Fuels for Distillate and Jet Market

US Liquid Fuels and Products Market Size (billion gallons/year)

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2050</th>
<th>Growth Rate 2015 – 2050 (%/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>141</td>
<td>114</td>
<td>-0.7%</td>
</tr>
<tr>
<td>Diesel</td>
<td>61</td>
<td>64</td>
<td>0.3%</td>
</tr>
<tr>
<td>Liquefied Petroleum Gas[1]</td>
<td>39</td>
<td>54</td>
<td>1.0%</td>
</tr>
<tr>
<td>Other[2]</td>
<td>31</td>
<td>38</td>
<td>0.7%</td>
</tr>
<tr>
<td>Jet Fuel</td>
<td>24</td>
<td>39</td>
<td>1.4%</td>
</tr>
<tr>
<td>Residual fuel oil</td>
<td>4</td>
<td>6</td>
<td>0.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>300</strong></td>
<td><strong>315</strong></td>
<td></td>
</tr>
</tbody>
</table>

1. Includes ethane, natural gasoline, and refinery olefins.
2. Includes kerosene, petrochemical feedstocks, lubricants, waxes, asphalt, and others commodities.


- Defense – Facilitating commercial scale production capacity
- Aviation – Testing and certification of alternative fuels
- Marine – Meeting environmental regulations
## DPA Initiative Accomplishments

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Feedstock</th>
<th>Capacity (million gallons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fulcrum</td>
<td>McCarran, NV</td>
<td>Municipal solid waste</td>
<td>10</td>
</tr>
<tr>
<td>Emerald</td>
<td>Gulf Coast</td>
<td>Fats, oils, and greases</td>
<td>82</td>
</tr>
<tr>
<td>Red Rock</td>
<td>Lakeview, OR</td>
<td>Woody biomass</td>
<td>12</td>
</tr>
</tbody>
</table>

- Fuels are approved for use as jet fuel by ASTM at up to 50/50 blends.
- Fuels successfully demonstrated during Rim of the Pacific (RIMPAC) demonstration in 2012 for ships and planes.
- Fuels can be utilized in Navy’s warfighting platforms with no degradation to performance or mission.
As fuels become available Navy will make advanced drop-in biofuels a regular part of its bulk fuel procurement.

USDA has awarded Fulcrum a $105 million Biorefinery Assistance Program loan guarantee through Bank of America for construction of their facility. The total project cost is $266 million. 147,000 tons/year of MSW will be gasified to synthesis gas followed by Fischer-Tropsch conversion to jet fuel.

Cathay Pacific Airways has become an investor in Fulcrum and has negotiated a 10 year supply agreement for jet fuel.

Southwest Airlines has signed a fuel purchase agreement with Red Rock for 3 million gallons/year of jet fuel. Blended product will be used at Southwest’s Bay Area operations. 140,000 dry tons/year of woody biomass feedstock will be converted into renewable jet, diesel, and naphtha.
Criteria for Alternative Fuels in Aviation

- Engine re-light at altitude, polar climate, in winter - transport properties of alternative fuels and/or blends have to be within acceptable limits (viscosity, freeze point, fluid flow at low temperatures)
- Flame stability – compounds in alternative fuels should not adversely impact flame stability
- Energy content – should be as high as fossil derived jet fuel or higher
- Emissions
  - Aromatics – too much can cause soot, too little can cause seal swell problems which becomes a maintenance issue
  - Greenhouse gas emissions should be lower than fossil derived jet fuel on a life cycle basis
ASTM Approved Pathways for Alternative Jet Fuels

- Biomass gasification, synthesis gas, Fischer-Tropsch conversion to produce synthetic paraffinic kerosene (FT-SPK) – 50% maximum blend (Fulcrum, Red Rock)
- Fats/oils/greases, oil seed crops, other lipids, Hydro-treated esters and fatty acids (HEFA-SPK) processed into jet fuel – 50% maximum blend, (AltAir, Paramount, California)
- Biochemical conversion of sugars to iso-paraffins (HFS-SIP) – 10% maximum blend (Amyris, farnasene, Brazil)
- Biomass gasification synthesis gas, Fischer-Tropsch conversion with aromatic alkylation (FT-SPK/A) – 50% maximum blend
- Biochemical conversion of sugars to iso-butanol followed by oligomerization to jet components, alcohol-to-jet (ATJ-SPK) – 30% maximum blend (Gevo, Luverne, MN)
Status of ASTM Certification of Alternative Jet Fuel

• **ASTM Certifications in process**
  - Catalytic hydro-thermolysis of lipids to jet fuel – ARA
  - Alcohol to jet – synthetic paraffinic kerosene (bio/thermochemical butanol or ethanol – Lanzatech, Byogy
  - Synthetic kerosene/synthetic aromatic kerosene – catalytic conversion of sugars and aqueous phase reforming to jet fuel – Shell/Virent
  - Hydro-treated esters and fatty acids+ (HEFA)+ - wider cut HEFA with renewable diesel – Boeing
  - Pyrolysis from lignocellulosic feedstocks – UOP, Kior
  - Fischer-Tropsch synthetic kerosene with aromatics – Sasol, Rentech
  - Co-processing – multiple approaches – Chevron, BP, Phillips 66

• **Pathways in future that could enter pipeline**
  - Vertimass – catalytic conversion of alcohols
  - Global Bioenergies – biochemical production of isobutene
  - Algenol – hydrothermal liquefaction of algae
Latest Activities

- **AltAir** - United Airlines has begun using commercial scale alternative jet fuel volumes for regularly scheduled flights from LAX. Purchase 15 mgy from AltAir Paramount over 3 years.

- **Gevo** – Lufthansa agreement for alcohol-to-jet from Luverne, MN facility. 8 mgy from Gevo or up to 40 mgy over 5 years.

- **Fulcrum** – Strategic partnership between United, Cathay Pacific, BP Ventures, Air BP businesses to invest $30 million. 10 year off-take for 50 mgy from plants in North America.

- **Red Rock** – 3 million gallons/year of renewable jet fuel for 3 years for FedEx Express. Southwest purchase agreement from Lakeview, Oregon facility to convert 140,000 dry tons/year of woody biomass into 15 million gallons/year of renewable jet, diesel, and naphtha.

- **Byogy** – AVAPCO biomass-to-ethanol with Byogy alcohol-to-jet process to produce jet fuel from woody biomass. DOE award of $3.7 million to develop demonstration scale biorefinery.

- **UOP** – Petrixo Oil and Gas to produce renewable jet and diesel at new refinery in Fujairah, UAE to convert 500,000 metric tonnes of renewable feedstocks into 1 million tons/year of biofuels.

- **KLM and SkyNRG** for 3 year agreement enabling LAX flights

- Neste, KLM, SAS, Lufthansa, SkyNRG Nordic, and Oslo Airport
The Issue of Scale

• From IAH there are at least IAH 7 non-stop flights/day to Europe

• Average flight time from IAH to Europe about 10.5 hour, additional 2 hours of fuel requirement for reserve and alternate destination requirements for total 12.5 hours of fuel

• Fuel burn 3,000 gallons/hour for wide-body aircraft

• Assume 20/80 biofuel/fossil ratio

• Fuel burn calculation suggests 19 million gallons/year facility could supply IAH for all 7 flights to Europe
Gas-to-Liquids Micro-Channel Technology

- First distributed scale Fischer-Tropsch product commercially produced at Envia landfill gas and waste biomass GTL plant in East Oak landfill, Oklahoma City, Oklahoma
- Team: Waste Management, NRG, Velocys, Ventech, Envia - to convert gas to paraffin wax, diesel, and naphtha at distributed scale
- Scale: 1,000 barrel/day (15 million gallons/year) compared to conventional Fischer-Tropsch scale of 30,000 barrels/day (460 million gallons/year) or more
- Price: with natural gas at $3.89/million Btu, Velocys can produce diesel at $1.57/gallon (no RIN or LCFS credits)
- Conversion efficiency: 57 – 76 gallons/ton waste biomass
- 15.3 million gallons/year from 200,000 tons of biomass
Well-to-Wake GHG Emissions of Alternative Jet Fuels

- LCA functional unit gCO2e/MJ of fuel consumption (from GREET2016)
- LUC-related emissions are not included
- Other key factors: Technology readiness level (TRL), production costs, resource availability and fuel types

Source: simulation results with GREET2016 by ANL
Corn-ethanol-based ETJ reduces GHG emissions by 23%, cellulosic by 71% compared to petroleum jet.

Stover-based STJ reduces GHG emissions by 27 – 71% depending on conversion process and hydrogen source.

Note: LUC-related emissions are not included; ETJ-corn could have LUC GHG of 8 grams/MJ; stover pathways do not cause LUC.

Source: Han, Tao, and Wang, 2017 in Biotechnology for Biofuels
Bio-aviation Fuel Pathways by Feedstock

- **Oil Crops**
- **Algae**
- **Waste Oil**
  - Oil Extraction
  - Bio-Oil
    - Hydroprocessing
  - Hydroprocessed Renewable Jet

- **Starch and Sugar Crops**
  - Fermentation
  - Alcohol
    - ATJ
    - Alcohol-To-Jet

- **Cellulosic Biomass** (e.g., Herbaceous, Woody, Ag. and Forest Residue, etc.)
  - Gasification
  - Sugar
    - STJ
    - Sugar-To-Jet
  - Syngas
  - Fischer-Tropsch Synthesis
  - Pyro-Oil
    - Hydroprocessing
    - Pyrolysis
    - Renewable Jet
Co-products in the Bio-Aviation Fuel Pathways

Oil Crops
- Algae
- Waste Oil
  - Oil Extraction
    - Meal
    - Bio-Oil
      - Hydroprocessing
        - Other fuels
          - Hydropreated Renewable Jet

Starch and Sugar Crops
- Fermentation
  - DGS
  - Electricity
    - Alcohol
      - ATJ
        - Alcohol-To-Jet
          - Other fuels
            - Hydroprocessed Renewable Jet
    - Sugar
      - STJ
        - Sugar-To-Jet
          - Other fuels
            - Fischer-Tropsch Jet
              - Other fuels
                - Pyrolysis Renewable Jet

Cellulosic Biomass
- Gasification
  - Syngas
    - Fischer-Tropsch Synthesis
      - Other fuels
        - Pyro-Oil
          - Biochar
            - Hydroprocessing
              - Other fuels