainties associated with large-scale commercial production. Diverting this limited production to DoD applications will likely result in less use in civilian applications, with nationwide greenhouse gas emissions being insensitive to the apportionment between civilian and military applications.

**If Defense Department efforts in alternative fuel testing, research, and promoting early commercial production are successful, the benefits of this work will accrue more to the nation as a whole rather than to DoD or the services.**

Alternative fuel use in DoD tactical systems offers national benefits in much the same way as do mandates for DoD to be an early user of renewable power at its installations.

## Findings on Alternative Fuel Programs in the U.S. Department of Defense

**Testing and certification of Fischer-Tropsch blends provides the Department of Defense with additional flexibility in purchasing jet fuel in certain locations.**

Fischer-Tropsch fuels are being commercially produced in South Africa, Malaysia, and Qatar, and additional production capacity will be coming on line over the next few years. Some of this production may be available for formulating JP-8 or JP-5 blends. Completing testing and certification work for blends will allow these fuels to be used in DoD aircraft.[1] Over the next 15 years, Fisher-Tropsch fuels are unlikely to

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[1] It is highly likely that all FT fuels being produced abroad have lifecycle greenhouse gas emissions that are above those of their conventional petroleum counterparts. If this is the case, purchases of these fuels for any DoD mobility use is prohibited under the provisions of section 526 of the Energy Independence and Security Act of 2007 (P.L. 110–140).

constitute more than a few percent of total global production of middle distillates. Therefore, there is little benefit to certifying blends with an alternative fuel content of greater than 50 percent.

**Large-scale testing and certification of hydrotreated renewable oils is premature.**

There is insufficient evidence that appreciable quantities of hydrotreated renewable oils can be affordably produced in the United States in a manner that does not increase lifecycle greenhouse gas emissions. Oil production from crops, even if they are not food crops, raises important land-use issues. Oil production from meat and poultry processing is inherently limited by the amount of available wastes. The prospects for affordably producing fuel from algae in a climate-friendly manner remain extremely uncertain.

All evidence from laboratory analyses and small-scale tests suggest that there are no technical barriers to the use of hydrotreated renewable oils in blends that could substitute for JP-8, JP-5, or Navy distillate derived from petroleum. If and when hydrotreated renewable oils become commercially available, fully establishing military fuel specifications should be a straightforward task. It will be much less costly, since test fuels will then be available at near-commercial prices.

This finding is further supported by the exceptionally high prices paid by DLE Energy in recent purchases of hydrotreated oils from camelina ($65 per gallon) and algae (over $400 per gallon).

**Parts of the Defense Department effort in alternative fuel technology development constitute important elements of the overall national energy R&D effort.**

When DARPA began its support of advanced approaches for producing alternative fuels, the U.S. Department of Energy's efforts on coal- and biomass-derived middle distillate fuels were limited and focused only on approaches involving gasification. With regard to biomass, that is no longer the case. The Department of Energy is now devoting considerable resources to the research, development, and demonstration of a broad range of technical approaches for producing middle distillate fuels from a variety of biomass feedstocks and algae. Nonetheless, some of the DARPA support of advanced concepts for producing fuels from algae and coal may be unique within the federal government. Likewise, some of the work being conducted by the services, especially on microprocessing, may have important civilian applications and may not be well covered by programs within the Department of Energy.

**Defense Department technology-development efforts overemphasize early demonstration and underestimate the difficulty of developing alternative fuel technologies that offer acceptable economic and environmental performance.**

Most of the DoD effort in alternative fuel development consists of a collection of independent projects, each focusing on a single engineering concept. Most of these projects are geared toward demonstrating technical viability as opposed to affordable, environmentally sound production. As decisionmakers in the U.S. Department of Energy have repeatedly learned, demonstrating technical viability is easy. Demonstrating affordable and environmentally sound production is difficult and requires investments in the research necessary for true progress, such as materials research, feedstock production research, and applied research dedicated to understanding fundamental problems and developing sound solutions.

**Current Department of Defense contracting authority is inadequate to allow DoD to cost-effectively promote early industrial production of alternative fuels.**

The five-year limit on contract duration and the $500 million limit on contract value severely limit DoD's ability to encourage investment in early alternative fuel production facilities. This is especially the case for the capital-intensive processes required to produce FT fuels.

## Recommendations

**Complete testing and certification of Fischer-Tropsch liquids for use in 50/50 blends, but do so economically.**

In view of current and projected FT production of middle distillates, as well as the strong market for that fuel in the civilian sector, there is no compelling military or national need to accelerate the current certification schedules being followed by the services. Service fuel and propulsion experts agree that large-scale, short-term flight tests provide little, if any, technical information relevant for certification. Continuing testing and certification efforts should strive to minimize such testing.

**Minimize DoD resources directed at testing and certification of hydrotreated renewable oils.**

Testing and certifying these fuels in the high-performance propulsion systems used by the services is simply not on the critical path for resolving uncertainties associated with these fuels. A far more productive use of federal funds would be (1) determining whether and how sustainable cultivation of oil-yielding crops can be achieved and (2) establishing the technology base for affordable oil production from algae.

**Clarify the roles of DoD and the Department of Energy in alternative fuel technology research.**

The better DoD efforts in alternative fuel development have filled and may continue to fill gaps in the federal energy R&D program. Success would broadly benefit the nation but yield minor, if any, direct benefits to DoD. This being the case, should defense funding of research in alternative fuels continue? If so, what are the criteria for DoD investments? For example, should DoD take responsibility for the national research program directed at algae-derived fuels? If not, what part of the national program makes sense for continuing DoD efforts?

**If the Department of Defense continues to support development of alternative fuel production technologies, consider consolidating and strengthening management.**

At present, no single DoD organization has the critical mass of expertise and engineering resources required to bring alternative fuel systems to commercial readiness. One option could be assigning responsibility for funding and managing all DoD efforts (or non-DARPA DoD efforts) in alternative fuel technology development to a single DoD or service organization. If this option is taken, that organization needs to be staffed with a group of program managers who together have the requisite technical expertise to cover the technologies under their purview. That organization also needs to have the capability to conduct independent engineering analyses. Another option is to assign management of the DoD alternative fuel portfolio to one or two of the national laboratories within the Department of Energy that already have the required expertise and resources.

**If the Department of Defense continues to support alternative fuel technology development, greater emphasis must be given to funding applied research directed at long-term gains and developing sound solutions to fundamental problems.**

If the Department of Energy is unwilling to support longer-term applied research in program areas in which DoD is investing, DoD should restructure or expand its programs so that there is a proper balance between shorter-term engineering development projects and applied research directed at long-term progress.

**If the Department of Defense is to promote early industrial experience in alternative fuel production, it should avoid long-term guaranteed fixed-price fuel contracts and instead consider a combination of low-price guarantees and income sharing.**

But to be effective, DoD must obtain legislative approval for longer-duration and higher-value contracts for fuel purchases.

APPENDIX A

# Public Law 110-417, Section 334

The following is the text of Section 334, which calls for the study presented in this monograph.

SEC. 334. STUDY ON ALTERNATIVE AND SYNTHETIC FUELS

(a) STUDY REQUIRED.—The Secretary of Defense shall conduct a study on alternatives to reduce the life cycle emissions of alternative and synthetic fuels (including coal-to-liquid fuels).

(b) MATTERS EXAMINED

The study shall examine, at a minimum, the following:

(1) The potential clean energy alternatives for powering the conversion processes, including nuclear, solar, and wind energies.

(2) The alternatives for reducing carbon emissions during the conversion processes.

(3) The military utility of domestically-produced alternative and synthetic fuels for military operations and for use by expeditionary forces compared with the military utility and life cycle emissions of mobile, in-theater synthetic fuel processes.

(4) The goals and progress of the military departments related to the research, testing, and certification for use of alternative or synthetic fuels in military vehicles and aircraft.

(5) An analysis of trends, levels of investment, and the development of refining capacity in the alternative or synthetic fuel industry capable of meeting fuel requirements for the Department of Defense.

(c) USE OF FEDERALLY FUNDED RESEARCH AND DEVELOPMENT CENTER

The Secretary of Defense shall select a federally funded research and development center to perform the study required by subsection (a).

(d) REPORT

Not later than March 1, 2009, the federally funded research and development center shall submit to the congressional defense committees and the Secretary of Defense a report on the results of the study required by subsection (a).

APPENDIX B

# Alternative Liquid Fuel Production with Hydrogen Addition

This appendix documents the analysis underlying the findings presented in Chapter Three regarding the use of hydrogen from a nuclear or renewable source in the production of military fuels using FT or other gasification-based methods. This analysis draws on recent work performed by the National Energy Technology Laboratory (Tarka et al., 2009), RAND (Bartis, Camm, and Ortiz, 2008), and the National Academy of Sciences (NAS, 2009).

Our analysis defines the potential benefits and issues related to adding sufficient hydrogen to a coal-to-liquids, biomass-to-liquids, or combined coal-and-biomass-to-liquids plant to permit greater utilization of feedstock carbon in the production of liquid fuels, such as diesel and naphtha, thus eliminating the venting of excess carbon as carbon dioxide to the atmosphere. For greenhouse gases, our analysis covers lifecycle emissions and takes into account the release of greenhouse gases in coal mining, biomass cultivation, fuel synthesis, and final fuel utilization.

## Coal Gasification Concepts

Operating without an external source of hydrogen, a coal-based FT plant would produce just over two barrels of liquid products for each ton of coal delivered to the plant. To illustrate the impact of adding hydrogen, we establish a performance baseline using an engineering analysis published by the National Energy Technology Laboratory (NETL) for a coal-based FT plant that does not incorporate carbon dioxide capture and sequestration (Tarka et al., 2009, Case 1). In the NETL engineering analysis, 21,719 tons per day of coal are delivered to the FT fuel production facility, and the final products are 34,250 bpd of diesel, 15,750 bpd of naphtha, and 35 megawatts of electricity. This design concept can be reconfigured so that a portion of the diesel product is replaced by JP-8, JP-5, and naval distillate.

The NETL analysis is based on an Illinois #6 coal. As received, this coal has the following characteristics (Tarka, 2009):

| | |
|---|---|
| Moisture (weight percentage) | 11.12 |
| Carbon (weight percentage) | 63.7 |
| Hydrogen (weight percentage) | 4.50 |
| Higher heating value (Btu/lb) | 11,666. |

Based on coal tonnage received, 13,845 tons per day of carbon are received by the FT fuel production plant. Of this amount, 5,400 tons per day are contained in the final liquid products (naphtha plus middle distillates). The NETL design analysis assumes that 138 tons per day of carbon is contained in the gasifier slag. The remainder, 8,307 tons per day, is emitted into the atmosphere in the form of carbon dioxide.

Overall, the lifecycle greenhouse gas emissions for the fuels produced from this baseline coal-to-liquids FT plant are about twice those of the counterpart petroleum-based fuels. Some readers might want a more precise estimate than “about twice.” But obtaining more precision requires making assumptions regarding what particular crude oil or group of crude oils is used to make the conventional fuel products, where and how the coal is mined, how the greenhouse gas emissions from the coal-to-liquids plant are apportioned between the liquid fuel products and the electricity sold by the plant, and whether the naphtha is upgraded to gasoline or used to manufacture petrochemicals. For the policymaking purposes of this document, further precision is not necessary; if the national interest is in reducing greenhouse gas emissions, coal-to-liquids plants that do not include provisions for controlling greenhouse gases are clearly not in the national interest.

### Adding Hydrogen

To understand what changes when an external source of hydrogen is available, consider a coal-to-liquids plant with the same input coal as the previously described NETL case, but with sufficient hydrogen available so that 95 percent of the carbon in the coal feed ends up in the liquid products.[1] We consider this example to be the “maximum-hydrogen” case because additional amounts of hydrogen cannot be put to productive use within a coal-to-liquids FT production plant.

As shown in the “Coal-to-Liquids with Hydrogen Addition” column of Table B.1, 13,154 tons per day of carbon are in the final products, which is about 2.4 times as much as the amount in the original case. Applying this factor to the overall fuel pro-

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[1] Of the 5 percent of feedstock carbon that does not appear in the final liquid products, we assume that about 20 percent is trapped in the gasifier slag (and therefore does not enter the atmosphere) and about 80 percent is vented into the atmosphere in the form of carbon dioxide. This amount of venting should be sufficient to avoid the buildup of nonreactive gases in recycle loops within the conversion facility.

## Table B.1
## Estimated Mass Flows and Power Requirements for FT Coal-to-Liquids, Biomass-to-Liquids, and Coal/Biomass-to-Liquids Plants with and without Hydrogen Addition

| Plant Configuration | Coal-to-Liquids without Hydrogen Addition | Coal-to-Liquids with Hydrogen Addition | Biomass-to-Liquids without Hydrogen Addition | Biomass-to-Liquids with Hydrogen Addition | 50/50 Coal/ Biomass-to-Liquids without Hydrogen Addition | 50/50 Coal/ Biomass-to-Liquids with Hydrogen Addition |
|---|---|---|---|---|---|---|
| Coal/biomass feed (tpd) | 21,719 | 21,719 | 4,084 | 4,084 | 6,482 | 6,482 |
| Carbon in feed (tpd) | 13,845 | 13,845 | 1,630 | 1,630 | 3,159 | 3,159 |
| Carbon at gasifier exit (tpd) | 13,708 | 13,708 | 1,614 | 1,614 | 3,128 | 3,128 |
| Carbon in products (tpd) | 5,400 | 13,154 | 540 | 1,549 | 1,136 | 3,001 |
| Diesel production (bpd) | 34,253 | 83,476 | 3,425 | 9,823 | 7,207 | 19,040 |
| Naphtha production (bpd) | 15,747 | 38,316 | 1,575 | 4,517 | 3,314 | 8,748 |
| Total liquid fuels (bpd) | 50,000 | 121,792 | 5,000 | 14,339 | 10,521 | 27,789 |
| Hydrogen requirement (tpd) | — | 4,832 | — | 569 | — | 1,102 |
| Hydrogen in feed (tpd) | 977 | 977 | 199 | 199 | 307 | 306 |
| Hydrogen added (tpd) |  | 3,855 |  | 370 |  | 796 |
| Oxygen produced (tpd) |  | 30,593 |  | 2,939 |  | 6,318 |
| Total power requirement (kilowatt-hour/barrel) |  | 1,509 |  | 1,232 |  | 1,366 |
| External power requirement (kilowatt-hour/barrel) |  | 1,334 |  | 1,127 |  | 1,227 |
| Generating Capacity Requirement (kilowatt/daily barrel) |  |  |  |  |  |  |
| Nuclear |  | 62 |  | 52 |  | 57 |
| Wind |  | 159 |  | 134 |  | 146 |
| Solar thermal capacity |  | 253 |  | 213 |  | 232 |

NOTE: tpd = tons per day.

duction of the original case, we calculate a net liquids production of 120,578 bpd for the maximum-hydrogen case.

If all of the carbon in the gasifier exit gas is to react with hydrogen and produce FT liquids, a close approximation for the overall chemical changes in the FT coal-to-liquids process is

$$C + \tfrac{1}{2}O_2 + 2.1H_2 \rightarrow CH_{2.2} + H_2O,$$

where $CH_{2.2}$ represents the chemical formula (on a per carbon basis) of a typical middle distillate fuel.

From this equation, each pound-mole (12.01 pounds) of carbon needs 2.1 pound-moles (4.23 pounds) of hydrogen gas. From the stoichiometric equation, the 13,708 tons per day of carbon at the gasifier exit needs to react with 4,832 tons per day of hydrogen. From the coal analysis, 977 tons per day of hydrogen are introduced with the coal feed, leaving a net deficit of at least 3,855 tons per day.[2] For the maximum-hydrogen case, all of this deficit would be met by hydrogen from an external source. On a per-barrel basis, each barrel of liquid product requires the addition of about 64 pounds of hydrogen.

### Electric Power Requirements

Electricity generated from nuclear power or renewable sources can be used to generate hydrogen (and simultaneously oxygen) from water using electrolysis. Current electrolysis technology operates at moderate pressures and temperatures and is capable of producing hydrogen and oxygen at pressures appropriate for FT synthesis (about 500 pounds per square inch [psi]). In our calculations, we assume an electrolysis system energy efficiency (HHV, electricity in and hydrogen and oxygen out at 500 psi) of 75 percent.[3] This efficiency may be slightly ahead of the current state of the art (Ivy, 2004a, 2004b) but is likely attainable through evolutionary technological improvements. Development of electrolysis units based on solid oxide fuel cell technology offers to significantly raise overall system efficiency.

At an electrolysis system efficiency of 75 percent, 1,509 kilowatt-hours of electricity are required for each barrel of alternative liquid fuel produced by the coal-to-liquids plant. A portion of this power can be cogenerated using the heat generated from the exothermic reactions taking place within the coal-to-liquids plant. Using a rough estimate of the cogeneration potential,[4] we calculate that 1,334 kilowatt-hours of electric-

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[2] The actual deficit is likely to be somewhat higher because some of the hydrogen in the coal feed will be converted to water during gasification (Boardman, 2009).

[3] System efficiency includes energy losses associated with power rectification, pumps, and other auxiliaries as well as the electrolysis units.

[4] We calculate that 176 kilowatt-hours per barrel can be cogenerated by the coal-to-liquids plant. This calculation is based on the assumption that 25 percent of total waste heat can be converted to electric power. Determin-

ity will need to be supplied by a generating plant external to the coal-to-liquids plant. To determine the required electric generating capacity, we assume that hydrogen storage capacity exists at the coal-to-liquids plant site and that power can be generated at a plant utilization rate (capacity factor) of 90 percent for nuclear energy, 35 percent for wind turbine systems (Wiser and Bolinger, 2009), and 22 percent for solar thermal electric generating plants (Sargent & Lundy LLC Consulting Group, 2003). Under these assumptions, each average barrel per day of FT fuel production requires 62 kilowatts of installed nuclear power generating capacity, or 159 kilowatts of installed wind turbine power generating capacity, or 253 kilowatts of installed solar thermal power generating capacity.

## Biomass Gasification Concepts

The analysis of biomass gasification concepts parallels the preceding analysis of coal gasification concepts. The baseline biomass-to-liquids plant is from an NETL engineering analysis in which 4,084 tons per day of switchgrass are delivered to the plant and the final products are 3,425 bpd of diesel and 1,575 bpd of naphtha (Tarka et al., 2009, Case 9). As received at the plant, the switchgrass has the following characteristics:

| | |
|---|---|
| Moisture (weight percentage) | 15 |
| Carbon (weight percentage) | 39.9 |
| Hydrogen (weight percentage) | 4.86 |
| Higher heating value (Btu/lb) | 6,851. |

The entries in the Table B.1 columns labeled “Biomass-to-Liquids without Hydrogen Addition” and “Biomass-to-Liquids with Hydrogen Addition” follow, based on the same methodology used in the preceding analysis of coal gasification concepts. In particular, we assume that 95 percent of the carbon in the biomass feed ends up in the liquid products. In this case, the net product yield increases by a factor of about 2.9 above the case in which hydrogen is not added.

Switchgrass is one of the perennial plants that might be cultivated with very low greenhouse gas emissions and on lands that are not candidates for food production (Tilman et al., 2009). If proper cultivation procedures are used, fuels produced via biomass gasification will have lifecycle greenhouse gas emissions that are close to zero. Considering that hydrogen addition significantly increases the liquid fuel yield per unit of biomass input, we estimate that liquid fuels produced with hydrogen addition will have lifecycle greenhouse gas emissions that are slightly positive but well below, i.e., less than one-tenth, of petroleum-derived fuels.

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ing whether this much coal-to-liquids plant waste heat can be converted to electricity requires a conceptual design analysis that was beyond the scope of this study.

## Combined Coal/Biomass Gasification

To obtain a rough estimate of the material balances of a combined coal/biomass-to-liquids plant, we considered a linear combination of the two previous examples, under the assumption that the plant input would be a mixture of coal and switchgrass, 50/50 based on energy content.

The size of the combined coal/biomass conversion plant is constrained by the amount of biomass that can be delivered, which we assume to be the same as for the biomass-to-liquids plant, 4,084 tons per day. To achieve a 50/50 blend by energy, the facility also receives 2,398 tons per day of coal. Without hydrogen addition, the output of the combined coal/biomass-to-liquids plant is about 10,500 bpd.

For hydrogen addition, we make the same assumptions as in the preceding analysis of coal-to-liquids and biomass-to-liquids plants. In particular, we assume that 95 percent of the carbon in the feed presents in the final liquid fuels. Compared with the combined coal/biomass-to-liquids facility operating without hydrogen addition, fuel production increases by a factor of slightly over 2.6. Facility material flows and requirements for external power and hydrogen are listed in the two rightmost columns of Table B.1.

In this co-fed plant, close to half of the carbon in the final products is derived from the biomass feed. The growth of the biomass removed this same amount from the atmosphere. The remaining half of the carbon in the final product is derived from coal. Considering greenhouse gas emissions associated with producing and refining crude oil, we estimate that fuel produced with hydrogen addition at a combined coal/biomass-to-liquids plant has lifecycle greenhouse gas emissions that are about 45 percent of those of conventional petroleum.

APPENDIX C

# DoD Organizations Contacted

During the course of this study, meetings were held with representatives of the following DoD organizations:

- Office of Developmental Test and Evaluation, Director, Defense Research and Engineering (DDR&E)
- Strategic Technology Office, Defense Advanced Research Projects Agency
- Quality/Technology Support Office, Defense Logistics Agency, DLA Energy
- Office of the Assistant Secretary of the Army, Installations and Logistics
- National Automotive Center (Warren, Michigan), U.S. Army Tank Automotive Research, Engineering and Development Center (TARDEC)
- Office of the Director, Fleet Readiness Division, Office of the Chief of Naval Operations
- Sea Warfare and Weapons Department, Office of Naval Research
- Propulsion and Power Engineering, Naval Air Systems Command
- Office of the Deputy Assistant Secretary of the Air Force (Energy, Environment, Occupational Safety, and Health)
- Air Force Alternative Fuels Certification Office
- Air Force Petroleum Agency
- Propulsion Directorate, Air Force Research Laboratory.

We also received information or held discussions with representatives of the following organizations:

- Office of the Assistant Secretary of the Army, Research and Technology
- Edgewood Chemical Biological Center, U.S. Army Materiel Command
- Renewable Energy Team, U.S. Army Communications–Electronics Research Development and Engineering Center (CERDEC).

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