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Emerging Supply Chains of Alternative Military Jet Fuels in the United States

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Dependence on imported oil poses a threat to US energy security, especially with escalating turmoil in oil producing countries. The United States Air Force, the largest fuel consuming service in the US military, announced a mandate requiring the procurement of 50% of its domestic aviation fuels from alternative resources by 2016. The objectives of this paper are (1) to review military-adopted mandates, policies, and programs aiming to accelerate alternative jet fuel supply chains in the United States and (2) report on their capacity to fulfill the military aviation fuel requirements in the near future. The federal and military policy structure supporting the alternative jet fuel technology pathways were reviewed. Three emerging supply chains based on the Fischer-Tropsch, Hydrotreated Esters and Fatty Acids, and Alcohol to Jet conversion processes were discussed with respect to their capacity to produce alternative jet fuels in the US. Analysis revealed that the military program has successfully expedited these supply chains, but the production that can be achieved with renewable biomass feedstock alone is modest compared to the military's ambitious targets. It was concluded that a blend of fossil/biomass feedstocks could bridge the gap between renewable jet fuel production and military requirements, and meet the emission thresholds of the Energy Security and Independence Act.
Keywords: Bioenergy policy, Military jet fuels, Fischer-Tropsch, Hydrotreated Esters and Fatty Acids, Greenhouse gases emissions

1. Introduction

Since the 1970s oil crisis, the United States military has considered disruption of its fuel supply a serious threat to national security [1]. As the largest energy consumer in the US military [2], the United States Air Force (USAF) is heavily reliant on imported oil for jet fuel production. The most widely used military turbine jet fuel by the USAF is known as Jet Propellant 8 (JP-8), which is also used by the British Royal Air Force and the North Atlantic Treaty Organization [3]. This fuel is similar to the commercial jet fuel A1 with the addition of few additives [3]. Like its commercial counterpart, JP-8 is a kerosene grade fuel (middle distillate fraction) produced from refining crude oil via the fractional distillation process. The US Navy uses a slightly modified version of JP-8 (known as JP-5) with a higher flashpoint to minimize fire risks on naval ships [3].

Alternative jet fuels refer to aviation fuels produced from feedstock other than petroleum – this could include renewable biomass or fossil feedstocks such as natural gas or coal. Three thermochemical processes capable of producing alternative jet fuels from non-petroleum feedstocks are the Fischer-Tropsch (FT) process, the Hydrotreatment of Esters and Fatty Acids (HEFA) process, and the Alcohol to Jet (ATJ) process. Alternative jet fuels have the potential to reduce the US military dependence on imported petroleum because they can be manufactured from a number of biomass and fossil feedstocks that are available locally (i.e., in the US and Canada). This paper will discuss how (1) military-adopted mandates, policies, and programs have accelerated the growth of alternative jet fuel supply chains in the US and (2) report on the current capacity of these supply chains to fulfill the USAF aviation fuel requirements.

2. Overview of alternative jet fuel technologies

Commercial supply chains for alternative military jet fuel production from the FT, HEFA and ATJ processes are shown in Figure 1, and the products of those conversion processes are listed in Table 1.

The FT process is an established method to produce alternative jet fuels. Developed in 1922 by Franz Fischer and Hans Tropsch, the process converts synthesis gas (syngas) composed of light (C_1-C_4) hydrocarbon chains into liquid transportation fuels (C_5-C_{20}) [4]. Feedstocks that could be gasified into syngas and converted to liquid in a FT reactor include coal (CtL), natural gas (GtL), biomass (BtL), and municipal solid waste.

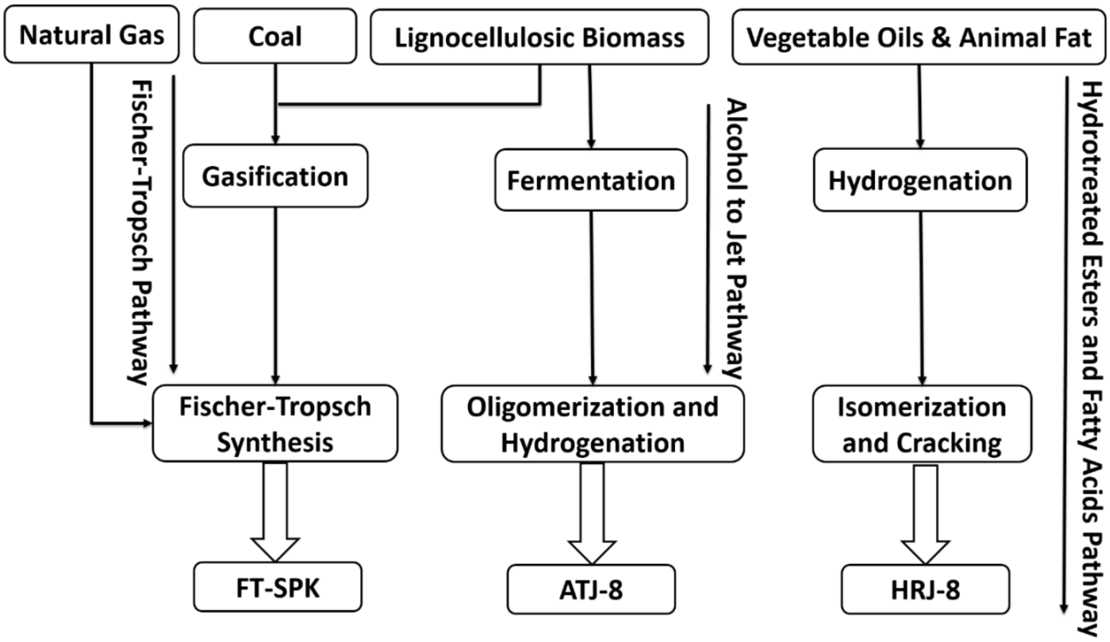

Figure 1: Schematic illustrating currently available supply chains for the production of alternative military jet fuels

A FT supply chain consists of two stages: (1) gasification, where the organic feedstock is converted to syngas (a mixture of H_2 and CO)[4]. After undergoing several cleaning and filtration steps, the syngas is (2) transferred to a reactor for FT synthesis, a catalytic process in which the smaller molecules of syngas react to form long chain alkanes (paraffins). Jet fuels produced from the FT pathway are referred to as FT Synthetic Paraffinic Kerosene (FT-SPK) and have similar properties as the middle distillate fraction from oil refining, thus can be used without engine modification [4].

The HEFA process converts vegetable oils and animal fats into various liquid transportation fuels. Among the feedstock options for HEFA are camelina, jatropha, soybean, rapeseed, salicornia, and animal tallow [6]. The process starts with hydrodeoxygenation of the feedstock in which oxygen is removed (deoxygenation), bonds are saturated (saturation), and propane backbone of the triglycerides are broken down (propanation) by introducing hydrogen [7]. The resulting paraffinic compounds undergo selective isomerization whereby branched isomers are created to lower the freezing point of the products. Finally, catalytic cracking breaks down long paraffin chains into shorter C_9-C_{15} (jet range) products [7]. Since the HRJ-8 fuel produced from the HEFA process is chemically identical to those produced from petroleum, this "drop-in" fuel require no engine modification.

The ATJ process relies on alcohols produced from fermentation of biomass, which could be from first-generation (grain) or second-generation (lignocellulosic) feedstocks [9]. Pioneered by Gevo, Inc. (GEVO), the ATJ has the potential to produce a JP-8 equivalent fuel (ATJ-8) [8]. The process starts with the dehydration of the alcohols to produce olefinic compounds (alkenes). In the next step, alkenes are oligomerized (monomer units are bound together) to form longer chain alkenes within the C_9-C_{15} range, then hydrogenated to saturate the bonds and create a product similar to JP-8 [8].

These alternative jet fuels are produced from controlled chemical processes, generating pure paraffinic compounds without appreciable aromatic content [10]. While the absence of aromatic compounds might be desirable from a combustion perspective, since aromatics increase soot formation [4], the American Society of Standards and Measurements (ASTM) requires at least 8% aromatic content in turbine aviation fuels to ensure the minimum seal swelling characteristics of the fuel, essential for safe storage [10]. For this reason, 50/50 blends of alternative jet fuels and JP-8 are preferred [10].

Table 1: Summary of commercial products produced via the FT, HEFA and ATJ supply chains

Technology	Feedstock	Company	Fuel Name	Process
Fischer-Tropsch (FT process)	Coal	Sasol	Iso Paraffinic Kerosene (IPK)	Sasol Coal to Liquid (CTL)
	Natural Gas	Shell	Shell FT Synthetic Paraffinic Kerosene (SPK)	Shell Middle Distillate Synthesis (SMDS®)
		Rentech	Rentech FT	RenJet®
Hydrotreated Renewable Jet (HEFA process)	Camelina	Honeywell UOP	HRJ-8 Camelina	Ecofining®
	Tallow	Honeywell UOP	HRJ-8 Tallow	Ecofining®
	Waste fat	Syntroleum	R-8	Bio-Synfining®
Alcohol to Jet (ATJ process)	Cellulosic Sugars	GEVO	ATJ-8	GEVO Integrated Fermentation Technology (GIFT®)

3. Policy background

Similar to other renewable energy industries, emerging supply chains of alternative jet fuels require policy support to overcome petroleum competition. The development of alternative fuel policy programs in the US dates back to the Energy Policy Act of 2005, which required renewable fuel blending with gasoline [11]. The 2007 Energy Independence and Security Act (EISA) increased the mandated volume of renewable fuels to 36 billion gallons by 2022 [11] and introduced second-generation fuels such as biomass-based diesel and cellulosic biofuels. This legislation favors renewable fuel products such as alternative jet fuels, which must comply with greenhouse gas (GHG) emission thresholds computed from life cycle assessment (LCA) of each biofuel supply chain. EISA mandates a 50% GHG emission reduction threshold for second-generation biofuel supply chains.

Alternative fuels produced from locally acquired feedstock are of great interest to the US military, and sparked a political debate in the US Congress in 2012 on whether the Department of Defense (DoD) should be allowed to procure alternative fuels that cost more than their conventional petroleum counterparts. The debate reached its climax when Republican representatives proposed amendments to the 2013 Fiscal Year of the National Defense Authorization Act (NADA) prohibiting the DoD from procuring alternative fuels [13,14]. The amendments were, however, struck down in November 2012 and the FY2013 NADA was signed into law on January 2nd 2013 [13].

Each branch of the US military has issued mandates for alternative fuel procurement. The USAF mandate requires the procurement of 50% of its domestic jet fuel consumption, amounting to 400 million gallons, from locally available, non-petroleum feedstocks at cost parity by 2016 [14]. The US Navy has a more aggressive mandate, known as the Great Green Fleet, in which a whole fleet running on alternative fuel blends would be deployed in 2016. The Navy also plans to acquire 50% of its total fuel requirements via 50% blends of alternative fuels by 2020, which requires another 650 million gallons [14]. Jet fuel constitutes around 47% of the Navy's overall fuel consumption [15].

In order to fulfill these mandates, the Navy launched a program under the authority of title III (Expansion of Productive Capacity and Supply) of the Defense Production Act (DPA), which allows the president to provide grants or loans to industries to expedite development and commercialization of military required technologies or products. The Navy Advanced Biofuel Program was launched in collaboration with the Departments of Energy and Agriculture in June 2012 [13] and consists of $120 million in awards (50/50 cost-sharing agreements [14]) to support private industries that would (1) design production facilities and (2) construct and commission facilities for alternative biofuels.

4. Requirements, testing, and certification

Figure 2 lists the technical, environmental, and economic requirements for the jet fuel products under the Navy Advanced Biofuels Program. The USAF and ASTM carried out the process of testing and certification of the alternative jet fuels. The FT-SPK and HRJ-8 products are the only two alternative jet fuels to receive ASTM approval for 50% blending with JP-8. In 2007, the USAF successfully flew the first B-52 bomber on a 50/50 blend of FT-SPK and JP-8. The products were provided by Syntroleum (S8) and Shell GtL fuels [16]. Generic FT SPK 50% blend was approved by ASTM and published in MIL-DTL-83133G the same year [10]. On March 25th 2010, USAF tested a blend of HRJ-8 (provided by UOP) and JP8 on an A-10 Thunderbolt II at the Eglin Air Force Base in Florida [17]. Later in July, ASTM approved 50% blends of HRJ-8 as a turbine aviation fuel and published the standard in ASTM D7566 [4]. Finally, on the 28th June 2012, ATJ-8, was also tested on the A-10 Thunder Bolt [18] but the product is still in the process of ASTM approval.

5. The emerging supply chains under the Navy Advanced Biofuel Program

Four companies, described in Table 2, received awards, each amounting to approximately $6 million to plan and design supply chains capable of producing alternative jet fuels that matched met the Navy's criteria (Fig. 2).

Red Rock Biofuels LLC, a subsidiary of IR1 group, received a $4 million award to assist in developing their woody biomass to liquid (BtL) transportation fuel process. Their plant, which was designed by the Oxford Catalyst Group (or Velocys®), will convert 170,000 tons of forestry derived biomass [21] into 16 million gallons of liquid fuels per year. They plan to access the estimated 55.1 million tons of wood available from forestry thinning in the US [24], and could expand to other sources (e.g., short rotation woody crops). Most common approach to woody biomass gasification involves using steam as a gasifying agent in fixed or fluidized bed reactors. Velocys uses their proprietary micro-channel reactors to perform the FTS, which is expected to exceed Sasol's traditional reactor rates (200 kg.m^{-3}.hr^{-1}) and reach a conversion rate of 1600 kg.m^{-3}.hr^{-1} [25].

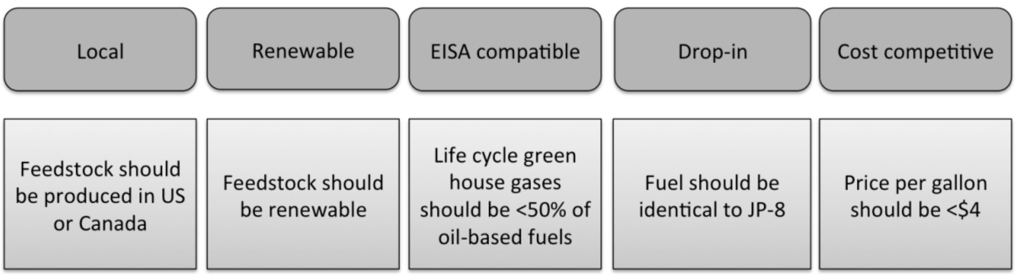

Figure 2: Requirements for alternative jet fuels under the Navy Advanced Biofuel Program [13, 14]

Table 2: List of companies that received awards in phase I of the Navy Advanced Biofuels Program to desing production facilities [17-23]. MGPY:Million Gallons Per Year

Company/HQ location	Process	Plant Location	Plant Capacity (MGPY)
Red Rock Biofuels [20, 21]	Wood Biomass to Liquid (Fischer-Tropsch)	Oregon	16
Fulcrum Bioenergy [22]	Municipal Solid Waste to Liquid (Fischer-Tropsch)	McCarran, Nevada	10
Emerald Biofuels LLC [19]	HEFA: Ecofining™	Plaquemine, Louisiana	85
Nature's Bioreserve [23]	HEFA	Sioux City, Nebraska	60

Fulcrum Bioenergy, Inc. converts Municipal Solid Waste (MSW) to liquid transportation products via the FT pathway. The company secured MSW feedstock at zero-cost by signing a 15 year agreement with Waste Management of Nevada. The heterogeneity of the MSW feedstock necessitates alternative means of gasification to syngas, which is achieved with a special plasma gasification technology known as Plasma Enhanced Melter PEM™ (developed by InEnTec®)treat the MSW. In the PEM reactor, the plasmatron applies a very high voltage between two electrodes causing an electrical discharge that ionizes the MSW to plasma. The elevated temperature (≈5000°C) of the plasma arc melts the inorganic content of the MSW and converts it into an environmentally friendly and safe vitrified slag (byproduct) that could be used for road construction. The remaining heat transforms organic compounds in the MSW to syngas [26]. Fulcrum demonstrated that their syngas product could be used either to produce ethanol (to blend with gasoline) or fed to a FT unit and converted into diesel and jet fuels.

Emerald Biofuels and Nature's Bioreserve both use the HEFA process. UOP and Eni licensed their Ecofining® process to Emerald to produce Green Diesel and HRJ-8. Emerald's plant has the largest production capacity of the four companies listed in Table 2 and it is expected to produce 85 million gallons of liquid transportation fuel annually. Nature's Bioreserve has not released details about their process but estimate the production capacity of their Nebraska plant would amount to 60 million gallons per year.

6. Discussion and conclusions

The motivation behind the Navy Advance Biofuels Program is to expedite the development of supply chains to meet the military alternative fuel mandates. The major question is: what is potential of these emerging supply chains to bridge the gap between the military targets and the projected production. With respect to the FT supply chains, operating parameters are solely responsible for the chemistry of long chain alkanes generated by the FT reactors, regardless of the feedstock. The Anderson-Schluz-Flory (ASF) distribution is a theoretical model that predicts the selectivity of FT products (m_n) as a function of operating parameters according to the following equation:

$$\boldsymbol{m_n = (1-\alpha)\alpha^{n-1}}$$

where α is the growth probability factor that reflects the rates of propagation and termination of the FT synthesis reaction and n is the carbon number of the alkane species produced [27]. The rates of propagation and termination are determined by operating conditions such as temperature, pressure and catalyst. Typically, α values range from 0.5-0.9 [27], with higher α values indicating greater probability of heavier alkane formation. For this analysis, it was assumed that the FT supply chains would operate their reactors to select higher order alkanes in the C_9-C_{15} range appropriate for jet fuels (α = 0.9 and n=9-15) [28]. The yield of jet fuels from this process could reach about 30% of the total FT products, giving an estimated jet fuel production from the two FT pathways of 8.6 million gallons per year.

The selectivity of HEFA products is determined by the hydrocracking step, shown in Figure 1. A recent study [28] estimated that alternative jet fuels represent approximately 44% of the HEFA products (under normal operating conditions). Using this estimate, 63.8 million gallons of jet fuel could be produced annually from Emerald and Nature's Bioreserve supply chains.

The USAF 2016 mandate of 400 million gallons of alternative jet fuels by 2016 and the Navy mandate amounts to 350 million gallon of jet fuel by 2020. The targets are obviously ambitious with respect to the modest production potential of the supply chains developed under the Navy Advanced Biofuel Program. Together, the FT and HEFA supply chains would yield 72.4 million gallons of alternative jet fuel per year (18% of the USAF mandate alone). The gap between the production capacity of the four companies listed in Table 2 and the mandates may narrow with the initiation of phase II of the Navy Advanced Biofuel Program, which will provide 1-3 awards, each worth $70 million, to successful supply chains. However, if the market gap persisted, it would allow for the fossil feedstock-based alternative jet fuel production to compete strongly with pathways that rely on renewable biostock feedstock. Although the Navy mandates require renewable feedstocks (Figure 2), the USAF does not list renewable feedstocks as a procurement requirement. As shown in Figure 3, the price of alternative jet fuels synthesized from fossil feedstock, procured by USAF for testing purposes in 2012, was at cost parity with conventional JP-8 [14].

Despite their attractive cost, alternative jet fuels generated from fossil feedstocks will be less competitive when judged by the EISA GHGs standards. Figure 4, adapted from Stratton et al. [6] depicts the GHGs emissions from several alternative fuel pathways. Only supply chains with GHG emissions less than 50% of the JP-8 baseline would meet the USAF mandates. This would include coal/switchgrass feedstock blends, which have GHG emissions close to EISA compliance requirements. The coal/switchgrass FT pathway (or any other fossil/biomass feedstock blend) is, therefore, a strong candidate to bridge the gap between the USAF mandate and the production anticipated from the emerging supply chains listed in Table 2.

It is also notable that GHG emissions are the only metric that indicates environmental impact of the fuel supply chains in both EISA and military mandates. Other environmental impacts of alternative jet fuel supply chains include direct and indirect land use change [6] and water stress [7], but they are not considered in advanced biofuel policies at this time.

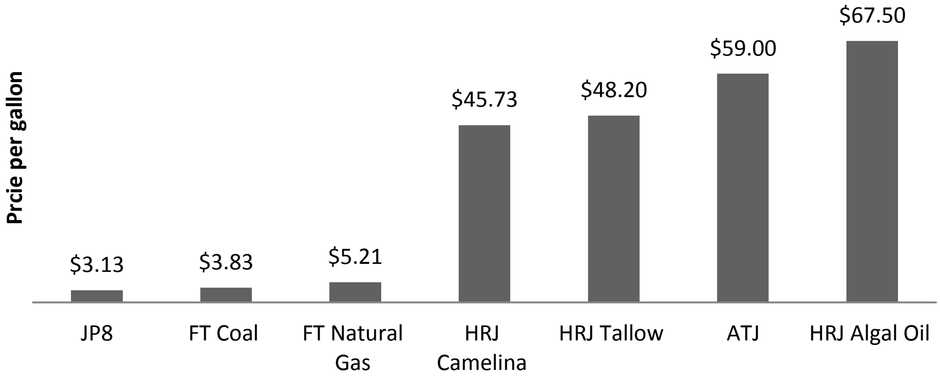

Figure 3: Price per gallon of alternative jet fuels procured for testing by the USAF in 2012. Plot is based on data from Blakeley [14].

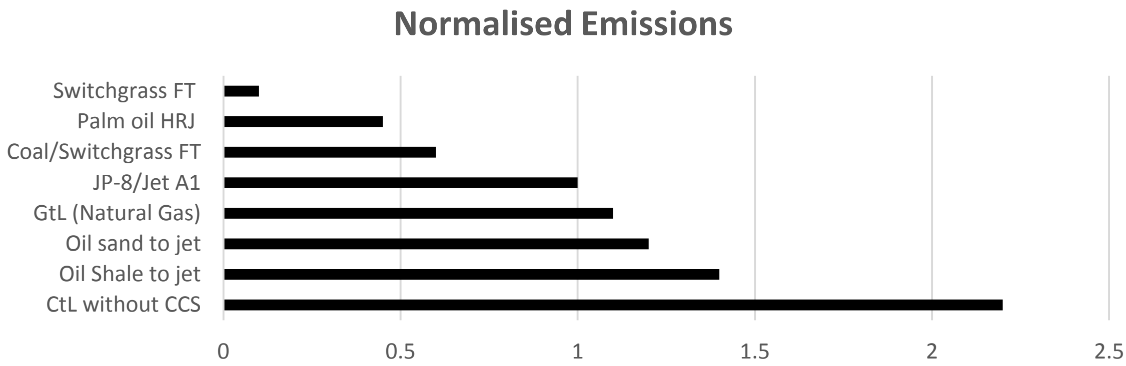

Figure 4: Life cycle assessment of greenhouse gas emission from alternative fuel supply chains. Adapted from Stratton et al. (2010) [6]. CCS: Carbon Capture and Sequestration.

7. Conclusions

The emergence of alternative jet fuel supply chains is a result of policies set by the US government and its military, and will have socio-economic and environmental impacts that are not yet fully quantified. This paper reveals a large gap between alternative jet fuel requirements to meet military targets and the production capacity of the emerging supply chains. Considering the cost of manufacturing jet fuel from biomass feedstocks and environmental quality (i.e., GHG emissions), fossil/biomass feedstock blends hold promise to bridge the targets/production gap. Continued military support of alternative jet fuel supply chains will narrow the production gap in the near future. One of the expected outcomes of the military policies and programs is that technology will diffuse to civilian aviation sector, resulting in further expansion of the supply chains and their complementary industries. Securing the production of alternative jet fuel in quantities that meet the US military mandates has important geopolitical implications (mostly in favor of the United States) as their dependency on imported oil declines.

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