ARPA-E
CHANGING WHAT'S POSSIBLE

Electrofuels Program Overview

B.1. BACKGROUND

Liquid fuels are a ubiquitous component of the nation's energy landscape, supplying reliable energy for all means of transportation, as well as heating, industrial manufacturing, and electricity production, all to a lesser extent.

The transportation sector is heavily reliant on liquid fuels. According to the Energy Information Administration, the United States consumed 27.8 quadrillion Btu of energy for transportation in 2008, of which 97% was supplied by liquid fuels[1,2].

Buffered largely by the projected increase in deployment of plug-in hybrids and electric vehicles and mandated increases to corporate average fuel economy standards, the demand for liquid fuels for transportation is projected to remain fairly constant over the next twenty years. As for the types of liquid fuel consumed, petroleum-derived motor gasoline, diesel, and jet fuel are still anticipated to comprise nearly 90% of the demand for liquid fuels in 2030[3].

The nation's dependency on petroleum-derived liquid fuels comes with an increasing economic cost. Net expenditures for crude oil (and petroleum products) imports are projected to increase at an average rate of 1.3% per year, rising from 273 billion dollars in 2006 to 377 billion dollars in 2030[4]. Further, the geo-political instability of foreign oil suppliers creates a significant vulnerability for national energy security.

Over the past several years, the federal government, notably the U.S. Department of Energy – especially the Office of Science and Office of Energy Efficiency and Renewable Energy, have spearheaded research, development, and deployment (RD&D) of next generation liquid fuel production technologies to address the challenges associated with reliance on foreign oil. In particular, DOE, in partnership with multiple Federal partners, including U.S. Department of Agriculture and Environmental Protection Agency, have dramatically increased the efficiency of first-generation corn grain ethanol and accelerated the deployment of second-generation biomass-ethanol technologies through targeted RD&D programs. Indeed, from 2002 to 2008, the U.S. fuel ethanol demand has increased from 2 billion gallons per year to 9.6 billion gallons per year, an amount equivalent to the displacement of 6.5 billion gallons of gasoline on an energy equivalent basis[5], thereby demonstrating the feasibility of new liquid fuels at commercial-scale.

While domestically-produced biofuels such as ethanol increase the nation's energy security, there remains considerable need for next-generation renewable fuels that integrate into the nation's current fuel refining and distribution infrastructure. Such next-generation fuels should not divert resources currently utilized for food production. To address this need, ARPA-E is interested in exploring new paradigms for the production of infrastructure-compatible renewable liquid fuels through this funding opportunity announcement. Specifically ARPA-E seeks innovation in the area of non-photosynthetic autotrophic production of infrastructure-compatible, energy dense liquid fuels. ARPA-E will fund high risk, high reward research efforts that, if successful, will have a transformational impact on renewable liquid fuels. Approaches that are only incremental improvements to existing technologies are not of interest.

B.2. OBJECTIVES

ARPA-E seeks to explore innovative opportunities and pursue new approaches to efficiently convert CO_2 and electrical energy to energy-dense, infrastructure compatible liquid fuels – diesel fuel, JP-8 aviation fuel, and high-octane fuels for four-stroke internal combustion engines – by non-photosynthetic means. Such electrical energy could be produced from

[1] DOE Energy Information Administration, Annual Energy Outlook 2009 Table 2. Energy Consumption by Sector & Source, http://www.eia.doe.gov/oiaf/aeo/excel/aeotab_2.xls
[2] For accounting purposes, transportation liquid fuels include liquefied petroleum gases, E85, motor gasoline, jet fuel, distillate fuel oil, residual fuel oil, liquid hydrogen, and other.
[3] DOE Energy Information Administration, Annual Energy Outlook 2009 Table 11. Liquid Fuels Supply and Disposition, http://www.eia.doe.gov/oiaf/aeo/excel/aeotab_11.xls
[4] In 2007 dollars; Ibid
[5] Renewable Fuels Association, http://www.ethanolrfa.org/industry/statistics/#B

sunlight or through other means, and might be imported into cells as dihydrogen, as reduced earth-abundant metal ions or readily available redox-active species that serve as energy carriers, or directly as electric current. A possible sub-objective might involve the export of electrons from photosynthetic bacteria, or the co-culture of photoactive bacteria. To this end, ARPA-E seeks innovative proposals in the following Area of Interest:

Area of Interest: Organism Development and System Integration

A description of the technical requirements for proposals submitted under the Area of Interest is provided below. Considering the breadth and scope of the Area of Interest, applicants are encouraged to partner together and bring a multi-disciplinary approach to the problem in order to more effectively and substantially address the program objectives.

B.3. AREAS OF INTEREST

Area of Interest: Organism Development and System Integration

High efficiency routes to energy-dense, infrastructure compatible liquid fuels for transportation from sunlight and CO_2 are urgently required. Although photosynthetic routes show promise, overall efficiencies remain low and the ability to deploy many possible configurations remains unclear. Progress has been made in the direct inorganic conversion of photosynthetic energy to reduced chemical species; however, the ability to form carbon-carbon bonds in a high-yielding predictable approach remains limited.

Much of the carbon on Earth is fixed via non-photosynthetic pathways, including the Wood-Ljungdhal pathway used by acetogens and the methanogenic pathways used by many Archaea. Although under heterotrophic growth conditions these organisms use CO_2 as electron acceptors, both groups are capable of autotrophic growth and carbon reduction, utilizing reducing equivalents as diverse as metal ions, dihydrogen and electric current. To date, these organisms have not been extensively evaluated for their ability to produce energy-dense, complex, infrastructure compatible liquid fuels for transportation.

Synthetic biology and metabolic engineering have demonstrated significant potential to modify microbiological metabolic pathways to produce non-native chemicals and fuels. ARPA-E is interested in leveraging and applying such technologies to develop novel biological systems that can directly utilize electrons, hydrogen, or reduced metal ions as a source of reducing equivalents for the conversion of CO_2 to liquid fuels. The desired organism will be robust and capable of being cultured and maintained at commercial scale. Organisms and biosynthetic routes should be amenable to independent, unbiased validation. Examples of topics sought include, but are not limited to:

- The direct use of electric current to produce energy-dense, infrastructure compatible liquid fuels directly from CO_2 as the only carbon source;
- The use of reversibly reducible earth abundant metal ions or of cheap, readily available redox active organic materials as intermediaries, transferring reducing equivalents into a cell, which produces energy-dense, infrastructure compatible liquid fuels directly from CO_2 as the only carbon source;
- The development of Calvin cycles variants that accepts reducing equivalents from regenerable agents other than Photosystems I and II or directly from solar current;
- The development of organisms that assimilate solar hydrogen with high affinity to produce energy-dense, infrastructure compatible liquid fuels directly from CO_2 as the only carbon source.

This FOA recognizes that organism development is only one component of program success. Large scale deployment requires creative approaches and innovation to design, develop, and integrate practical and economically viable production systems. The entire production system must be scalable, robust, and relatively straightforward to maintain and operate. System design and development should seek to maximize efficiency and minimize cost. Examples of topics include, but are not limited to:

- The design and development of a large-scale, economically viable reverse microbial fuel cell;

- The development of innovative concepts for the effective shuttling and recycling of reduced metal ions or readily available organic cofactors and coupling to biological systems;
- The transformational design and development of novel bioreactors that maximize efficiency and reduce cost.

In the Concept Paper phase, applicants should ideally present data to quantitatively describe the current and/or anticipated performance of the proposed technology concept, the technology attributes that would be enabled as a result of a successful program, and the benefits of the proposed technology over the current state-of-the-art. The Concept Paper should acknowledge the general requirements for the Area of Interest as outlined in this Section. The Concept Paper should distinguish the proposed work from other R&D in substantively similar areas, especially if DOE is funding efforts that appear to be similar.

In the Full Application phase, applicants must present data to quantitatively describe the current and/or anticipated performance of the proposed technology concept, the technology attributes that would be enabled as a result of a successful program, and the benefits of the proposed technology over current state-of-the-art. Performance metrics (e.g. $/Btu of final fuel) must be identified, and the applicants shall propose final deliverables and target final values for performance metrics. Improvements to energy efficiency and cost need to be supported by an energy and cost model with explicitly stated assumptions and variables. The Full Proposal will acknowledge the general requirements for the Area of Interest as outlined in this Section. ARPA-E will provide the final structure and requirements of the Full Application when Concept Paper notifications are issued.

General Requirements

The proposal must clearly define the following components:

- Specify liquid fuel type (diesel fuel, JP-8 aviation fuel, and/or high octane fuels for four-stroke internal combustion engines); liquid fuels ≥ 85 research octane or ≥ 40 cetane are desirable
- Anticipated liquid fuel energy density ≥ 32 megajoules per kilogram is desired
- Anticipated liquid fuel heat of vaporization < 0.5 megajoules per kilogram is desired
- Anticipated liquid fuel-energy-out to photon/electrical energy-in of the envisioned system; an overall energy efficiency > 1% is required
- Rare earth elements or organic redox shuttles that cannot be deployed economically at scale should be avoided