

Aviation Fueling: A Cleaner, Greener Approach

R.C. Hendricks,¹ D.M. Bushnell,² and D.T. Shouse³

¹NASA Glenn Research Center
Cleveland, Ohio 44135, USA

Phone: 216-433-7507, Fax: 216-433-5473, E-mail: Robert.C.Hendricks@nasa.gov

²NASA Langley Research Center, Hampton, Virginia 23681, USA

³AFRL/WPAFB, Wright-Patterson Air Force Base, Ohio 45433, USA

ABSTRACT

Projected growth of aviation depends on fueling where specific needs must be met. Safety is paramount, and along with political, social, environmental and legacy transport systems requirements, alternate aviation fueling becomes an opportunity of enormous proportions. Biofuels—sourced from halophytes, algae, cyanobacteria, and “weeds” using wastelands, waste water, and seawater—have the capacity to be drop-in fuel replacements for petroleum fuels. Biojet fuels from such sources solves the aviation CO₂ emissions issue and do not compete with food or freshwater needs. They are not detrimental to the social or environmental fabric and use the existing fuels infrastructure. Cost and sustainable supply remains the major impediments to alternate fuels. Halophytes are the near-term solution to biomass/biofuels capacity at reasonable costs; they simply involve more farming, at usual farming costs. Biofuels represent a win-win approach, proffering as they do—at least the ones we are studying—massive capacity, climate neutral-to-some sequestration, and ultimately, reasonable costs.

INTRODUCTION

We are dealing with opportunities of enormous proportions driven by conflicts between energy, food and freshwater demands, population growth, and climatic changes.

By 2026 world liquid fuels (Reilley et al., 2007; and Energy Information Administration, 2009a) demand is projected to grow by 20%–25%, implying an increased U.S. demand from over 20 million bbl/day (2007) to 24 million bbl/day. In order to meet that demand with alternative fuels, even if one could grow algae on the open seas fed by continent-sized nutrient streams under the most opportune of conditions and convert it to oils, the equivalent volume demand would require nearly half the Gulf of Mexico,¹ 0.8 million km².

By 2026 the world's jet fuel consumption is also projected to grow from 95 billion gal (2007) to around 221 billion gal (836 million liters) per year (Daggett et al., 2009)]. Replacing

10% with a renewable jet fuel would be similar in scale to current world-wide liquid biofuels (ethanol and biodiesel) production. The need for replacement fueling and the effects of biofuels on both legacy and future aircraft performance and design has been established in prior publications (Daggett et al., 2006 and 2007; and Hendricks, 2007). These publications clearly illustrate the conflicts between fuel types and the crops and crop land necessary for alternate aircraft fueling. The aviation industry requires specific mobility fuels and cannot replace jet fuel with current renewable fuels (ethanol, biodiesel, or hydrogen electricity). It is therefore pursuing new, large-scale, secure, sustainable biofuels within several “do no harm” restraints including (i) not competing with arable land or freshwater resources needed for food/feed production, (ii) low carbon footprints that do not lead to deforestation, and (iii) not engendering adverse environmental or social impacts.

Two tons of jet fuel generates over 1.6 tons of carbon and over 2½ tons of water when burned. Globally, aviation fuel has been growing at about 4% per year despite a 1% per year improvement in airplane fuel efficiencies. The resulting high-altitude cloud formations and carbon footprint (CO₂ emissions) are of increasing concern to the commercial aviation industry, who have set a goal that future growth in the industry should be carbon-neutral. Thus, renewable jet fuels are a critical need for this industry. The Commercial Aviation Alternative Fuels Initiative (CAAIFI) and commercial aviation industry have set a goal of certifying a blended renewable jet fuel in the 2009–2010 time frame. To reach this ambitious goal, a program is underway to establish the technical feasibility, environmental sustainability, and eventual commercial viability of renewable biojet fuels. The basic technical feasibility of synthetic paraffinic kerosene (SPK) jet fuels produced from coal or natural gas or of hydrogen-treated renewable jet fuels (HRJ) produced from vegetable oils or similar sources having the same properties as conventional jet fuels has already been proven through several flight demonstrations by the U.S. Air Force, commercial airline partners, and four aircraft engine OEMs (original equipment manufacturers). The next stage is to develop secure scalable, sustainable, and economically viable feedstocks for biojet fuels that satisfy the aircraft industry's “do no harm” constraints and reduce their reliance on petroleum-based fuels.

¹Assumes equivalency between refined barrels of plant oil and petroleum. Ami Ben-Amotz algae production: $(0.8 \times 10^{12} \text{ m}^2) (0.02 \text{ kg-biomass/m}^2\text{-day}) (3/10 \text{ gal/kg}) (1/42 \text{ bbl/gal}) (20\% \text{ bio-oil/biomass})$; John Benneman algae estimate: $(0.8 \times 10^{12} \text{ m}^2) (4.2 \times 10^3 \text{ gal bio-oil/ha-yr}) (10^{-4} \text{ ha/m}^2) (1/365 \text{ yr/day}) (1/42 \text{ bbl/gal})$.

We are a society addicted to hydrocarbons. Our planet is gripped by our addiction to hydrocarbon energy generation sources.

"We take pride in our clean, green identity as a nation and we are determined to take action to protect it. We appreciate that protecting the climate means behavior change by each and every one of us." Prime Minister Helen Clark, New Zealand

- Reduce hydrocarbon addiction?
- Reduce CO₂, NO_x, etc., nanoparticulate, altitude H₂O clouds, and emissions health and climate hazards?
- Reduce foreign control of our future?
- Require cooperative world-wide investments?
- Require a paradigm shift in source and use of energy?

1. Population is expected to grow 40% in 40–50 yr.
2. Aviation is expected to grow at 4%/yr.
3. 95 billion gal jet fuel was used in 2007 with 220 billion gal projected for 2026; replacement or even low-percentage blends requires huge investments and huge biomass production.
4. Projected fuel burn reductions: air traffic management (ATM), 15%; future aircraft, 50%; future engines (intercool, recuperator), 25% (must respect laws of thermodynamics)
5. Legacy aircraft + future ATM + future fleet implies a fleet (2026) with less than 40% fuel burn reduction
6. CO₂ goals
 >80% reduction + no increase in other emissions
7. Aviation ground rules limit fueling options to “do no harm.”
8. Given issues 1–5, goals for 6 and 7 cannot be met.
9. Aviation and fueling industries recognize 8; however, space does not.
10. Given issues 1–9, will aerospace grow, decline, or equilibrate?
11. Alternative fueling requires a paradigm shift in the conception, source, use of energy, AND its funding. It will cost more with reduced dependence on coal/gas/nuclear.

12. IF serious consideration is given to issues 1–11, biomass fueling could provide a resolution to issue 10, using multiple sources.
13. Our resources are 97% seawater, 43% arid land, and a solar source of energy
14. Our goals are to conserve freshwater and arable land and to protect our food supply, health, and climate.

Secure
Sustainable
Economically viable
Sufficiently available
satisfy the ground rules

BIOMASS RESOURCES

These realities engender the food or fuel issues and their detriments, benefits, and limitations. Gressel (2008) argues for biomass diversity and that biomass production (e.g., switchgrass) does not defy uptake of essential nutrients such as water and nitrogen (Fig. 1) where freshwater demands are given in Table 1.

Gressel proposes that the food-feed-fuel issue cannot be resolved within the framework of genetics alone, pointing out several problems such as (1) does one develop and use algae or cyanobacteria, (2) how to contain unwanted organisms.

Liter(water)/liter(product)	Liter(water)/kg(product)	Liter(water)/kg(product)
Bottled water 3-4	Cup of coffee 1120	Coconut 2500
Milk (process/cow) 7/1000	Bread 1300	Sugar 1500
Glass of beer 300	Cotton 11 000	Barley 1300
Glass of orange juice 850	Hamburger 16 000	Alfalfa 900-2000
Glass of wine 950	Microchip 16 000	Wheat 900-2000
	Roasted coffee 21 000	Corn/Maize 1000-1800
		Soybeans 1100-2000
		Rice 1900-5700

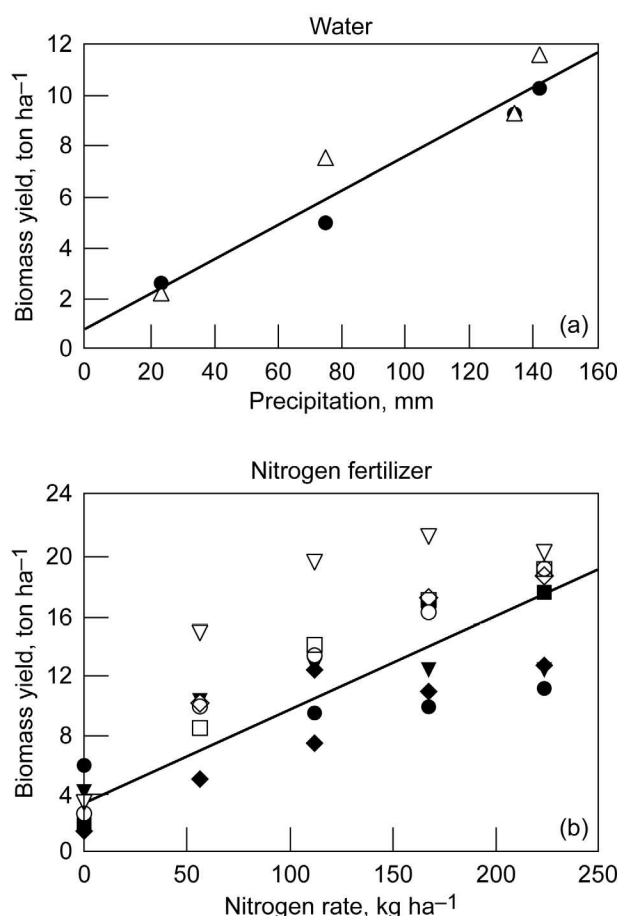


Fig. 1 Biomass productivity depends on water and nutrients (Gressel, 2008)

(3) transgenic spillage and “going wild” again, and (4) oil content and co-product proteins (feed). Ho and Cummins (2009) discuss some aspects of transgenic crops while favoring domestication of wild halophytes, identifying genes involved in plant salt tolerance and crop improvements through marker-assisted breeding. Gressel (2009) also points out that often co-product values are higher than the oil content, as is often the case for corn and soybean meals.

While freshwater is a renewable resource, and peak-water estimates are inaccurate, peak ecological water results from climatic anthropogenic changes (Gleick, 2009). Many watersheds are running low, as is occurring in the Canadian Rocky Mountains, because of glacier melt and lack of snow mass and intensive Colorado River, Southwestern United States, water demands, of which much is used for crop irrigation. As a result of high demand and low water levels, many aquifers are slowly becoming saline.

Conservation of arable land and freshwater biodiverse regions along with the development of saline agriculture and aquaculture can provide proteins, oils, as well as renewable biomass resources for food, medicines, livestock feed, and fuel. Arguments and justification for use of world sea and brackish water along with arid and semi-arid land and agriculture and human wastes as sustainable fuel and food resources have been presented previously (e.g., Hendricks and Bushnell, 2008a; and Hendricks, 2009).

Adherence to conservation and selective cultivation practices establish “do no harm” ground rules for aviation fueling as our first set of limitations (Daggett et al., 2009; and Hendricks and Bushnell, 2008b):

1. Does not compete with arable land food or feed production
2. Does not require freshwater resources
3. Does not cause deforestation or adverse social or environmental harm
4. Can be scaled to assure secure sustainable sufficient supply
5. Can be competitive with JP-8 or Jet-A
6. Life cycle carbon reduction, >50% fossil CO₂ reduction

BIOMASS FEEDSTOCK POTENTIAL RESOURCES

Biomass feedstock sources include halophytes (micro and macro), algae, bacteria, weeds-to-crops, and wastes. Algae are prolific producers and promoted by many as the solution to our energy dilemma. Reviews by the Sustainable Energy Ireland agency found algae could prosper in the lower temperature and sunlight and produce fuels at higher than today’s petroleum market prices (Burton et al., 2009). Prof. Ami Ben-Amotz and Dr. John Benemann serve as resource persons for any individual or corporation further interested in algae production, as dealing with living cultures and sustainability is quite involved. The major issue with algae fueling is cost and much attention is currently given to this issue (Ben-Amotz, 2009; Daggett et al., 2007; Daggett et al., 2009; Hendricks and Bushnell, 2009; and Algal Biomass Organization, 2009).

In an attempt to address economics and biomass production, Hendricks and Bushnell (2009) looked to the nutrient-rich Gulf of Mexico and floating biomass growth scaffolds. Even under the most favorable conditions—for only U.S. domestic commercial use—a 50:50 biojet:Jet-A blend (7 B/gal/yr) requires 22,500 km² (see Hendricks et al., 2010). This is a large area to manage in view of the risks, including storms and invasive species (Dearen, 2009), nearly the size of the Gulf’s 21,000 km² hypoxic zones (Gulf of Mexico, 2009), and biomass cultivation may be feasible as dead zone remediation (Trent et al. in Baltic Sea Solutions and STP Productions, 2009) and fuel feedstock source. However, the objective of the Mississippi River Delta project (Hendricks et al., 2009, Appendix)—where the focus is on prevention and remediation—is to neutralize sources engendering hypoxic zones; perhaps both are feasible. It should also be noted that 63% of petroleum leakage into North American waters comes from natural seepage and 33% from user spills, (Energy Information Administration, 2009b).

Venter’s fourth-generation synthetic fuels (Schill, 2009a) with promises for enhanced productivity due to enhanced percentage oil/biomass, solar spectra absorption, and environmental adaptivity have been given a major investment boost. Modifying marine algae, however, is not that simple; it has not been very successful in the past and may be more difficult to manipulate than higher plants (Ben-Amotz, 2008). Further, the effects of light—both the wavelength and time of exposure—have a demonstrated direct effect on plant communication, reproduction, and biomass growth that requires assessment (Belousov et al., 2007).

Halophytes are salt-water- and brackish-water-tolerant plants that address the environmental triangle of conflict issues (food, energy, water). Seawater is 35,000 ppm salt. One cannot drink water with more than 3,000 ppm, and normal potable water is 500 ppm. *Salicornia bigelovii*, seashore mallow (grain and straw crops), and *distichlis spicata* (a remedial grass) are a sampling of thousands of halophyte species (Hendricks and Bushnell, 2008a).

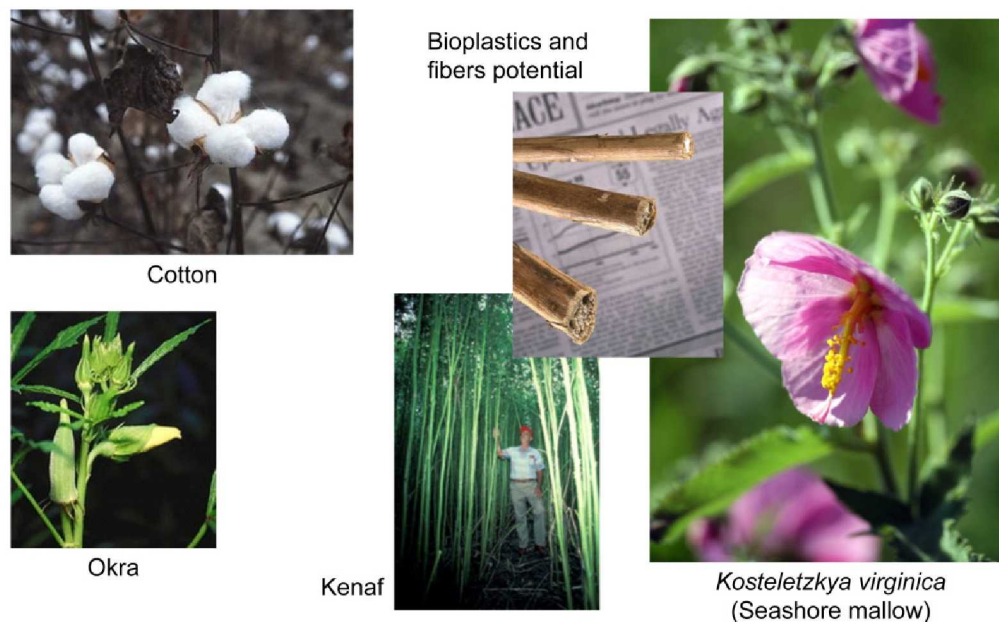


Fig. 2 Malvaceae family (Wikipedia, 2009a, 2009b, and 2009c) with halophyte seashore mallow (*kosteletzkya virginica*)

Table. 2 Halophyte water requirements and salt tolerance

Halophyte	Salt tolerance	Water requirements*
Seashore Mallow, perennial, (Gallagher, 2009)	salt tolerant to coastal seawater	< 1.5 times glycophyte irrigation (<1500–3000 L/kg)
Salicornia, annual (The Seawater Foundation, 2007)	salt tolerant to 2 times seawater, optimum productivity to 1.3 times seawater	1.35 times glycophyte irrigation (1300–2700 L/kg)

*Prevents salt build-up at roots—soil texture, drainage, natural rainfall, evapotranspiration dependent.

In seeking suitable seed and cellulosic biomass, plant genesis becomes a good indicator of utility. Seashore mallow belongs to the malvaceae family, which includes kenaf, okra, and cotton (Fig. 2). Additional potential markets include fibers, bioplastics, food/feed, and pyrolysis fuels.

Seashore mallow is harvested using conventional equipment. Halophytes can sequester salts at the roots or in the foliage. At the roots, excess saltwater/brackish water is used to flush the soils to provide nutrients and prevent significant salt buildup. For foliage, some grasses are considered forage grasses where the ruminant livestock seem to thrive. In other cases, the CaCl or NaCl is secreted as surface nodules and plant (tree) biomass as C sequestration in C trading schemes. The collection and disposal of salts en masse has not yet been addressed other than via dilution. Other uses include high-quality sea salt as common-salt replacement. Seawater irrigation requirements are higher, to control salt build-up in the root areas, requiring adequate well planned and executed irrigation and drainage. However for seashore areas as for the seashore mallow the plant foliage and soil is also flushed with rainwater. So some balance must be achieved (see Table. 2). In the life cycle system of Dr. Hodges (The Seawater Foundation, 2007), freshwater lenses are also developed to conserve freshwater.

Camelina is a weed-to-crop that can be intercropped (McVay and Lamb, 2007). It looks like wild mustard, can prosper on marginal lands, matures in 85–105 days, has small oil seeds that yield 3.2 tonnes/ha 35%–45% oil and are high in omega-3 with crop residue potential as pyrolysis fuel.

Pennycress (*thlaspi arvense*), a weed becoming a crop, claims 2.25 tonnes/ha oil seed with 36% oil/seed with a potential to produce 660 gal-biodiesel/ha on Illinois farmland, which competes with arable land and freshwater resources (Wikipedia, 2009d; and Schill, 2008).

CELLULOSIC BIOMASS

Worldwide, 4 billion tons of crop residue are produced with 0.5 billion tons in the United States. Unattended lignocellulosic biomass residuals (e.g., straw, corn stover, and some roadside grasses) have a potentially negative economic and environmental value. Such residuals are of little value as ruminant feed, require fungicide prior to the next crop, bind nutrients while biodegrading, and harbor pathogens if not burned or release CO₂ if they are (Gressel, 2008, p. 195). They appear, however, as candidates for pyrolysis or fermentation fuels. One ton lignocellulosic biomass produces 100 gal ethanol (Lal, 2007). However, Lal (also Washington State University, 2008; United States Department of Agriculture, 2006; and Glassner et al., 1998) points out that crop residues are a commodity essential to the soil. They control erosion, recycle nutrients, and maintain soil structure and tillage, sustaining biomass agronomic yield. Indiscriminant conversion of biomass to energy is wasteful of a commodity essential to soil health. Thus soil carbon can be remediated or produce power, but not both, where removing more than 70% biomass residuals is considered harmful. Lal (2007) suggests proper life cycle analysis, soil residue management, and choosing appropriate warm-season grasses, some perennials and

halophytes, which will respond in brackish or sea water in arid regions.

Potentially, the United States could produce 35 billion gal ethanol from crop residues. Producing fuels from lignocellulose is not novel or new as it was practiced prior to and during WWII, but large-scale production of sustainable economically viable renewable lignocellulose fuels becomes the challenge (Regalbuto, 2008; Virent Energy Systems, Inc., 2007; Hsu, 1974; and Graham et al., 1976).

Water hyacinth (*eichhomia crassipes*), a tropical plant that will remediate waste water, was investigated by Dr. Bill C. Wolverton (NASA-Stennis, retired) under the NASA(NSTL) vascular aquatic plant program. Considered a noxious weed, it produces 5–10 kg-biomass/m²-yr (similar to macro-algae), a source of pyrolysis fuels with beneficial water treatment (Wolverton, 2009, 2001, and 1997). Another noxious weed is Kudzu with similar pyrolysis benefits with roots a source of starch and some edible leaves.

Other plants such as *Arundo donax* produce 23–50 ton/acre. It tolerates some salinity and brackish waters and also overwhelms native vegetation. Seaweed, a macro-algae, has enormous potential in the Sargasso seas as a cellulosic fuel and food source.

Honge (*Pongamia pinnata*), like *jatropha*, palm, and coconut, are but a few of the trees producing oil-seeds that are processed into biodiesel. Experiments show that Honge tolerate brackish water and need little nitrogen fertilizer, with oil yields similar to palm. Honge and *jatropha* are both toxic (Wikipedia, 2009e).

PROCESSING

Market oil grades range from unrefined (crude), to refined, bleached, and deodorized (RBD) oils (food grade). RBD-quality oil processes are degumming, neutralization, bleaching, hydrogenation, deodorization, and winterization or crystallizations, but for RB grade degumming and bleaching usually reduces contaminants to acceptable levels.

Tree-plant oils (e.g., palm, coconut, *jatropha*, olive, etc.) as well as vegetable oils (e.g., soybean, canola, rapeseed, camelina, castor, etc.) algae oils, and animal fats are all analyzed for specific contaminants (Na, P, Ca, N species), which would determine the extent of contaminant removal (clean-up) required. Phospholipids are typical contaminant species removed during degumming as are nitrogen or amino groups found in algae oils. Tar and ash found in biomass-to-oil processes (e.g., low-temperature biomass gasification) are unsuitable for the processors such as that used by UOP, and generally not found in vegetable oil feedstocks. Common vegetable oil fuel feedstocks include palm, rapeseed, soybean, *jatropha*, castor, and the lesser known halophytes such as *salicornia* and *seashore mallow*.

Holmgren et al. (2007) note that RB biomass triglyceride feedstocks contain oxygen, which complicates catalytic processing into biojet fuel. An illustration of seed-oil triglycerides is shown in Fig. 3, “where the glycerol skeleton (on left) has coupled with three fatty acids: palmitic (top chain), oleic acid (middle chain), and α -linolenic acid (bottom chain) where glycerol is on the left side, palmitic acid (top), oleic acid (middle) and α -linolenic acid (bottom).

Holmgren et al. (2007) makes direct use of existing technologies including blending or co-processing, to produce renewable diesel fuels that are primarily paraffins rather than esters. Such fatty acid methyl esters (FAME) are common in biodiesel.

Hydroprocessing by decarboxylation and hydrodeoxygenation removes oxygen from the three-carbon structure of the triglyceride

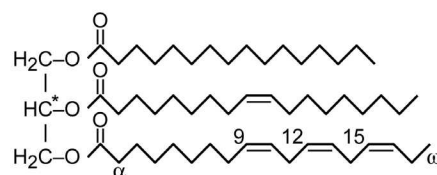
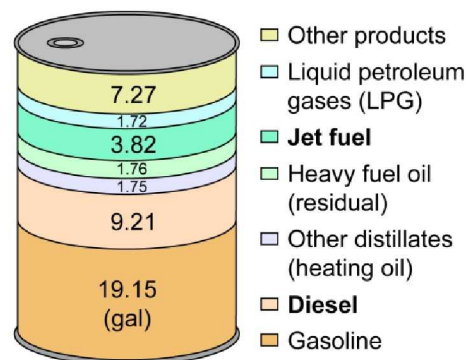
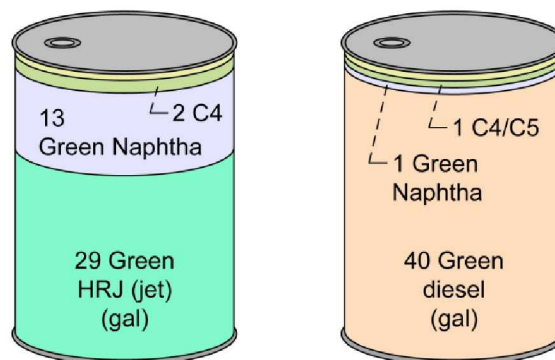


Fig. 3 Triglyceride (TAG) C₅₅H₉₈O₆ (Wikipedia, 2009f; see also Zamora, 2005)



Petroleum bbl (eia)



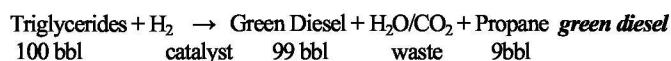
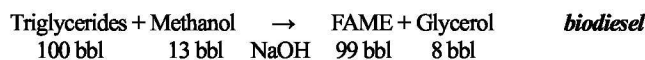
□ < 1 other (light fuels, LPS, H₂O, CO₂)

UOP-HRJ process bbl

UOP-Green diesel process bbl

Fig. 4 Gallons of distillates from a barrel of oil (Energy Information Administration, 2009b) and liquid sunshine processes UOP HRJ and green diesel (Holmgren, 2009)

molecules, yielding green-diesel along with propane that is recovered in the refinery process and waste. The product consists only of paraffins, as all olefinic bonds are saturated, and has no sulfur or aromatics (Holmgren et al., 2007). The oxygen waste is rejected as CO/CO₂ or water, whereas in the FAME process, recovery of methanol and NaOH are necessary, as is the disposal of glycerol. Holmgren et al. compare the two process streams as follows:



Alternate Fuels Processed Barrels

It is instructive to compare fuels obtained from a barrel of unprocessed oil (Fig. 4). For example, one barrel of petroleum oil

produces 3.82 gal of jet fuel, and a barrel of vegetable oil produces 29 gal of jet fuel (HRJ or fully renewable HRJ), and for other transportation fuels, a barrel produces 28.36 gal from petroleum oil and 40 gal from vegetable oil.

The UOP green diesel and HRJ biojet processes are designed for the conversion of triglycerides or free fatty acids, where the raw oil clean-up process conversion loss is less than 5%. Most feedstocks have the same C-chain length (18–22) but differ in number of double bonds and propensity to form free fatty acids. The UOP process can also convert FAME (biodiesel, the fatty acid methyl ester), algae oils, which are similar, and animal fats, which are also very similar (Holmgren, 2009).

Aviation Fuel Standards

Jet-A fuel must satisfy ASTM D1655. Fischer-Tropsch (FT-) derived fuels (e.g., from coal (CTL) or natural gas (GTL)) must satisfy ASTM D7566 Aviation Turbine Fuel Containing Synthesized Hydrocarbons (August 4, 2009) (Commercial Aviation Alternative Fuels Initiative, 2009a), a parallel to MIL-DTL-83133F (11 April 2008), regulating 50:50 blends with Jet-A and JP-8, respectively. Biojet (HRJ) has specific requirements beyond those of green diesel in that must satisfy ASTM D7566 with anticipated approval of fuel blends in 2010 (Commercial Aviation Alternative Fuels Initiative, 2009b). One of the first hurdles a potential fuel must pass is the freezing point test (−40 °C commercial, −47 °C military). Other companies (e.g., Syntroleum) can also process seed oils to biojet.

SPK AND HRJ CARBON SPECTRA

Although the carbon distributions of synthetic paraffinic kerosene (SPK) and hydrotreated renewable jet (HRJ) fuels differ widely, they qualify under ASTM D7566 specifications as jet fuels. When blended up to 50% with petroleum-based Jet-A or JP8, they provide “drop in” fueling replacements for aircraft. The weight percents for three biojet flight fuels camelina (Japan Airlines), jatropa (Air New Zealand) and jatropa algae (Continental Airlines), shown in Fig. 5, illustrate similar carbon-number distributions. The high isomer:normal-paraffin ratio

across the carbon-number distribution also provides vegetable oils with lower freezing points.

ALTERNATE-FUELED FLIGHT TESTS

In the late 1800’s the U.S. alternate fuels industry produced quantities of oils (e.g., coal oil) that were replaced by cheap oil. The use of synthetic FT fuels became prominent in Germany during WWII, yet it could not be sustained because of bombings and controlled use of petroleum fuels. In response to sanctions imposed on hydrocarbon fuel imports, South Africa became a world leader in production and use of FT synthetic jet fuels. More recently, the Air Force Research Laboratory (AFRL) took the initiative to test, fly, and certify aircraft for FT-fuel blends to 50% with JP-8 with several commercial airlines flight testing alternate fueling as illustrated in Fig. 6 and in the following list.

As of June 2009, SPK- and RHJ-fueled flights have had no discernable problems, with ASTM (D7566) approval and final approval eminent.

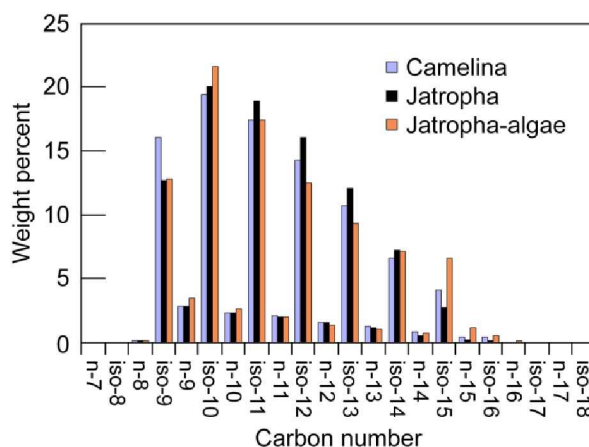


Fig. 5 Relative weight percent carbon spectra for camelina, jatropa, and jatropa-algae flight fuels blended with Jet-A. Jennifer.Holmgren@uop.com



Fig. 6 Alternate-fueled flight testing

Recorded alternate-fueled flights include

- (1) August 8, 2007, USAF B52H
Aircraft flight certified
Fuel blends up to 50% synjet (SPK) with JP-8
SPK fuel specification MIL-DTL-83133F
- (2) February 24, 2008, Virgin Atlantic 747-400 40-min biojet fueled flight
One of four GE CF6-80C2B5F turbofan engines
London to Amsterdam (320 km) altitude to (7.6 km)
80% Jet-A: 20% processed coconut oils
Ground tests to 60JetA:40biojet no discernable problems
- (3) February 1, 2008, Airbus A380 3-hr GTL fueled flight
One of four Rolls-Royce Trent 900 engines fueled
Bristol to Toulouse to assess environmental impact
GTL (gas-to-liquid) fueling 50% Jet-A: 50% GTL Blend
Goal regulatory 50:50 blend (2009): 100% GTL (2013)
- (4) December 30, 2008, Air New Zealand, 747-400 2-hr biojet fueled flight
One of four Rolls-Royce RB211 engines fueled
Auckland over Hauraki Gulf
Fueled 50:50 blend processed-jatropha UOP biojet and Jet-A
- (5) January 7, 2009, Continental 737-800 1.5 hr biojet fueled flight
One of two GE CFM56-7B engines fueled
Flight over Gulf of Mexico
Fueled 50:50 blended biofuel of (47.5% jatropha + 2.5% algae) UOP biojet + Jet-A
Pilot reported enhanced fuel economy
- (6) January 30, 2009 JAL 747-300 1.5 hr biojet flight
Number 3 P&W JT9D engine fueled
Flight about Haneda Airport
Fueled 50:50 blend biojet:Jet-A [feedstocks camelina 84% (sustainable oils), jatropha (Terrasol) <16%, and algae <1% (Sapphire) UOP processed

Organizations contributing to alternate-fueled flight include the Commercial Aviation Alternate Fuels Initiative (CAAIFI) in areas of research, emissions, business, and Regulations; and the Transportation Research Board (TRB) in areas of road, rail, air, marine, and transit.

For more details see Hendricks (2009).

GENERAL AVIATION (GA) AND UNMANNED AERIAL VEHICLES (UAV)

GA is seeking environmentally friendly carbon-neutral biomass fueling (biofuels) as future fueling replacement for aviation gas (Av-gas).

The U.S. piston fleet represents 71.4% of GA aircraft, a total of 165,189 aircraft, which represents a significant number of planes and pilots that need assistance in transitioning from Av-gas to biomass fueling. The Café Foundation (2009) was established to enable alternate-fueled general aviation flight based on environmentally sound principles with a carbon neutral/negative footprint.

The number of aircraft in the USA-GA fleet (excludes military, airlines, charter operations, and aircraft of over 12,500 lb) is 213,488, and these are typified in the 2006 Nall Report (AOPA, 2006).

One of NASA's general aviation (GA) engine programs, originating in the mid-90s, is summarized in a work presented at Oshkosh (Burkhart, 2001).

Early aviators used gasoline (80/87) octane ratings. Fuels developed in the 1950s and 60s for GA use were a blend of naphtha alkylate (mixture of isooctanes and some reformate),



Fig. 7 An American Aviation AA-1 Yankee being refueled with 100LL Av-gas (Wikipedia, 2009g)



Fig. 8 Rotax 914, a four-cylinder, four-stroke, 101-horsepower engine, the same engine type commonly used on snowmobiles, rotates the Predator's two-blade, variable-pitch pusher propeller (Valdes, R., 2009; Rotax Aircraft Engines, 2009; and Thielert Aircraft Engines, 2009)

which along with tetra-ethyl-lead (TEL = 1.12g/L), enabled 100/130 octane ratings for lean/rich engine fueling mixtures (e.g., cruise and take off). These fuels for the most part have been replaced by 100LL (low lead TEL= 0.56g/L (Fig. 7) (EPI Inc., 2008). Avgas will be the C8, as it is predominantly alkylate (made from two C4 compounds) The JP-8 spectra will pick up where the Avgas leaves off with little overlap. The volatility is typically controlled by blending in isopentane so there will be C5 present as well (AVweb Editorial Staff, 2008).

While the FAA is already funding efforts to develop and certify alternate-fuel drop-in replacements for Jet-A (JP-8), supplier Exxon considers Jet-A unsuitable for diesel piston engines citing, among others, freezing point concerns as commercial jets fly fast enough for friction to heat wing tanks, but others like Diamond Aircraft disagree (ExxonMobile Aviation, 2008).

Potential biofuel replacement feedstocks for Av-gas include halophytes, algae, bacteria, "weeds-to-crops," and wastes. However, nearly all feedstock oils can be UOP-processed to biojet fuel; that is, nearly feedstock independent (Holmgren et al., 2007) and with demand, the process could be modified to produce bio-Av-gas for both civil and military (Fig. 8) GA applications.

INFRASTRUCTURE

Postprocessing fueling distribution infrastructure includes pipeline, storage, airport, and aircraft fueling systems. Most of these systems exist and are applicable or adaptable to a variety of processed biofuel feedstocks. Even though the processes, such as UOP's, have a wide range of applicability, it is difficult to predict future feedstocks. Further, process-plant and fueling infrastructure life needs to exceed 20 years, requiring long fabrication-to-operation lead times with price stability and support.

ECONOMICS

Currently, the biomass industry is dealing with highly volatile regulations (Global Subsidies Initiative, 2009; Green Car Congress, 2009; and Schill, 2009b), life cycle analysis, and costing issues (Daggett et al., 2009; Schill, 2009b; and Daggett, 2009). Most biomass to oil startups advertize costs at or just above the DARPA targets of \$1–\$2/gal (DARPA, 2007), which is half of the Daggett et al. (2009) optimistic projection for algae oils and at least order of magnitude less than common market algae oils. Even established markets for crops such as palm and soybeans struggle to survive fuel cost and political barriers. Until biomass oils enjoy similar support and subsidies as petroleum, including costs of security and defense, they simply cannot compete with drilled petroleum production at less than \$2/bbl. Price stabilization could enable investor assessment of risk, projected value, and return on investment.

World aviation conversion to biojet fueling in today's transportation market becomes marginal unless vegetable oils, which in today's market trade at a higher price than petroleum on a per barrel basis, become cost effective, secure, sustainable, and of sufficient supply. Biofueling is high risk, high payoff, and *existential* to survival.

CONCLUDING REMARKS

Producing transportation fuels that can be blended with petroleum that meet political, social, environmental, and legacy transport systems requirements becomes an opportunity of enormous proportions.

Aviation fueling is particularly important as safety is a paramount issue, and very specific fueling needs and requirements have to be met. To date, specifications for synthetic paraffinic hydrocarbon fuels (SPK) primarily from coal (CTL) or gas (GTL) and hydrogentreated renewable jet fuels (HRJ) have been established for MIL- and ASTM-approved SPK and biojet blended fuels with demonstrated flight performance to 50:50 blends. Sources of coal and gas are well established. Now begins the difficult task of determining what the fueling feedstock sources and resources are and how biomass such as halophytes, algae (micro and macro), bacteria, weeds-to-crops, and wastes can meet aviation fueling needs.

The aviation industry, which consumes 85 to 95 billion gal “fossil” fuel (2006), growing 4 percent per year worldwide with a projected demand of 221 billion gal (2026), is actively seeking alternate-fuel replacements. Concurrent demands to increase fuel availability and reduce fuel consumption and emissions can be met with biomass-derived fuels:

1. Biofuels—if sourced from halophytes, algae, cyanobacteria, and “weeds” (e.g., jatropha, castor, and camelina) that use wastelands, waste water, and seawater—have the capacity to be drop-in fuel replacement for petroleum fuels. However, increased biomass productivity from various sources all require water and nutrients.

2. Biojet fuel from such sources SOLVES the aviation CO₂ emissions issue without the downsides of “conventional” biofuels, such as competing with food and freshwater resources. These fuel feedstocks are also restrained by self-imposed restraints to not compete with food or feed crops, freshwater needs, or the social fabric, nor are they detrimental to the environment.

3. Most of the existing fuel infrastructures are applicable to biofuels, which include pipelines and airport and aircraft fueling systems, yet they will require new processing facilities with long fabrication-to-operation lead times with price stability and support.

4. Biojet fuel blends to 50:50 with Jet-A have been flight tested with no discernable problems. An ASTM specification has been approved. SPK blended to 50:50 has also received approval, with most military aircraft certified to fly on these fuels. While there are significant variations in the carbon distribution of the various SPK and biojet fuels produced from various feedstocks, the MIL or ASTM fueling requirements are still fully satisfied.

5. Traditional biofuels (corn, soybeans, and palm), which rely on freshwater and arable land, essentially lack the capacity and solutions provided by nontraditional feedstocks such as halophytes, algae, cyanobacteria, and “weeds” that use waste lands, waste water, or saline water and have an immense capacity potential. The use of cellulosic waste residuals—whether crop, forestry, or other—require a form of pyrolysis or fermentation in order to be further processed to satisfy jet fuel requirements. Disagreements persist relative to residue removal in terms of pathogens and use of soil fumigants as well as soil carbon requirements, which require resolution.

6. A barrel of petroleum produces about 28 gal general transportation fuels and 3.8 gal jet fuel of a total of 44.6 gal/bbl. Currently a barrel of processed biomass oil provides 29 gal green jet and 13 gal of naphtha that can be further processed to fuels. A similar process converts a barrel of biomass oil to 40 gal green diesel. In discussing replacement of petroleum, the oil feedstock and most importantly the processing must be taken into account.

7. General aviation requirements differ in that piston engine type aircraft require different fueling. Still, the processed biofuel stream could be diverted to a secondary processing stream to meet those specifications for both high-octane fuels and diesel, resulting in drop-in replacements for low-lead aviation gas.

8. Cost is the major issue of biomass fueling, or for that matter alternate fueling in general. Algae has a major cost problem. However, halophytes simply involve more farming, at (acceptable) the usual farming costs (similar to cellulosic). Therefore, halophytes are the near-term solution to biomass/biofuels capacity at reasonable costs and without use of freshwater or arable land. Much effort in research, development, and investments into nontraditional crops is required to enable the same levels of support that traditional biomass agricultural enjoys.

9. Biomass fuels must utilize, recycle, and sequester existing and exhausted atmospheric carbon (CO₂ and emissions in general) along with soils remediation if they are to be truly “green” and useful in combating climate change to the extent possible.

10. Renewable energy approaches, each of which can replace all of the “fossil” fuel demands, are drilled geothermal, solar photovoltaic, solar thermal, and biomass sourced from halophytes, algae, cyanobacteria, or “weeds” on wastelands using waste or salt water. Wind and wastes are secondary sources of energy with energy from wastes based on pyrolysis or fermentation processes. Biofuels represent a win-win approach,

proffering as they do—at least the ones we are studying—massive capacity, climate neutrality to perhaps even carbon negativity through sequestration, and ultimately reasonable costs.

REFERENCES

- Algal Biomass Organization—Algae for Energy, 2009, “Algal Biomass Events.” <http://www.algalbiomass.org/events/>
- AOPA Air Safety Foundation, 2006, “2006 Nall Report: Accident Trends and Factors for 2005.” <http://www.aopa.org/asf/publications/06nall.pdf>
- AVweb Editorial Staff, 2008, *AVwebFlash*, vol. 14, no. 48b.
- Baltic Sea Solutions and STP Productions, 2009, “Presentations,” *Wind—Sea—Algae: International Workshop on Offshore Algae for Biofuels and Beyond*, Lolland, Denmark. http://wind-sea-algae.org/?page_id=248
- Belousov, L. V., Voeikov, V. L., and Martynyuk, V. S., 2007, *Photonics and Coherent Systems in Biology*, Springer Science and Business Media, LLC, New York, NY.
- Ben-Amotz, A., 2008, NBT Ltd., Eilat, Israel, personal communication.
- Ben-Amotz, A., Polle, J. E. W., Rao, D. V. S., 2009, *The Algae Dunaliella Biodiversity, Physiology, Genomics and Biotechnology*, Science Publishers, Enfield, NH.
- Burkhart, L., 2001, “Accomplishments of NASA G/A Propulsion Program,” Oshkosh paper number 123, EAA AirVenture Oshkosh 2001, Oshkosh, WI. <http://www.forums4.us/fl2001.html>
- Burton, T., Lyons, H., Lerat, Y., Stanley, M., and Rasmussen, M. B., 2009, “A Review of the Potential of Marine Algae as Source of Biofuel in Ireland,” Sustainable Energy Ireland (SEI), Glasnevin, Dublin 9, Ireland.
- Café Foundation, 2009, “CAFE: Comparative Aircraft Flight Efficiency.” Santa Rosa, CA. www.cafefoundation.org
- Commercial Aviation Alternative Fuels Initiative, 2009a, “ASTM Passes Synthetic Jet Fuel Specification.” <http://www.caafi.org/news/News.aspx?id=39>
- Commercial Aviation Alternative Fuels Initiative, 2009b, “Landmark Synthetic Jet Fuel Specification Passes Critical Hurdle.” <http://www.caafi.org/files/altfuelstandard-rls6-09.pdf>
- Daggett, D., 2009, Boeing Commercial Airplanes, Seattle WA, private communication.
- Daggett, D. L., Ben-Amotz, A., and Benemann, J., 2009, “Feasibility of Algal Oil for Renewable Jet Fuel,” submitted to *Journal of Applied Phycology*.
- Daggett, D., Hadaller, O., Hendricks, R., and Walther, R., 2006, “Alternative Fuels and Their Potential Impact on Aviation,” ICAS 2006–5.8.2, 25th International Congress of the Aeronautical Sciences, Hamburg, Germany.
- Daggett, D. L., Hendricks, R. C., Walther, R., and Corporan, E., 2007, “Alternate Fuels for Use in Commercial Aircraft,” ISABE–2007–1196, Beijing, China.
- DARPA Strategic Technology Office, 2007, “BioFuels—Cellulosic and Algal Feedstocks,” BAA08–07, DARPA, Arlington, VA. <http://www.darpa.mil/STO/solicitations/baa08-07/index.html>
- Dearen, J., 2009, “Killer Miso Soup Kelp Invades San Francisco Bay,” *The Huffington Post*, July 13. http://www.huffingtonpost.com/2009/07/13/killer-miso-soup-kelp-inv_n_230836.html
- Energy Information Administration, 2009a, “Chapter 1—World Energy Demand and Economic Outlook,” International Energy Outlook 2009, Report #DOE/EIA–0484(2009). <http://www.eia.doe.gov/oiaf/ieo/world.html>
- Energy Information Administration, 2009b, “Nonrenewable Oil (Petroleum).” <http://www.eia.doe.gov/kids/energyfacts/sources/non-renewable/oil.html#Howused>
- EPI Inc., 2008, “The Need for Leaded Avgas, Availability Declining Worldwide.” http://www.epi-eng.com/aircraft_engine_products/demise_of_avgas.htm
- ExxonMobil Aviation, 2008, “Jet Fuel Supply to Diesel Powered Aircraft.” ExxonMobil Fuels Marketing Company, Fairfax, VA. <http://thenog.org/docs/Exxonrefusesfuelda42.pdf>
- Glassner, D. A., Hettenhaus, J. R., and Schechinger, T. M., 1998, “Corn Stover Collection Project,” BioEnergy '98: Expanding BioEnergy Partnerships, U.S. Department of Energy, Madison, WI. <http://www2.ctic.purdue.edu/Core4/bio98paper.pdf>
- Global Subsidies Initiative, 2009, “Biofuel Subsidies,” Geneva, Switzerland. <http://www.globalsubsidies.org/en/research/biofuel-subsidies>
- Graham, R. W., Reynolds, T. W., and Hsu, Y. Y., 1976, “Preliminary Assessment of Systems for Deriving Liquid and Gaseous Fuels From Waste or Grown Organics,” NASA TN D–8165, NASA Glenn Research Center, Cleveland, OH. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19760011589_1976011589.pdf
- Green Car Congress, 2009, “EPA Proposes New Regulations for Renewable Fuel Standard to Implement Requirements of EISA; GHG Reduction and Indirect Land Use Change Effects Included.” www.greencarcongress.com/2009/05/epa-nprm-20090505.html
- Gressel, J., 2008, *Genetic Glass Ceilings: Transgenic for Crop Biodiversity*, Johns Hopkins University Press, Baltimore, MD.
- Gressel, J., 2009, “Why Transgenics Are Imperative for Biofuel Crops,” OAI–NASA Lecture, Ohio Aerospace Institute, Brook Park, OH, March 10.
- Hendricks, R. C., 2007, “Sustainable Secure Alternate Aviation Fueling,” 2007 NASA Seal/Secondary Air System Workshop, NASA/CP–2008-215263/VOL1, Cleveland, OH, pp. 75–99.
- Hendricks, R. C., 2009, “Alternate-Fueled Flight: Halophytes, Algae, Bio-, and Synthetic Fuels,” NASA/TM–2009-215222 (see also www.atlanticgreenfuels.com).
- Hendricks, R. C., and Bushnell, D. M., 2008a, “Halophytes Energy Feedstocks: Back to Our Roots,” ISROMAC12–2008–20241, *The 12th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery*, Honolulu, HI.
- Hendricks, R. C., and Bushnell, D. M., 2008b, “Synthetic and Biomass Alternate Fueling in Aviation,” 2008 NASA Seal/Secondary Air System Workshop, NASA/CP–2009-215677, Cleveland, OH, pp. 91–130.
- Hendricks, R. C., and Bushnell, D. E., 2009, “Synthetic and Biomass Alternate Fueling in Aviation,” *Mechanical Engineering Today*. http://www.asme.org/NewsPublicPolicy/Newsletters/METoday/Articles/Synthetic_Biomass_Alternate.cfm
- Hendricks, R. C., Bushnell, D. M., and Shouse, D. T., 2010, NASA/TM–2010-XXXXXX, to be published 2010.
- Ho, M.-W., and Cummins, J., 2009, “Saline Agriculture to Feed and Fuel the World Institute for Science in Society,” ISIS Report 24/02/09, The Institute of Science in Society, London. <http://www.i-sis.org.uk/SalineAgriculture.php>
- Holmgren, J., 2009, UOP LLC, private communication.

- Holmgren, J., Gosling, C., Marinangeli, R., Marker, T., Faraci, G., and Perego, C., 2007, "A New Development in Renewable Fuels: Green Diesel," *105th National Petrochemical and Refiners Association (NPRA) Annual Meeting*, Paper AM-07-10, San Antonio, TX. www.npra.org and www.uop.com
- Hsu, Y. Y., 1974, "Clean Fuels From Biomass," *10th Southeastern Seminar on Thermal Sciences*, NASA-TM-X-71538 (see also *Energy Quarterly*, vol. VI, no. 1, 1976), New Orleans, LA.
- Lal, K., 2007, There Is No Such Thing as a Free Biofuel From Crop Residues," *CSA News*, V52 NO5 May 2007, pp. 12-13.
- McVay, K. A., and Lamb, P. F., 2008, "Camelina Production in Montana," *MontGuide*, Montana State University Extension, Bozeman, MT.
<http://msuextension.org/publications/AgandNaturalResources/MT200701AG.pdf>
- Palaniappan, M., and Gleick, P. H., 2009, "Peak Water," *The World's Water 2008-2009: The Biennial Report on Freshwater Resources*, Gleick, P. H., Chapter 1, and Data Table 19. Water Content of Things, Island Press, Washington, DC, pp. 335-338.
- Regalbuto, J., 2008, "NSF Biofuels Activities," *BRDI TAC Meeting*, National Science Foundation, Arlington, VA.
<http://www.brdisolutions.com/Site%20Docs/TAC%20Meeting%20Dec%202008/REGALBUTO%20BCIWG%20TAC%20NSF.pdf>
- Reilley, J., Paltsev, S., and Choumert, F., 2007, "Heavier Crude, Changing Demand for Petroleum Fuels, Regional Climate Policy, and the Location of Upgrading Capacity: A Preliminary Look," MIT Joint Program on the Science and Policy of Global Change, Report No. 144, Massachusetts Institute of Technology, Cambridge, MA.
http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt144.pdf
- Rotax Aircraft Engines, 2009, "914," BRP-Rotax GmbH & Co. KG, Gunskirchen, Austria.
http://www.rotax-aircraft-engines.com/a_engine_914.htm
- Schill, S. R., 2008, "Making Pennycress Pay Off," *Biodiesel Magazine*, Grand Forks, ND.
http://biodieselmagazine.com/article-print.jsp?article_id=2047.
- Schill, S. R., 2009a, "Exxon Announces \$600 Million Algae Project," *Biodiesel Magazine*, Grand Forks, ND.
http://www.biodieselmagazine.com/article.jsp?article_id=3586&q=venter&category_id=5
- Schill, S. R., 2009b, "House Bill Grandfathers Biodiesel Into RFS, Orders Study of Indirect Land Use," *Biodiesel Magazine*, Grand Forks, ND.
http://www.biodieselmagazine.com/article.jsp?article_id=3573
- Schobert, H., 2006, *JP-900 Jet Fuel Summit Meeting*, The Seawater Foundation, State College, PA.
<http://www.seawaterfoundation.org/>.
- Thielert Aircraft Engines, 2009, Hamburg, Germany.
<http://www.thielert.com/>
- United States Department of Agriculture, National Resources Conservation Service, 2006, "Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations," Soil Quality—Agronomy Technical Note No. 19, Washington, DC.
http://soils.usda.gov/sqi/management/files/sq_atn_19.pdf
- University of Delaware, 2009, "John L. Gallagher," Newark, DE. <http://www.ocean.udel.edu/people/profile.aspx?jackg>
- University of Michigan, 2009, "Researchers Predict Large 2009 Gulf of Mexico 'Dead Zone'," Space & Earth, Ann Arbor, MI. <http://www.physorg.com/print164546116.html>
- Valdes, R., 2009, "How the Predator UAV Works," HowStuffWorks, Inc., Atlanta, GA.
<http://science.howstuffworks.com/predator1.htm>
- Virent Energy Systems, Inc., 2007, Madison, WI.
<http://www.virent.com/>
- Washington State University, 2008, "Crop Residue May Be Too Valuable To Harvest For Biofuels," *Science Daily*, Rockville, MD.
<http://www.sciencedaily.com/releases/2008/07/080715190110.htm>
- Wikipedia, 2009a, Cotton. <http://en.wikipedia.org/wiki/Cotton>
- Wikipedia, 2009b, Okra. <http://en.wikipedia.org/wiki/Okra>
- Wikipedia, 2009c, Kenaf. <http://en.wikipedia.org/wiki/Kenaf>
- Wikipedia, 2009d, "Thlaspi Arvense,"
http://en.wikipedia.org/wiki/Thlaspi_arvense
- Wikipedia, 2009e, "Pongamia Pinnata."
http://en.wikipedia.org/wiki/Pongamia_pinnata.
- Wikipedia, 2009f, "Triglyceride."
<http://en.wikipedia.org/wiki/Triglyceride>
- Wikipedia, 2009g, "Avgas."
<http://en.wikipedia.org/wiki/Avgas>
- Wolverton, B. C., 1997, *How to Grow Fresh Air*, Penguin Books, New York, NY.
- Wolverton, B. C., and Takenaka, K., (Scheduled Release Fall 2009), *Plants: How They Contribute to Human Health and Well-being*, Roli Books, New Delhi.
- Wolverton, B. C., and Wolverton, J. D., 2001, "Growing Clean Water: Nature's Solution to Water Pollution," Wolverton Environmental Services, Inc., Picayune, MS.
- Zamora, A., 2005, "Fats, Oils, Fatty Acids, Triglycerides," *Scientific Psychic*.
<http://www.scientificpsychic.com/fitness/fattyacids.html>